Durham University

Durham E-Theses

Examining the Potential for Isotope Analyses of Carbon, Nitrogen, and Sulphur in Burned Bone from Experimental and Archaeological Contexts.

SARAH HEATHER MORRISON

How to cite:

MORRISON, SARAH HEATHER (2022) Examining the Potential for Isotope Analyses of Carbon, Nitrogen, and Sulphur in Burned Bone from Experimental and Archaeological Contexts. Doctoral thesis, Durham University.

Use policy

The full-text may be used and/or reproduced, and given to third parties in any format or medium, without prior permission or charge, for personal research or study, educational, or not-for-profit purposes provided that:

- a full bibliographic reference is made to the original source
- a https://etheses.durham.ac.uk/id/eprint/14356/ is made to the metadata record in Durham E-Theses
- the full-text is not changed in any way

The full-text must not be sold in any format or medium without the formal permission of the copyright holders.

Please consult the full Durham E-Theses policy for further details.

Academic Support Office, The Palatine Centre, Durham University, Stockton Road, Durham, DH1 3LE
e-mail: e-theses.admin@durham.ac.uk Tel: +44 0191 334 6107
https://etheses.durham.ac.uk

Examining the Potential for Isotope Analyses of Carbon, Nitrogen, and Sulphur in Burned Bone from Experimental and Archaeological Contexts.

Sarah Morrison

Thesis submitted for the degree of Doctor of Philosophy

Department of Archaeology

Durham University

2021

“The copyright of this thesis rests with the author. No quotation from it should be published without the author’s prior written consent and information derived from it should be acknowledged.”

Acknowledgements:

This thesis would not have come to fruition without the support and assistance of many people. First, I would like to thank my supervisors, Rebecca Gowland and Janet Montgomery, whose guidance and expertise were essential to this project. I would like to thank my external advisor, Tim Thompson, for his expertise and advice in designing heating experiments and in understanding FTIR data. To my examiners, Andrew Millard and Christophe Snoeck, thank you for reviewing my thesis and helping to correct my mistakes – any that remain are my own. I am indebted to Darren Gröcke for his advice on lipid removal procedures and for the analysis of 126 isotope samples. I would like to thank Jeff Veitch for his assistance with photography and for his input on colour appearance models and thank you to Chris Caple who explained how to use the spectrophotometer so that I could take advantage of Jeff's advice. To Beth Upex and Steve Robertson, thank you for help in the design and actualisation of my controlled heating experiment. Thank you to Helga Halldorsdottir for explaining how to use the FTIR at Teesside and to Kamal Badreshany for providing the same assistance with the FTIR in Durham. I would also like to thank Sarah Ellingham for digging out her own FTIR research to help me understand my results. To Kurt Gron, Jo Moore and Janet Montgomery, thank you for showing me around the isotope laboratory. Thank you also to Rose Nicholson who allowed me to access the Elsham and Cleatham collections.

I would like to thank Team Durham and specifically the Durham Fencing Team for providing me with funding during this project. Thank you to Laszlo and Rit for all the time they spent on our team and to my teammates over the many years at Durham. I also must thank Jujie, the coach who became family, for training me to the point where someone was willing to pay to have me on their team!

Finally, to the people who supported me along the way. To Brady, Jamie, James, and Emilio for pretending that every statistical, mathematical, or coding problem I begged you to fix was in fact a fun activity. To John and Liz who took me in and treated me like family from day one. To my parents and my sister who have supported me through everything I have

ever tried to do and for loving me whether I succeeded or not. Ultimately, to Simon, you were there for me at every turn, and I never could have done this without you.

Abstract:

The aim of this project was to determine whether isotope analyses of carbon, nitrogen and sulphur can be conducted on collagen extracted from burned bone. This project was conducted in two phases: a controlled heating experiment and an archaeological application. The controlled heating experiment used cow (*Bos taurus*) bone to test the temperature thresholds for the conservation of $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ values. These samples were also used to test the efficacy of Fourier Transform Infrared spectroscopy (FTIR) and colour analysis, for determining the burning intensities experienced by bone burned in unknown conditions.

The experiment showed that $\delta^{13}C$ values were relatively unchanged up to 400°C (<2‰ variation), while $\delta^{15}N$ values were relatively stable up to 200°C (0.5‰ variation). Values of $\delta^{34}S$ were also relatively stable up to 200°C (1.4‰ variation). Colour change and FTIR data were well correlated with the change in isotope ratios. Models estimating burning intensities were created from the FTIR data.

For the archaeological application, samples were selected from two early Anglo-Saxon cemetery sites: Elsham and Cleatham. Samples were selected from both inhumed and cremated individuals. Among the inhumed individuals $\delta^{13}C$ values suggested a C_3 terrestrial diet and $\delta^{15}N$ values suggested protein derived largely from terrestrial herbivores, as expected for the early Anglo-Saxon period. However, $\delta^{34}S$ values suggested the consumption of freshwater resources and that this consumption was related to both the age and sex of the individual.

The experimental data shows that there is potential for isotope analyses of cremated remains, as during the cremation process heat exposures are not uniform across the body. The samples selected for the archaeological application, however, were not successful. Bone samples heated in controlled conditions produced viable collagen for isotope analysis; however, there are several differences between experiments conducted in a muffle furnace and open-air pyre cremation that need to be investigated further. Additionally, the influence of taphonomy on collagen survival in burned bone needs to be quantified. Finally, methods of sample selection need to be improved to find bone samples from

archaeologically cremated remains that are most likely to retain viable collagen. While there is significant research that must be conducted before this research can be widely applied there are a multitude of cultures that practised cremation throughout history and around the world that could be investigated through the analyses proposed in this project.

Table of Contents

Chapter 1: Introduction 17

1.1 Introduction 17

1.2: Cremations in early Anglo-Saxon England 20

1.3 Focus and Scope 22

1.4 Relevance to the Discipline 22

1.5 Research Questions 24

1.6 Aims and Objectives 25

1.7 Definition of Terms 26

1.8 Structure of the Thesis 27

Chapter 2: Anglo-Saxon Background: 29

2.1 Introduction 29

2.2 The Development of Anglo-Saxon Archaeology 30

2.2.1 Antiquarian: 30
2.2.2 Victorian: 31
2.2.3 Culture-Historic: 33
2.2.4 Processual: 35
2.2.5 Post-processual: 36
2.2.6. Feminist Archaeology: 37
2.2.7. Post-structuralism: 39
2.2.8. Incorporating Osteology: 40

2.3 Dating the Anglo-Saxons 49

2.4 Cremation Burial 52

2.4.1 The Funeral Pyre 54
2.4.2 Collection of Remains 58
2.4.3 Cremation Urns: 60
2.4.4 Pyre and Grave Goods: 64
2.4.5 Burial: 71
2.4.6 Summary: 73

2.5 Mixed Rite Cemeteries 74

2.6 Conclusion 77

Chapter 3: General Cremation Research 79

3.1: Introduction 79

3.2: History of Cremation Research 79

3.3: Fire Dynamics 83

3.4: Reaction of Human Remains to Fire 85

3.4.1: Soft Tissue 85
3.4.2: Thermal Alteration of Bone 88

3.5: Methods of Analysis for Burned Human Remains 97

3.5.1: Developing an Osteoprofile 97
3.5.2: Colour 100
3.5.3: Weight 108

3.5.4. Histology 110
3.5.5: Crystallinity 115
3.5.6: Other Methods of Analysis 122
3.6: Summary 123
Chapter 4: Isotopic Studies: 125
4.1: Introduction 125
4.2: Basic Terminology 126
4.3: Sample Materials 127
4.4: Carbon 131
4.5: Nitrogen 135
4.6: Sulphur 139
4.7: Interpreting Diet 147
4.7.1 Stress Studies: Weaning and Starvation 158
4.8: Isotope Studies on Burned Bone 160
4.9: Isotopic Diet Reconstructions on Anglo-Saxon Populations 167
4.10: Summary 170
Chapter 5: Materials and Methods: 171
5.1 Introduction: 171
5.2 Controlled Heating Experiment - Materials: 172
5.3 Controlled Heating Experiment - Methods: 173
5.3.1 Sample Preparation: 173
5.3.2 Heating Experiment: 175
5.3.3 Colour Analysis: 176
5.3.4 FTIR Spectroscopic Analysis: 179
5.3.5 Lipid Removal: 180
5.3.6 Collagen Extraction: 181
5.3.7 Isotope analysis: 182
5.3.8 Statistical Methods: 184
5.4 Archaeological Application – Materials: 185
5.4.1 The Kingdom of Lindsey: 186
5.4.2: Cleatham 190
5.4.3: Elsham 203
5.4.4: Geochemical Context of Northern Lincolnshire: 212
5.4.5: Sample Selected for Isotope Analysis 219
5.5 Archaeological Application – Methods: 225
Chapter 6: Controlled Heating Experiment Results: 226
6.1 Introduction: 226
6.2 Temperature Fluctuation: 226
6.3 Changes in Bone due to Heat Exposure: 228
6.3.1: Change in Mass: 228
6.3.2: Colour Change: 229
6.3.3: Chemical Changes: 232
6.4 Collagen Yield: 236

6.5 Isotope Analyses: **239**
6.5.1 Carbon and Nitrogen Isotope Analyses: 239
6.5.2 Sulphur Analysis: 244

6.6 Conclusions: **248**

Chapter 7: Results from Archaeological Application: ***249***

7.1 Introduction: **249**

7.2 Temperature Estimation: **249**
7.2.1 Colour Analysis: 250
7.2.2 Fourier Transform Infrared (FTIR) Spectroscopic Analysis: 253

7.3 Collagen Yield: **259**

7.4 Isotope Analyses: **262**
7.4.1: Carbon and Nitrogen Analyses: 262
7.4.2 Sulphur Analysis: 278

7.5 Conclusion: **288**

Chapter 8: Discussion ***290***

8.1 Introduction **290**

8.2 Results from the Controlled Heating Experiment **290**
8.2.1: Mass 290
8.2.2 Colour Analysis 291
8.2.3 Fourier Transform Infrared Spectroscopy (FTIR) 291
8.2.4 Collagen Yield 292
8.2.5 Stable Isotope Analysis 293
8.2.6 Experiment Design: 298
8.2.7 Summary 301

8.3 Results from the Archaeological Application **302**
8.3.1 Data from Inhumed Individuals 302
8.3.2 Data from Cremated Individuals 312

8.4 Comparing the Results of the Controlled Heating Experiment and the Archaeological Application **313**

8.5 Wider Research Context **316**
8.5.1 Determining Unknown Burning Conditions 316
8.5.2 Variation in Cremation Strategies Over Time 318
8.5.3 Cremated Animal Remains 325
8.5.4 Forensic Applications 326
8.5.5 Dearth of Archaeological Research on Cremated Remains 331

8.6: Summary **333**

Chapter 9: Conclusion ***335***

9.1 Introduction **335**

9.2 Research Questions **336**

9.3 Limitations and Points for Consideration **340**
9.3.1 Controlled Heating Experiment Design 340
9.3.2 Colour Analysis by Spectrophotometer 340
9.3.3 Estimating Burning Conditions via FTIR Analysis 341
9.3.4 Method of Collagen Extraction 342
9.3.5 Selection of Samples from Cremated Individuals 343

9.3.6 Small Sample Sizes 344
9.3.7 Methodology Involves Destructive Testing 345
9.3.8 Interpretation of Isotope Results 345
9.4 Future Research 347
9.5 Summary 350
References: 353
Appendix 1: Written Sources for the Early Anglo-Saxon Period 393
A1.1 Gildas and the Fall of Roman Britain 393
A1.2 Bede and the Conversion of the English 400
A1.3 Nennius, the Romantic British Perspective 404
A1.4 The Anglo-Saxon Chronicle, the West Saxon annals 406
A1.5 Law Codes of the Anglo-Saxon Kings 408
A1.6 Beowulf, early English poetry 410
Appendix 2 – Temperature Fluctuations during the Controlled Heating Experiment 415
Appendix 3 – Change in Mass During the Controlled Heating Experiment – Raw Data ... 416
Appendix 4 – Photographs of Bone Samples from Controlled Heating Experiment 418
Appendix 5 – Raw Colour Data from the Controlled Heating Experiment 452
Appendix 6 – FTIR Data from the Controlled Heating Experiment 472
Appendix 7 – Collagen Extraction for Controlled Heating Experiment 475
Appendix 8 – Stable Isotope Analysis Data from Controlled Heating Experiment 478
Appendix 9 – Photographs of Samples taken from Burials at Elsham and Cleatham 480
Appendix 10 – Colour Data from the Archaeological Application 506
Appendix 11 – FTIR Data from the Archaeological Application 520
Appendix 12: Collagen Extraction from Samples taken from Inhumed Individuals at Elsham and Cleatham 524
Appendix 13: Collagen Extraction from Samples taken from Cremated Individuals at Elsham and Cleatham 525
Appendix 14: Stable Isotope data from Archaeological Samples 528

Figure Number	*Description*	*Page Number*
1.1	World map of cultures practicing cremation	*23*
2.1	Images from Inventorium Sepulchrale (Faussett, 1856)	*31*
2.2	Map of England circa 673	*33*
2.3	Variations in Anglo-Saxon female dress over the lifecycle (Stoodley, 2000)	*37*
2.4	Seven main burial positions (Mui, 2018)	*41*
2.5	Group of seven inter-related urns at Cleatham (Leahy, 2007)	*49*
2.6	Anglo-Saxon pyre structure	*55*
2.7	Average weight of bone recovered from cremation burials at Anglo-Saxon cemeteries	*59*
2.8	Comb and toiletry set (Faussett, 1856; Leahy, 2007)	*67*
2.9	Proportion of Anglo-Saxon cremation burials containing grave/pyre goods and faunal remains (McKinley, 1994a; Bond, 1996; Squires, 2016)	*69*
3.1	Laminar versus turbulent energy flow	*84*
3.2	Progression of thermal exposure in human remains (Symes et al., 2015)	*86*
3.3	Pugilistic posture	*88*
3.4	Thermal alteration of bone collagen (Richter, 1986; Koon et al., 2010)	*91*
3.5	Thermal alteration phases of bone (Mayne Correia, 1997; Thompson, 2005)	*92*
3.6	'Sandwich' colour pattern seen in burned bone	*108*
4.1	Equation for calculating delta values	*127*
4.2	The carbon cycle	*135*
4.3	The nitrogen cycle	*139*
4.4	The sulphur cycle	*146*
4.5	Food source map for $\delta^{13}C$ and $\delta^{15}N$ values	*150*
4.6	Food web diagram	*150*
4.7	Examples of linear mixing models	*152*
4.8	Equations for determining the proportional contributions of food sources	*152*
4.9	Examples of dietary shift seen through $\delta^{13}C$ and $\delta^{15}N$ values	*153*
4.10	Potential of sulphur analysis to recognise freshwater dietary contributions	*156*
4.11	Dietary model, $\delta^{13}C$ and $\delta^{34}S$ values	*157*
4.12	Anglo-Saxon dietary data from previous studies, $\delta^{13}C$ and $\delta^{15}N$ values	*169*
5.1	Sample preparation from bovine humerus for controlled heating experiment	*174*

5.2	Change in mean standard deviation to determine number of measurements needed for colour analysis	*178*
5.3	Spectrophotometer set-up	*178*
5.4	Schematic of elemental analyser and isotope ratio mass spectrometer for carbon and nitrogen analyses	*183*
5.5	Equation for calculating the critical value for the Kolmogorov-Smirnov test	*184*
5.6	Equation for calculating U values for two populations, U_1 and U_2, and equation for calculating z_U for the Mann-Whitney U test	*185*
5.7	Site plan for Cleatham cemetery	*192*
5.8	Histogram showing frequency of pyre and grave goods identified at Cleatham	*202*
5.9	Distribution of weights of burned bone recovered from cremation burials at Cleatham	*203*
5.10	Site plan of Elsham cemetery	*204*
5.11	Histogram showing frequency of pyre and grave goods identified at Elsham	*211*
5.12	Distribution of weights of burned bone recovered from cremation burials at Elsham	*212*
5.13	English and Welsh map of $\delta^{34}S$ values	*213*
5.14	Geology surrounding Elsham	*214*
5.15	Geology surrounding Cleatham	*214*
5.16	Watercourses around Elsham and Cleatham	*215*
5.17	Map of England and Wales showing archaeological sites with previously published $\delta^{34}S$ data	*217*
5.18	Dietary data from previous studies: $\delta^{13}C$, $\delta^{15}N$ and $\delta^{34}S$	*218*
5.19	Colour scales used in selecting cremated bone from Elsham and Cleatham	*222*
5.20	Example of samples selected from Cleatham individual MT84FT.	*223*
6.1	Temperature fluctuation during controlled heating experiment	*227*
6.2	Scatterplot of temperature fluctuations versus target temperatures during the controlled heating experiment	*227*
6.3	Change in mass of bone samples during the controlled heating experiment	*228*
6.4	Euclidean distance between before and after colour coordinates in CIEL*a*b* colourspace	*231*
6.5	Colour data in CIEL*a*b* colourspace	*231*
6.6	FTIR data from controlled heating experiment, absorbance versus wavenumber	*233*
6.7	Crystallinity Index versus temperature	*234*
6.8	A_{1415}/A_{1035} versus temperature	*234*
6.9	A_{1650}/A_{1415} versus temperature	*235*
6.10	A_{900}/A_{1035} versus temperature	*235*

6.11	A_{1650}/A_{1035} versus temperature	235
6.12	A_{1650}/A_{1455} versus A_{1035}/A_{1415}, colour coded by temperature	236
6.13	Collagen yield versus temperature	237
6.14	Cumulative proportion of collagen yield by exposure time	238
6.15	Carbon content versus temperature	240
6.16	Nitrogen content versus temperature	240
6.17	Carbon content versus nitrogen content, colour coded for temperature	241
6.18	Variation in atomic C:N ratio by temperature	242
6.19	$\delta^{13}C$ values by temperature	242
6.20	$\delta^{15}N$ values by temperature	243
6.21	$\delta^{13}C$ versus $\delta^{15}N$ values, colour coded by temperature	244
6.22	$\delta^{13}C$ versus $\delta^{15}N$ values, colour coded by temperature with food map values superimposed	244
6.23	Sulphur content versus temperature	245
6.24	$\delta^{34}S$ versus temperature	246
6.25	$\delta^{34}S$ versus $\delta^{13}C$, colour coded by temperature	247
6.26	$\delta^{34}S$ versus $\delta^{15}N$, colour coded by temperature	247
7.1	Colour data in CIEL*a*b* colourspace, inhumations and cremations	253
7.2	FTIR data from archaeological application, absorption versus wavenumber	254
7.3	Absorption peak values versus collagen yield	255
7.4	Crystallinity Index versus collagen yield	256
7.5	A_{1650}/A_{1035} versus collagen yield	257
7.6	A_{1455}/A_{1415} versus collagen yield	258
7.7	Collagen yield by site and mortuary rite	260
7.8	Cumulative proportion of collagen yields by mortuary rite	261
7.9	Carbon content versus nitrogen content from inhumed individuals	263
7.10	Atomic C:N ratios by site from inhumed individuals	263
7.11	$\delta^{13}C$ versus $\delta^{15}N$ values from inhumed individuals	264
7.12	Cumulative proportion of $\delta^{13}C$ values by site	265
7.13	Cumulative proportion of $\delta^{15}N$ values by site	265
7.14	$\delta^{13}C$ versus $\delta^{15}N$ values by sex	267
7.15	Cumulative proportion of $\delta^{13}C$ values by sex	268
7.16	Cumulative proportion of $\delta^{15}N$ values by sex	268
7.17	$\delta^{13}C$ versus $\delta^{15}N$ values by age	270
7.18	Cumulative proportion of $\delta^{13}C$ values by age	271
7.19	Cumulative proportion of $\delta^{15}N$ values by age	272
7.20	Elsham and Cleatham $\delta^{13}C$ and $\delta^{15}N$ data against previous published faunal data	274
7.21	Elsham and Cleatham $\delta^{13}C$ and $\delta^{15}N$ data against previously published data from other Anglo-Saxon sites	275

7.22	Carbon content versus nitrogen content from cremated individuals	*276*
7.23	Atomic C:N ratio by site from cremated individuals	*277*
7.24	$\delta^{13}C$ versus $\delta^{15}N$ values from cremated individuals	*277*
7.25	$\delta^{13}C$ versus $\delta^{15}N$ values, cremated versus inhumed individuals	*278*
7.26	Sulphur content versus nitrogen content from inhumed individuals	*279*
7.27	$\delta^{34}S$ versus $\delta^{13}C$ values from inhumed individuals	*280*
7.28	$\delta^{34}S$ versus $\delta^{15}N$ values from inhumed individuals	*280*
7.29	Cumulative proportion of $\delta^{34}S$ values by site	*281*
7.30	$\delta^{34}S$ versus $\delta^{13}C$ by sex	*283*
7.31	$\delta^{34}S$ versus $\delta^{15}N$ by sex	*283*
7.32	Cumulative proportion of $\delta^{34}S$ values by sex	*284*
7.33	$\delta^{34}S$ versus $\delta^{13}C$ values by age	*285*
7.34	$\delta^{34}S$ versus $\delta^{15}N$ values by age	*286*
7.35	Cumulative proportion of $\delta^{34}S$ values by age	*287*
8.1	Collagen yield versus temperature from this experiment versus previously published studies	*293*
8.2	$\delta^{13}C$ versus $\delta^{15}N$ data from this experiment versus previous published studies	*295*
8.3	Collagen extracts from the controlled heating experiment	*298*
8.4	Commercially available smoker fueled by calibrated wood pellets	*301*
8.5	Geographic distribution of Anglo-Saxon sites used as a dietary reference population	*306*
8.6	Elevation map of England, Scotland and Wales	*308*
8.7	$\delta^{13}C$ versus $\delta^{15}N$, $\delta^{13}C$ versus $\delta^{34}S$, and $\delta^{15}N$ versus $\delta^{34}S$ from this experiment versus previously published studies	*311*
8.8	Colour variation in Neolithic cremations (Cataroche and Gowland, 2015)	*320*
8.9	Colour variation in Roman cremations (Thompson et al., 2016)	*325*
8.10	$\delta^{13}C$ versus $\delta^{34}S$ data by continent and by European country from modern forensic studies	*329*

Table Number	Description	Page Number
1.1	Key to map of cultures practicing cremation	24
1.2	Definitions of frequently used terms	27
3.1	Fuel potential of human body tissues	87
3.2	Comparisons of colour analyses of burned bone from previously published studies	105
3.3	Colour changes associated with the burial environment	107
3.4	SEM observations of changes to the surface morphology of burned bone	113
3.5	FTIR absorption peak ratios used to estimate burning intensities	118
3.6	FTIR absorption peaks associated with organic components in bone	118
5.1	Allocation of bone samples by burning condition for the controlled heating experiment	176
5.2	Body position of inhumations at Cleatham	193
5.3	Age and sex data of inhumed individuals at Cleatham	194
5.4	Number of urns attributed to each phase at Cleatham	197
5.5	Cremated individuals assigned to each age category at Cleatham	199
5.6	Number, crude prevalence rate, and true prevalence rate of pathological markers identified on cremated individuals at Cleatham	200
5.7	Demographic attributes, grave goods, and pathologies of Anglo-Saxon individuals excavated at Elsham	206
5.8	Number of cremated individuals assigned to each age category at Elsham	207
5.9	Number, crude prevalence rate, and true prevalence rate of pathological markers identified on cremated individuals at Elsham	209
5.10	Inventory of samples taken from inhumed individuals at Elsham	220
5.11	Inventory of samples taken from inhumed individuals at Cleatham	221
5.12	Inventory of samples taken from cremated individuals at Elsham	224
5.13	Inventory of samples taken from cremated individuals at Cleatham	224
6.1	Colour analysis data of bone samples before burning	229
6.2	Colour analysis data of bone samples after burning	230
6.3	Mann-Whitney U comparison of collagen yields varying by exposure time	239
7.1	Colour analysis data of bone samples from inhumed individuals	251

7.2	Colour analysis data of bone samples from cremated individuals from Elsham	*251*
7.3	Colour analysis data of bone samples from cremated individuals from Cleatham	*252*
7.4	Collagen yields from cremated and inhumed individuals	*259*
7.5	Mann-Whitney U comparison of collagen yields varying by funerary rite and site	*262*
7.6	Mann-Whitney U comparison of $\delta^{13}C$ and $\delta^{15}N$ values by site	*266*
7.7	Mann-Whitney U comparison of $\delta^{13}C$ and $\delta^{15}N$ values by sex	*269*
7.8	Mann-Whitney U comparison of $\delta^{13}C$ and $\delta^{15}N$ values by age	*273*
7.9	Mann-Whitney U comparison of $\delta^{34}S$ values by site	*282*
7.10	Mann-Whitney U comparison of $\delta^{34}S$ values by sex	*284*
7.11	Mann-Whitney U comparison of $\delta^{34}S$ values by age	*288*
8.1	Comparison of colour data from this experiment and previous studies	*291*
8.2	Comparison of experiment designs from previous studies of the thermal alteration of $\delta^{13}C$ and $\delta^{15}N$ values	*299*
8.3	Soil data from Anglo-Saxon mixed rite cemeteries	*318*
8.4	Relative frequency of animal remains recovered from cremation burials across time periods	*326*
8.5	Element used in forensic isotope studies to provenance unidentified human remains	*327*
8.6	Relative proportion of articles on skeletal remains that discuss cremated remains	*332*

Chapter 1: Introduction

1.1 Introduction

Stable isotope research was introduced to archaeology in 1977 by Johann Vogel and Nikolaas van der Merwe, who used the analysis of carbon isotopes to infer the contribution of maize to the diets of archaeological populations from New York State. From these beginnings isotope research in archaeology has grown to include analyses of hydrogen, carbon, nitrogen, oxygen, sulphur, lead, and strontium (DeNiro and Hastorf, 1985; Ericson, 1985; DeNiro, 1987; Ambrose, 1991; Shoeninger and Moore, 1992; Montgomery et al., 2000; Craig et al., 2006; Montgomery and Evans, 2006; Lee-Thorp, 2008; Reynard and Hedges, 2008; Nehlich, 2015). Analyses of hydrogen, carbon, nitrogen, and sulphur isotope ratios are used to investigate the diets of past populations (Schoeninger and Moore, 1992; Lee-Thorp, 2008; Reynard and Hedges, 2008; Nehlich, 2015). Nitrogen isotope analyses have also been used to examine breastfeeding and weaning practises in past cultures, as well as physiological stress such as starvation (Fuller et al., 2006a; Beaumont et al., 2015; Beaumont and Montgomery, 2016; King et al., 2017). These analyses are most effective when used in concert, observing multiple axes of isotopic differences to produce more nuanced dietary models (Schwarcz, 1991; Nehlich, 2015). Isotope analyses of hydrogen, oxygen, sulphur, lead, and strontium are used to investigate the geographical origins of individuals from archaeological sites, tracking the mobility of past populations (Montgomery et al., 2000; Montgomery and Evans, 2006; Vika, 2009). Movement of individuals can also be investigated if data from dental tissues, indicating childhood or early adult geochemical conditions, are compared against data from bone samples, indicating conditions experienced over approximately the last decade of life (Hedges et al., 2007; Beaumont et al., 2015). An important caveat in mobility and migration research conducted via isotope analyses is that none of these methods can confirm a local signature; instead, outliers are identified and compared against potential areas of origin (Sealy, 2001). The majority of this research has been focused on inhumed individuals from archaeological populations; however, there have been a few isotopic studies focused on cremated individuals or samples of experimentally burned bone utilizing both collagen and apatite (DeNiro et al.,

1985; Munro et al., 2007; Schurr and Hayes, 2008; Schurr et al. 2008; Harbeck et al., 2011; Snoeck, 2014; Snoeck et al., 2014; 2018).

Previous research has found that while isolated collagen denatures at approximately 60°C, mineralised collagen in the bone matrix is unaltered up to approximately 112°C (Holden et al., 1995; Etok et al., 2007). Some early isotope studies utilized burned bone samples from archaeological contexts, though Chisholm and colleagues (1983) found burned samples produced 'non-reproduceable' results (Bender et al., 1981). In 1985 DeNiro and colleagues investigated the influence of thermal exposures on the isotope ratios of bone collagen; they found that low temperatures did not affect bone collagen but exposures of 295°C or higher altered the carbon and nitrogen isotope ratios of collagen. For two decades this study was accepted without further testing. However, in 2008 further research suggested that the threshold for conservation of biogenic isotope ratios of carbon and nitrogen was approximately 200°C (Schurr and Hayes, 2008; Schurr et al., 2008). Later research confirmed this threshold (Harbeck et al., 2011). However, these four experiments did not agree on the direction or magnitude of change that occurred in the $\delta^{13}C$ and $\delta^{15}N$ values of bone samples heated to higher temperatures (DeNiro et al., 1985; Schurr and Hayes, 2008; Shurr et al., 2008; Harbeck et al., 2011).

To build upon previous research, this study aims to examine the previously observed threshold of 200°C for the conservation of biogenic $\delta^{13}C$ and $\delta^{15}N$ values in burned bone and to determine the expected effect that higher temperatures would have on $\delta^{13}C$ and $\delta^{15}N$ values through a controlled heating experiment. This experiment also analysed, for the first time, heat-induced changes in $\delta^{34}S$. Sulphur isotope analysis within archaeology is still relatively new and fewer investigations of this isotope have been undertaken overall (Nehlich, 2015). Furthermore, the majority of isotope research conducted on burned bone has focused on bone mineral, which contains minimal sulphur (Lanting et al., 2001; Munro et al., 2007; 2008; Snoeck, 2014; Snoeck et al., 2014; Nehlich, 2015; Geodert et al., 2016; Snoeck et al., 2018).

The focus on the mineral portion of bone as a material for isotope analysis when studying bone from archaeological cremations is understandable; many researchers assume that only the mineral portion of bone remains after cremation. Archaeological reports on cremation burials often refer only to the maximum temperatures attained by the pyre (McKinley, 2015). The maximum temperatures are typically established not through

analyses of the human remains, but from evidence provided by artefacts placed on the pyre with the deceased; melted bronze and glass found in association with cremated remains provide evidence of temperatures in excess of 1000°C (McKinley, 1994a; McKinley, 2015; Squires, 2011). Bone is known to go through recognised stages of heat-induced change: first dehydration, beginning at 105°C; the loss of organic material, beginning at 300°C; growth of apatite crystals, beginning at 700°C; and finally, the bone crystals melt when exposed to temperatures in excess of 700°C (Mayne Correia, 1997; Thompson, 2005). There is overlap in the temperature ranges at which these changes occur and some disagreement in the literature regarding the definition of these temperature ranges; however, all organic material is lost in bone heated to 800°C or higher (Mayne Correia, 1997; Thompson, 2005). Considering that pyre temperatures are recorded as reaching temperatures of higher than 1000°C, researchers may be justified in rejecting analyses that require the retention of organic material (DeNiro et al., 1985; McKinley, 2015). However, pyre cremation is not a uniform process (McKinley, 1994a; 2000; Squires, 2011). The centre of the pyre reaches the highest temperatures, while the periphery is considerably cooler (McKinley, 2000; Wahl, 2015). The body may be shielded by pyre goods, clothing, or the platform on which the corpse is placed (McKinley, 1994a; McKinley, 2015; Thompson et al., 2016). Furthermore, the body's soft tissues shield the skeleton initially from the heat of the pyre; the overlying tissue must be split open and consumed by the fire before the bone is affected (Symes et al., 2015). Portions of the vertebrae, scapulae, proximal femur, innominates, and some elements of the skull are often found to show less intense heat exposure than other areas of the body due to poor oxygen flow to the dorsal surface or thick layers of overlying tissue (McKinley, 1994a; Squires, 2011; Symes et al., 2015). Additionally, elements such as the distal phalanges of the hands and feet with little overlying tissue may detach from the body and fall through the pyre in the early stages of burning (McKinley, 1994a). Thus, while maximum temperatures suggest that no organic material would remain in archaeologically cremated remains, the range of temperatures experienced in an open-air pyre instead suggest that some bone fragments from archaeological cremations may retain organic material – including the collagen necessary for isotope analyses of carbon, nitrogen, and sulphur (DeNiro et al., 1985; McKinley, 1994a; Schurr and Hayes, 2008; Schurr et al., 2008; Harbeck et al., 2011; Squires, 2011; Thompson et al., 2016). The study of these remains requires accurate estimations of the burning conditions experienced by archaeologically

cremated skeletal remains. Research conducted on experimentally burned bones has established several methods for evaluating burning conditions in bone recovered from forensic and archaeological contexts, including: assessments of colour; resistance to penetration; changes to microstructures viewed through light microscopy, scanning electron microscopy (SEM), or transmission electron microscopy (TEM); changes in chemical structures as observed via x-ray diffraction (XRD), Fourier Transform Infrared spectroscopy (FTIR) or Raman spectroscopy (Ellingham et al., 2015a).

1.2: Cremations in early Anglo-Saxon England

The early Anglo-Saxon period in England offers a compelling opportunity to test our ability to reconstruct the diets of individuals who were cremated in the past due to the large cemeteries of this period at which both inhumation and cremation were practised (McKinley and Bond, 1993; McKinley, 1994a; Leahy, 2007; Squires, 2011). The cemetery at Spong Hill in Norfolk is the largest of these with 2323 cremation burials and 57 inhumation burials recovered at the site (Hills and Lucy, 2013). However, there are nine early Anglo-Saxon cemeteries that consist of over one hundred cremation burials: Spong Hill, Norfolk; Cleatham, Lincolnshire; Elsham, Lincolnshire; Mucking II, Essex; Sancton I, Norfolk; Millgate, Nottinghamshire; Rayleigh, Essex; Illington, Norfolk and Loveden Hill, Lincolnshire (Kinsley, 1989; Davison et al., 1993; McKinley and Bond, 1993; McKinley, 1994a; Leahy, 2007; Ennis, 2008; Hirst and Clark, 2010; Squires, 2011; 2012). Inhumation burials were excavated from each of these sites, although in the case of Rayleigh only one inhumation burial was recovered (Kinsley, 1989; Davidson et al., 1993; McKinley and Bond, 1993; McKinley, 1994a; Leahy, 2007; Ennis, 2008; Hirst and Clark, 2010; Squires, 2011; 2012). At these large cemeteries cremation was the dominant rite, with inhumation practised in a minority of cases; however, throughout England there are also many smaller cemeteries where these two rites are practised in comparable numbers or where cremation is the minority practise (Williams, 2014). This practise of burying contemporary individuals both as intact corpses and as cremated remains allows for the direct comparison of stable isotope data obtained from these individuals. Perhaps more significantly, by not including cremated individuals in isotope studies from this period there are large populations that are ignored. We cannot assume that there will be no difference in the data obtained from cremated individuals by

studying inhumed individuals alone; this is true not only of isotope analyses but also of any studies of human bioarchaeology conducted on populations using both funerary rites. Furthermore, the pyre and grave goods associated with cremation burials from this time show significant differences from the goods that accompany inhumation burials, suggesting a cultural difference between the populations practicing inhumation and the ones practicing cremation (Lucy, 2000). Inhumation burials appear to follow a distinct gender-defined pattern with masculine-gendered burials accompanied by weapons and feminine-gendered burials accompanied by jewellery and dress accessories (Stoodley, 1999). Cremation burials do not show this gendered patterning of accompanying goods (Richards, 1987; McKinley, 1994a; Lucy, 2000; Williams, 2003; Squires, 2013). Instead, toiletry sets, combs, and animal remains are the most common goods found with cremation burials of either sex (Bond, 1996; Bond and Worley, 2006; McKinley, 2006; Williams, 2013; 2015; French, 2017). Thus far, isotopic dietary data from the Anglo-Saxon period are very tightly clustered; thus, if dietary differences exist between populations practicing cremation and those practicing inhumation, they should be readily apparent via isotope analyses of carbon and nitrogen (Privat et al., 2002; Fuller et al., 2006b; Lucy et al., 2009; Mays and Beavan, 2012; Hannah et al., 2018). There have been subtle inter- and intra-population patterns found in the isotope data from Anglo-Saxon sites. Differences in $\delta^{15}N$ values of individuals that appear to be influenced by an intersection of sex, age, wealth, and geography have been found. For instance, in their multi-site study of Anglo-Saxon dietary patterns Mays and Beavan (2012) found no differences among female age groups but a significant difference between males aged 18-29 years and males ages 30-49 years, the younger group having lower $\delta^{15}N$ values. Sulphur isotope analysis may help to explore these patterns, as the consumption of freshwater resources remains unquantifiable through carbon and nitrogen analysis. Unfortunately, there is little comparative data for sulphur isotope analysis from the Anglo-Saxon period; however, if this experiment shows that these data can be obtained from cremated remains the large population of cremated individuals and the animals that were cremated with them would then be available to provide this contextual information.

1.3 Focus and Scope

This research project focuses on the potential for stable isotope analysis of burned bone. Specifically, whether isotope analyses of carbon, nitrogen, and sulphur isolated from bone collagen can be conducted on bones that have been heated and whether these analyses can be used to infer dietary information. To determine this a controlled heating experiment was conducted and used to evaluate collagen yields, collagen quality indicators, and isotope ratios of carbon, nitrogen, and sulphur at temperatures ranging from 100°C through 400°C. Additionally, heat-induced changes were observed by spectrophotometer and Fourier Transform Infrared spectroscopy (FTIR) to model temperature exposures. This data was then applied to archaeologically cremated bone samples collected from individuals that had been interred at Elsham and Cleatham Anglo-Saxon cemeteries. Samples from inhumed individuals were also taken from these cemeteries for comparison. The archaeological bone samples were analysed by spectrophotometry and FTIR analysis to estimate temperature exposures. Collagen was then extracted from these bone samples and analysed for collagen yield, collagen quality indicators, and isotope ratios of carbon, nitrogen, and sulphur. This experiment was designed to determine the temperature ranges at which collagen retains biogenic isotope ratios, allowing for legitimate inferences regarding the diet of the individuals being analysed. Furthermore, the analysis of bone samples from individuals buried at Elsham and Cleatham cemeteries was conducted to determine whether the methodology developed under controlled-laboratory conditions could be applied to archaeologically cremated remains.

1.4 Relevance to the Discipline

Cremation as a funerary tradition has been practised by cultures ranging throughout the world and throughout history and prehistory; see figure 1.1 and table 1.1. The earliest known cremations were excavated in Australia at Lake Mungo; two cremated individuals and a third inhumed individual were dated to between fifty thousand and forty thousand years ago (Bowler et al., 1970; 2003). In areas, such as India, where Hinduism, Buddhism, Sikhism, or Jainism are major religions, cremation is an ancient tradition that continues to be practised today (Davies et al., 2005). In Europe, cremation was practised by cultures from the Mesolithic through to the Migration Period, losing ground to inhumation with the

spread of Christianity (Davies, 2005; Schurr et al., 2008; McKinley, 2015; Wahl, 2015). There are several pre-contact cultures in the Americas that practised cremation as a mortuary rite, including the Hohokom, Mogollon, Hopewell, Late Woodland, Trincheras, and Jê (Schurr et al., 2008; Ulgium, 2015; Watson et al., 2015). Throughout the archaeological record, cremation has often been a predominant mortuary rite; however, cremated remains are rarely studied by archaeologists (McKinley, 1994a; b; 1997; 2009; Thompson et al., 2009; Squires et al., 2011; Squires, 2013; Thompson, 2015a; Thompson et al., 2016; Carroll and Squires, 2020a). In the last few decades this situation has improved with greater attention being devoted towards archaeological cremations and the methods used to study them (Kujit et al., 2014; Thompson, 2015b; Schmidt and Symes, 2015). This research builds on this recent attention, utilising methods developed to estimate burning conditions used in archaeological cremations and seeks to facilitate investigation into the diets of the cremated dead that we encounter from innumerable sites (DeNiro et al., 1985; Schurr and Hayes, 2008; Schurr et al., 2008; Harbeck et al., 2011; Thompson, et al., 2013; Devlin and Herrmann, 2015; Ellingham et al., 2015a; Thompson et al., 2016). Isotopic analyses of diet allow archaeologists to determine dietary information at an individual level; this allows for comparisons both between and within populations, uncovering dietary patterns related to sex, age, socio-economic status, or occupation periods (Schoeninger and Moore, 1992).

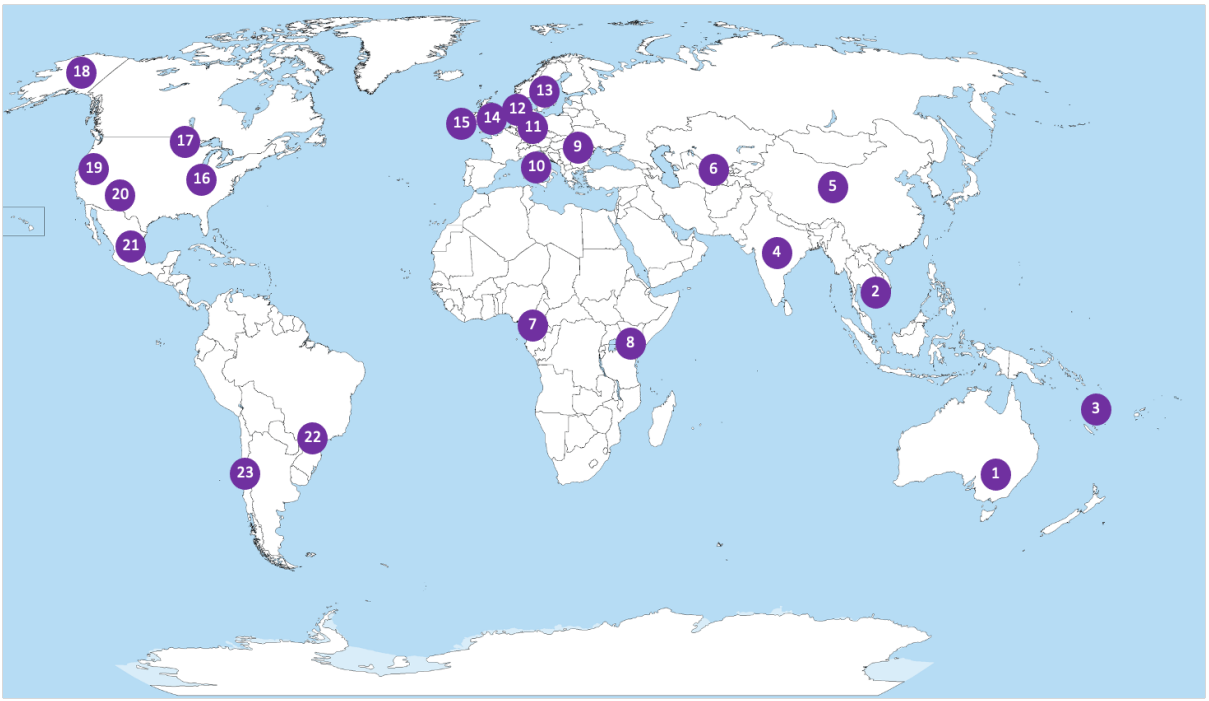


Figure 1.1: Map showing cultures practicing cremation as a funerary rite. This is not an exhaustive list, but only meant to indicate the prevalence of cremation as a mortuary rite in the past. The key to the map is provided in table 1.1. Figure by author.

Table 1.1: Key to the map of cultures practicing cremation presented in figure 1.1, providing the location, time period, further context and the reference used to source the data.

Number	Location	Time Period	Context	Source
1	Australia	50,000-40,000 ya	Lake Mungo	Bowler et al., 2003
2	Cambodia	1500-1000 BC	Bronze Age	Quinn et al., 2014
3	Vanuatu, Pacific Islands	900 BC	Prehistory	Quinn et al., 2014
4	India	Began ~1500BC	Late Harappan	Mughal, 1990
5	China	8000 BC	Neolithic	Fengming et al., 2005
6	Uzbekistan	1800-1200 BC	Late Bronze Age	Quinn et al., 2014
7	Cameroon	1000 BC	Shum Laka	Lavachery, 2001
8	Kenya	1000 BC	Elmenteitan	Merrick and Monaghan, 1984
9	Romania	2000-1500BC	Middle Bronze Age	Quinn et al., 2014
10	Italy	AD 100-500	Late Republic Rome	Quinn et al., 2014
11	Germany	750-15 BC	Iron Age	Wahl, 2015
12	Denmark	1500-1000 BC	Early Bronze Age	Quinn et al., 2014
13	Southern Scandinavia	5000-2300 BC	Mesolithic to Neolithic	Quinn et al., 2014
14	England	4000 BC - AD 650	Neolithic to early Anglo-Saxon	McKinley, 2015
15	Ireland	3800-2500 BC	Neolithic	Quinn et al., 2014
16	United States	AD 0-1200	Middle Woodland to Mississippian	Quinn et al., 2014
17	United States	6000 BC- AD 1000	Precontact Midwest	Quinn et al., 2014
18	United States	11, 500 BP	Beringia	Irish et al., 2015
19	United States	10,000 BC	Prehistoric California	Quinn et al., 2014
20	United States	AD 450-1500	Hohokam	Quinn et al., 2014
21	Mexico	1000 BC	Formative Mixtec	Quinn et al., 2014
22	Brazil	220 BC-contact	Prehistoric Jê	Ulgium, 2015
23	Chile	4000 BC	Archaic	Quinn et al., 2014

1.5 Research Questions

1) Does collagen survive in experimentally heated bone, and if so, to what range of temperatures and exposure times?
2) Does the collagen from experimentally heated bone retain biogenic ratios of $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$? To what range of temperatures and exposure times?
3) Does colour accurately reflect the chemical changes occurring in bone when heated?
4) Does FTIR analysis allow for the modelling of temperature exposures in the range of 100°C to 400°C?
5) Can colour and FTIR analysis be used to select samples of bone from archaeological cremations that have been exposed to low temperatures?
6) Can collagen be extracted from bone samples taken from archaeological cremations, specifically from cremated individuals buried at Elsham and Cleatham cemeteries?

7) Are the diets of cremated individuals different than inhumed individuals buried at the same cemetery, when inferred by analyses of $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$, thus suggesting differentiated social identities underpinning the choice of funerary rite?

1.6 Aims and Objectives

The overarching aim of this project is to determine whether dietary reconstructions, as inferred from isotope analyses of carbon, nitrogen, and sulphur, can be conducted on archaeologically cremated remains. In order to achieve this, four more specific aims and ten related objectives are presented below:

Aim One: Determine the range of temperatures at which viable collagen can be extracted from bone.

Objective One: Conduct a controlled heating experiment using *Bos taurus* bone as a proxy for human bone.

Objective Two: Observe collagen yields, collagen quality indicators, and values of $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$.

Objective Three: Establish the temperature threshold at which isotope analyses from collagen no longer accurately represent *in vivo* ratios.

Aim Two: Determine methods for estimating temperature exposures of archaeologically cremated bone, specifically ones that are effective at temperatures below 500°C.

Objective Four: Evaluate heat-induced colour change via spectrophotometer to relate colour ranges to expected temperature ranges.

Objective Five: Evaluate thermal alterations to FTIR spectra to create models of low temperature chemical changes.

Aim Three: Determine whether dietary reconstruction via isotope analysis can be applied to cremated individuals from the early Anglo-Saxon period.

Objective Six: Select appropriate samples of cremated bone from individuals interred at Elsham and Cleatham early Anglo-Saxon cemeteries using criteria determined during the controlled heating experiment.

Objective Seven: Select comparative samples from among the inhumed individuals interred at Elsham and Cleatham cemeteries.

Objective Eight: Conduct analyses of $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ on the samples selected from early Anglo-Saxon burials.

Aim Four: If aim three is successful, investigate the dietary differences between cremated and inhumed individuals at two early Anglo-Saxon cemeteries.

Objective Nine: Compare $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ values of cremated and inhumed individuals from Elsham and Cleatham cemeteries.

Objective Ten: Analyse patterns in the data to determine whether choice of mortuary rite is reflected in dietary choices.

1.7 Definition of Terms

There are several terms used frequently in this research that are either specific to a niche focus or are used ambiguously within archaeological research. These are defined in more detail when they arise throughout the later chapters, but a list is provided in table 1.2 for ease of reference.

Table 1.2: Definitions of frequently used terms.

Section	Term	Definition(s)
Anglo- Saxon Period	Anglo-Saxon	The period dating from circa AD 410 through AD 1066 and the cultures dating from this period. Divided into: Early: 5th-7th centuries Mid: 7th-8th centuries Late: 8th-12th centuries
	Anglian	The peoples and culture predominant in East and Middle Anglia, Mercia and Northumbria as laid out by Bede.
	Saxon	The peoples and culture predominant in Essex, Wessex, and Sussex as laid out by Bede.
	Jutish	The peoples and culture predominant in Kent and on the Isle of Wight as laid out in Bede.
	Native British	Peoples and culture outside of the range of the Anglian, Saxon and Jutish kingdoms with cultural traditions relating to the Romano-British period or earlier.
Cremation Research	Cremation	A ritual process through which a corpse is altered by fire.
	Cremation Burial	A deposit of human remains that have been thermally-altered in a ritualized manner before being interred. In some cases, disturbance of the feature prevents secure identification as a burial; in these cases 'cremation-related deposit' is used.
	Burned Bone	Thermally-altered bone from non-ritualised contexts; e.g. experimental or forensic.
	Charred Bone	Thermally-altered bone that appears black due to the carbonization of organic material. Typical of temperature exposures of ~300° to ~450°
	Calcined Bone	Bone exposed to temperatures sufficient to remove all organic material and alter the crystal structure of apatite. Typical of temperature exposures in excess of 700°.
Isotope Research	Isotope	Atoms of an element with an equal number of protons but with varying numbers of neutrons.
	Stable Isotope	Isotope of an element not subject to spontaneous decay.
	Radioactive Isotope	Isotope that is not stable, dissipates energy over time via radiation. The reaction is random for each atom, but a pool of atoms decay at an expected rate, referred to as a half-life.
	Radiogenic Isotope	Isotope created through the radioactive decay of an unstable isotope.
	Fractionation	The effect that determines local gradients of isotope ratios. Lighter isotopes react more readily than heavier isotopes resulting in concentration of heavier isotopes in the most stable phase of a system.
	Delta Notation	Isotope ratios are written as delta values using the Greek letter 'δ'. Delta units are a comparison of a sample's isotope ratio against an established standard.
	Per Mille	Delta values are expressed in parts per thousand using the symbol '‰'

1.8 Structure of the Thesis

In order to frame this experiment in the context of the existing archaeological research three areas of background information are required: Anglo-Saxon background provided in chapter two, a background to cremation research provided in chapter three, and a background to isotope studies of diet provided in chapter four. The Anglo-Saxon Background includes the theoretical development of Anglo-Saxon archaeology and the context of cremation burials during the Anglo-Saxon period, absent through much of the

development of the discipline. The cremation background outlines the history of cremation research, the ways in which fire affects the human body, and methods used to analyse thermally-altered bone. The isotope background chapter provides the basic terminology used; specific variations found among carbon, nitrogen, and sulphur isotope ratios; how these ratios are combined to infer diet; explores the few studies that have studied isotope ratios from burned bone samples; and outlines the isotopic context for Anglo-Saxon northern Lincolnshire, where Elsham and Cleatham are located. The materials and methods for both the controlled heating experiment and the archaeological application are laid out in chapter five. Chapter six presents the results from the controlled heating experiment. Results from the archaeological application are presented in chapter seven and discussed in chapter eight. Chapter eight also relates the results of this project to the wider research context. Conclusions are presented in chapter nine.

Chapter 2: Anglo-Saxon Background:

2.1 Introduction

The individuals sampled for the archaeological application of the method examined in this thesis lived during the early Anglo-Saxon period and this chapter provides some background context. The term 'Anglo-Saxon' is applied to a period from circa AD 410, dated from the Honorian Rescript, through 1066, the Norman Conquest; with the 'early' Anglo-Saxon period applying to the period from the fifth through early seventh centuries (Hamerow et al., 2011; Williams, 2014). The term 'Anglo-Saxon' is not contemporary to this earlier period. Instead, the term dates to the ninth century and is inherently problematic. Firstly, the term suggests an ethnic specificity that is not supported by either the literary or archaeological evidence – ignoring the existence of not only the native Britons, but also the Jutes, Frisians, and later Danes who contributed to the societies of this period (Hamerow et al., 2011). Secondly, the term is indelibly tied to the early culture-historic interpretations founded on ideas of racial 'purity' and 'superiority' (Lucy, 2000). Thirdly, these interpretations have been conscripted by fascists, Nazis, Confederates, and racists throughout the twentieth century with a recent resurgence in popularity among right wing nationalists of various creeds (Dockray-Miller, 2017; Elliot, 2017; Harland, 2017). In a climate where silence is complicit, the author wishes to make clear that Anglo-Saxon England was not a period of racial homogeneity (Kim, 2017; see Hsy and Orlemanski, 2017 for further dissipation of this myth) and the term 'Anglo-Saxon' as used here denotes only the period in question.

This chapter begins with the development of Anglo-Saxon archaeology in section 2.2. As cemetery evidence forms a significant majority of the evidence from this period, the major foci of the research discussed are the excavation and interpretation of these sites (Campbell, 1982; Yorke, 1990; Lucy, 2000). Furthermore, as cremation burials were not investigated until the latter half of the twentieth century, the development section focuses heavily on studies of inhumation burials. Persistent issues in establishing a chronology of the early Anglo-Saxon period are discussed in section 2.3. Section 2.4 discusses the context of

cremation burials during the Anglo-Saxon period. Finally, section 2.5 explores mixed rite cemeteries and their interpretation. This context is unavoidably biased towards those large cremation cemeteries that have been studied in detail in Norfolk and Lincolnshire (McKinley, 1994a; Squires, 2011, 2013, 2016).

2.2 The Development of Anglo-Saxon Archaeology

2.2.1 Antiquarian:

Anglo-Saxon archaeology began inadvertently with Roger of Wendover in the twelfth century; he recounted the search of burial mounds in Hertfordshire for the remains of Saint Amphibalus. Description of the associated grave goods, including knives and spearheads, match descriptions of Anglo-Saxon inhumations (Meaney, 1964; Lucy, 2000). Not until the seventeenth century was there a definite description of an Anglo-Saxon excavation, the 1658 publication by Sir Thomas Browne, "Hydrotaphia, Urn Buriall". He described a series of urns found in Norfolk as Roman period British burials, but later examinations of his illustrations indicate these urns were Anglo-Saxon in style (Lucy, 2000). In the eighteenth-century interest in excavation grew. Artifacts were increasingly valued on evidentiary merits, rather than on solely aesthetic ones (Dickinson, 2011). However, Anglo-Saxon burials continued to be misidentified as Romano-British. The thorough excavations of barrow burials at Gilton, Kingston Down and Sibertswold by Reverend Faussett began a shift towards more deliberate investigation, ultimately excavating 750 burials; examples of his research are shown figure 2.1 (Lucy, 2000). Captain James Douglas discovered post-Roman coins in his excavations, also in Kent. A younger contemporary of Faussett, he was the first to document his findings as Anglo-Saxon (Dickinson, 2011). Faussett and Douglas, however, were exceptional among their contemporaries for their systematic excavation and meticulous recording. Destruction of burial sites was common, with any artefacts retrieved distributed as curiosities (Lucy, 2000). Archaeology was not yet an independent discipline in Britain, rather it was seen as a discipline subordinate to history (Jakob, 2004). Passionate antiquarians, dismayed by the damage to Anglo-Saxon sites, founded the

British Archaeological Association to lobby for improved excavation standards and greater recognition for British archaeological finds (Lucy, 2000).

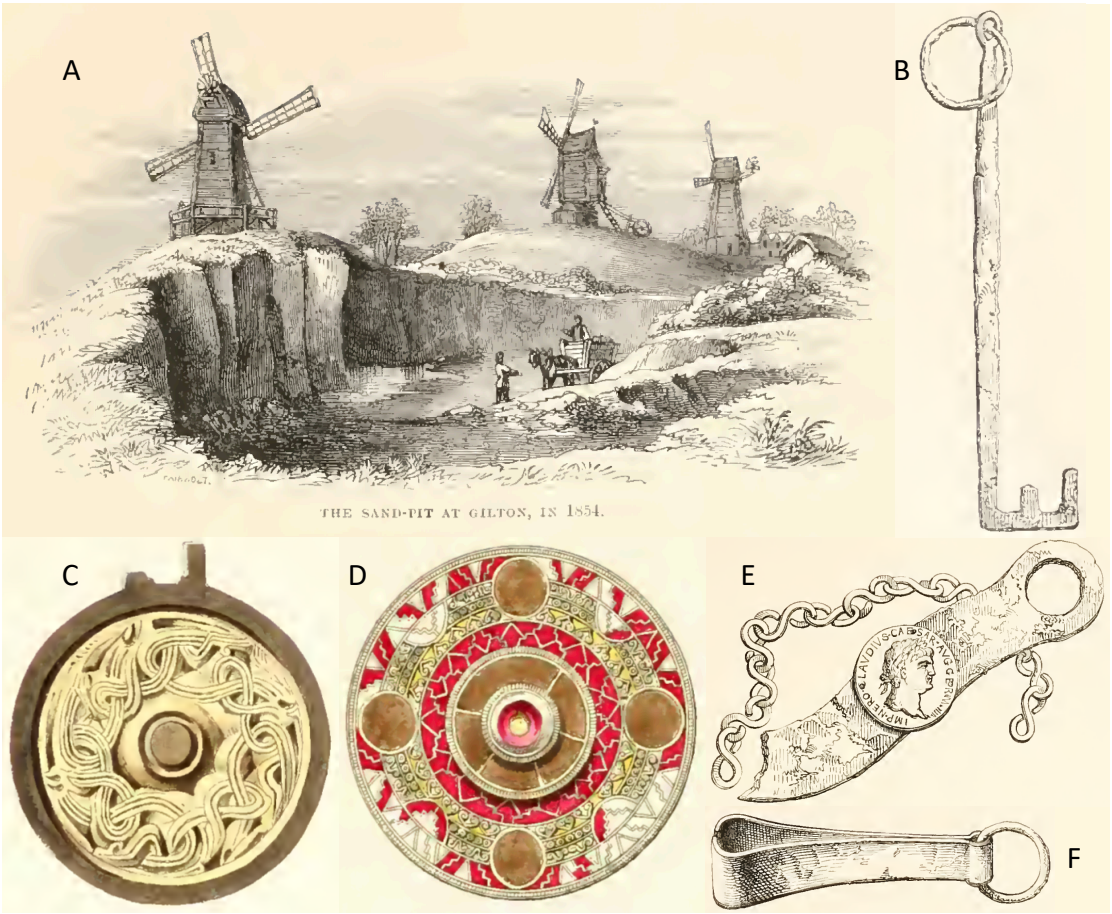


Figure 2.1: Images from Inventorium Sepulchrale from excavations at Gilton-Town 1760, 1762 and 1763. A) Site location in sand pit at Gilton (p.1). B) Iron key (Grave 15, p.8). C) Fibula subnectens, gilt brass (Grave 69, plate III). D) Fibula subnectens, gold and garnet (Grave 42, plate II). E) Iron bridle with copper Nero coin incorporated (Grave 83, p. 27). F) Tweezers (cremation burial with Grave 50, p. 19). (Faussett, 1856).

2.2.2 Victorian:

During the Victorian Period there was an explosion of interest in Anglo-Saxon archaeology (Brugmann, 2011). Expansion of towns and the growth of the English railway system led to a plethora of archaeological finds during this period (Lucy, 1998; Jakob, 2004). The proliferation of material evidence and journal reports that arose from this enthusiasm required a theoretical framework; a model for Anglo-Saxon society was established from Bede, the Anglo-Saxon Chronicle, and Beowulf (Dickinson, 2011). Charles Roach Smith brought focus to the Anglo-Saxon material, confirming James Douglas' assertion that these finds, at this time largely found in

Kent, were of a Post-Roman date (Lucy, 2000). As more material was uncovered, regional variation was recognized and interpreted by Charles Roach Smith and Thomas Wright as evidence of the tribes identified by Bede: the Angles, Saxons, and Jutes; see figure 2.2 (Dickinson, 2011). John Kemble was the first to recognize parallels between English and northern Germanic cremation cemeteries; the similarities convinced him a pagan migration was responsible for the shift in English mortuary practise (Brugmann, 2011; Dickinson, 2011). This research, grounded in historical literature, fostered an enduring narrative for the Victorian antiquarians. Artefacts and excavations were studied within this model and used as evidence for it; a discussion of the historical literature available is provided in Appendix 1 (Dickinson, 2011). These interpretations fed into 19th century nationalist ideals, legitimising racial identities by tying them with ethnic divides, the earlier in history the better (Lucy, 2002). The 'Anglo-Saxon' as an ancestor to the 'British' was useful in smoothing out internal conflict between the English, Scottish, and Welsh (Lucy, 1998). The research of this period rested on two major assumptions: that artefacts could be categorized along ethnic lines, and, that the presence of such artefacts indicated the ethnic identity of those associated with them (Lucy, 2000). 'Germanic' grave-goods were considered sufficient evidence of an Anglo-Saxon incursion and variation in the style of these artefacts divided burials ethnically into Angles, Saxons, or Jutes (Dickinson, 2011). The Victorian belief that the modern British people originated from the incursion of 'noble but ignorant barbarian[s]', the Anglo-Saxons, proved persistent (Hamerow, Hinton, and Crawford, 2011: xxi).



Figure 2.2: Britain circa 673. Jutish territories in red text, Saxon in blue, Anglian in Green and British in purple. (Reproduced from Higham, 1992 after Bede's Ecclesiastical History.)

2.2.3 Culture-Historic:

In the early twentieth century improved systems of artefact classification, dating, and mapping enabled broad historical reconstruction of Anglo-Saxon England and further comparison with Continental evidence. "The Archaeology of Anglo-Saxon Settlements" by E.T. Leeds, a work that has influenced the field since its publication in 1913, constructed a temporal and geographical analysis of Anglo-Saxon artefacts around Bede's historical narrative (Leeds, 1913; Dickinson, 2011). In 1915, Baldwin Brown furthered this trend of codification in "The Arts in Early England" – a complete survey in two volumes of Anglo-Saxon cemeteries and grave-goods (Baldwin Brown, 1915; Dickinson, 2011). These were two of the most influential publications in the formative years of Anglo-Saxon archaeology, but both were based entirely on material recovered from cemetery sites (Lucy, 2000; Brugmann, 2011). The first excavation of an Anglo-Saxon settlement, discovered

near Sutton Courtenay, was conducted by Leeds and not published until 1923 (Leeds, 1923; Lucy 2000). However, the focus in Anglo-Saxon archaeology remained firmly on cemetery sites, and more specifically on the grave goods found therein, with a heavy focus on the codification of various artefact types (Dickinson, 2011). Nils Åberg, a Swedish archaeologist, contributed to the chronological understanding of Anglo-Saxon material with his work "The Anglo-Saxons in England", which gathered vast amounts of data from both English and Continental sources organized into an evolutionary sequence of artefact typologies (Åberg, 1926; Lucy, 2000). These early publications cemented the idea, established earlier in the Victorian period, that the change in material culture seen in fifth century England was derived from the mass migration of Germanic peoples that settled into territories divided along ethnic lines (Lucy, 2000). Throughout the twentieth century excavation standards improved and more detailed analyses were completed on grave goods (Lucy, 2000). Typologies began to focus on specific artefact types, as with Evison's work on shield bosses or Myers' work on pottery (Evison, 1963; Myers, 1969; Myers, 1977; Dickinson, 2011). Regionally focused research also flourished, as with Eagles' work on Humberside, Welch's work on Sussex, or Hines' focus on Anglian territories – by limiting research to individual regions these scholars were able to make detailed primary analyses and synthesize a manageable amount of data in their classifications (Eagles, 1979; Welch, 1983; Hines, 1984; Dickinson, 2011). During this time methods of excavation, analysis, and reporting were all being refined, but interpretation of Anglo-Saxon material continued to be dominated by the culture-historic approach. Classifications of artefacts were related to differences of ethnicity and religion, with the presence of specific artefact types considered proof of the ethnic identity of the related individuals (Lucy, 1998). For instance, cruciform brooches were found mostly in regions that Bede recorded as being settled by the Angles; therefore, the presence of cruciform brooches in a burial was considered evidence of the Anglian ethnicity of the deceased (Lucy, 2000). The value of Bede's narrative as an evidentiary model was not seriously challenged until the 1970s (Lucy, 2000).

2.2.4 Processual:

The culture-historic model, based around Bede's *Ecclesiastical History of the English People* and other historical sources, was disputed by processual archaeologists (Lucy, 2000). Processual theory argued that material culture and the societies that produced it were malleable and evolved in response to social and economic stimuli (Willey and Phillips, 1958). Applied to mortuary archaeology, graves and their associated artefacts were interpreted as direct evidence of social organization reflecting status, gender roles, age, and occupations of the deceased (Lucy, 2000). Previous research identifying artefacts, categorizing them, and dating the resultant typologies provided essential data that continued to be utilized. However, the assumption that variation in material culture arose solely from ethnic differences was challenged. In fact, this assumption was questioned in 1956 by T. C. Lethbridge. He also questioned the theory of a mass migration of Anglo-Saxons in the fifth century, instead suggesting the movement of a small number of elite individuals of Germanic culture (Lethbridge, 1956). In this model economic factors influenced the indigenous majority to adopt Germanic material culture. However, Lethbridge's interpretations were largely ignored (Brugmann, 2011). Chris Arnold and John Shephard argued that changes in burial practices related to economic and social adaptations (Shephard, 1979; Arnold, 1980; Dickinson, 2011). Arnold is particularly well-known for advocating the elite-dominance model of Anglo-Saxon migration, further asserting that the incoming Germanic population was predominantly male and therefore took wives from within the indigenous British population (Arnold, 1984; Brugmann, 2011). Research in this period was founded on the belief that funerary ritual reflected the burying society, a direct and functional relationship that would allow the structure of the past society to be 'read' from the grave goods and burial structure (Lucy, 1998; Dickinson, 2011). For instance, Arnold quantified the labour and resources expended in individual burials from these data calculating 'wealth-scores' that he equated to social status or rank within the living Anglo-Saxon society (Arnold, 1980). The processual focus on quantifying material culture led researchers to fixate on the investigation of social hierarchies, and the

furnished burials of the early Anglo-Saxon period provided abundant data for these studies (Dickinson, 2011).

2.2.5 Post-processual:

Critiques of processual interpretations of Anglo-Saxon material arose coeval with their rise to prominence in the early 1980s (Gowland, 2002). In 1969 Peter Ucko argued that processual interpretations were overly simplistic. Citing his ethnographic experience, Ucko found fault with the wealth scoring of burials being used to represent social status, discussing various scenarios in which the honours given to the dead could be absent from the archaeological record (Ucko, 1969). However, these views were not applied to Anglo-Saxon archaeology until the work of Ellen-Jane Pader and Ian Hodder (Hodder, 1980; Pader, 1980). Hodder argued that processual theory failed to account for human agency, deliberate or not, in the creation of the archaeological record (Hodder, 1985). Furthermore, he argued that archaeological interpretations were subjective and invested in the political landscape from which the researcher drew their beliefs (Hodder, 1985). Post-processual theory saw mortuary technologies as ritual actions on the part of the mourners, equally capable of manipulating the identity of the deceased as of accurately representing it (Lucy, 1998; Dickinson, 2011). The symbolism evoked by an artefact was neither inherent nor static; instead, the post-processualists believed that meaning was impermanent, contextual, and multi-dimensional (Gowland, 2002; Dickinson, 2011). Pader advocated the understanding of artefacts as symbols, with multiple possible meanings that became codified within a culture via repetition. Archaeologists might not be able to reconstruct the ideology that informed the use of various symbols, but by observing correlations one might be able to understand the relationships being demonstrated by recovered artefacts (Pader, 1980). For instance, Nicholas Stoodley was able to correlate female burial assemblages with two major distinct age thresholds. His research shows that the Anglo-Saxons conceived female identity as consisting of three age-related stages, though not why female identity was understood in this way; see figure 2.3 (Stoodley, 1999).

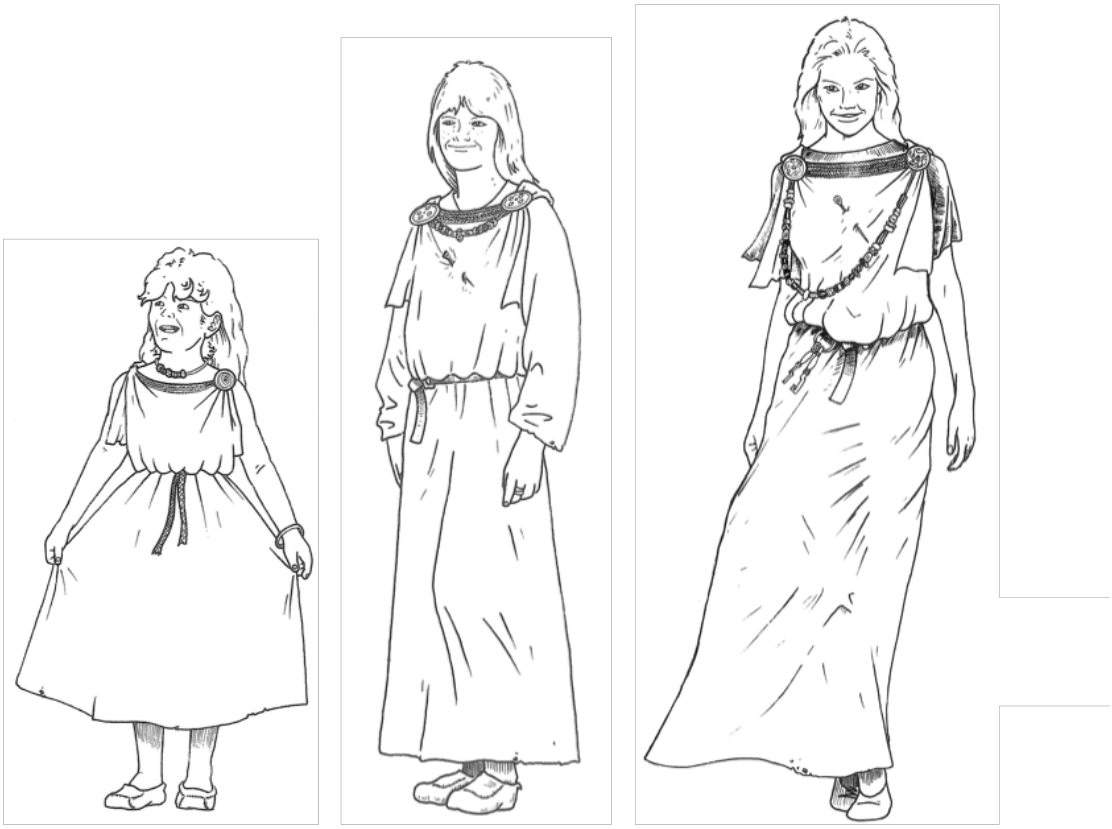


Figure 2.3: Variation in female dress over the life cycle. Three thresholds: under 2-3 years of age few grave goods provided; after this simple collections of dress accessories found, as seen in the young girl on the left; another threshold between 10-14 years of age after which more elaborate grave goods are provided, including paired brooches and increasing numbers of glass beads; final threshold between 18-20 years, after which the most elaborate collections of dress accessories are found (Stoodley, 2000, pp. 462, 464).

2.2.6. Feminist Archaeology:

Growing out of the self-critical perspective of post-processualism and the influence of feminist theories introduced in a variety of research areas, the feminist critique of archaeology grew in the 1970s and 1980s. However, little of this critique reached Anglo-Saxon archaeology until the late 1990s (Lucy, 1997). Feminist theories as applied to archaeological theory introduced several threads of inquiry or re-assessment. First, there was acknowledgement of the androcentrism of earlier research and the lack of research into women in past societies: their lives, relationships, and technologies. Furthermore, recognition of the bias that had been written into the existing historical record that was derived from the assumption that gender and gender roles were based on an innate, biological constant (Wright, 1996). The belief that our modern understanding of gender could be applied directly to past societies was questioned. In practise, feminist approaches to archaeology

require the recognition of researcher bias, not only related to gender but in multiple facets of enquiry (Wright, 1996; Wylie, 2007). Applied to Anglo-Saxon archaeology the feminist critique involved questioning the assumption that individuals buried with jewellery were female and individuals with weapons or tools were male (Lucy, 1997). This included the recognition of burials of biological females with weapons and biological males with jewellery through the application of osteological analyses that previously had not been given much credence (Lucy, 1997; Knüsel and Ripley, 2000). Additionally, it was recognised that a gender binary does not explain the entirety of the burial evidence available, even among those traditionally assigned to 'feminine' or 'masculine' identities based on their burial assemblages. The intersection of age, gender, and ethnicity creates several potential identities that are neither innate nor constant throughout the life of an individual; instead, several evolving identities can be inferred through correspondence analyses utilizing grave goods and osteobiographical data (Stoodley, 1999; Ravn, 2000).

Feminist critiques in archaeology also challenged the 'little adult' interpretation of children in past societies, instead recognising that children have their own subcultures that may be reflected both in their material culture and their treatment after death (Crawford, 2000). Ellen Pader was one of the first archaeologists to recognise that 'sub-adults' required separate interpretations (Pader, 1980). A major tenant of these critiques was that the terms 'child' and 'childhood' may not be applicable to past societies, where age categories may not have been distinctly compartmentalised or where multiple age thresholds may have been culturally significant (Sofaer, 1997; Crawford, 2000; Gowland, 2006; Stoodley, 2011). Furthermore, there is no reason to assume that the age thresholds that are considered significant in modern Western cultures should be recognised as such in other cultures (Crawford, 2000; Gowland, 2006; Stoodley, 2011). In Anglo-Saxon archaeology the investigation of 'childhood' has been constrained by the relative scarcity of burials found of those under the age of twelve, and especially of those under the age of one (Buckberry, 2000; Crawford, 2000; Stoodley, 2000). However, both archaeological evidence and written records, specifically law codes, suggest that there was a significant threshold between the ages of ten to twelve years after which Anglo-Saxon individuals began to express adult identities (Crawford, 2000;

Stoodley, 2000; Gowland, 2007). Before this age threshold few of the typical 'gendered' grave goods are found (Stoodley, 2000; Gowland, 2006, 2007). There are less significantly demarcated thresholds as well, with very young individuals found with few grave goods and more often found in multiple burials (Stoodley, 2000; Gowland, 2006; Crawford, 2007). While feminist archaeology has expanded the focus of archaeological inquiry and attempted to address some of the inherent bias resulting from decades of androcentrism, feminist analyses can be conducted under various theoretical frameworks (Wright, 1996).

2.2.7. Post-structuralism:

Another theory built from the self-critical impetus of post-processual theory is post-structuralism. Post-structural interpretations emphasize the use of material culture in the creation of cultural identities and social systems (Richards, 1995; Gowland, 2002; Lucy 2005). Symbols do not have inherent meanings, only meanings developed through traditional association; by defining those meanings and codifying their associations cultures are established (Richards, 1995). These associations are not typically consciously established, but they may be used by dominant cultures – to identify and differentiate 'others' or to cultivate cultural unity (Lucy, 2005). Mortuary behaviours in the Anglo-Saxon period can, therefore, be understood as a means of defining, classifying, and communicating identities related to sex, age, gender, ethnicity, and status (Richards, 1995). This type of analysis requires detailed contextual information and can only be applied to regional data sets, as the nuances of symbolism involved in local material culture become lost in wider generalisations (Gowland, 2002). The traditionally interpreted 'Anglian', 'Saxon', and 'Jutish' ethnicities and their associated material culture interpreted through this lens would appear to be a later construction meant to bolster political allegiance among the Anglo-Saxon elite (Lucy, 2005). However, there have been few post-structural interpretations of Anglo-Saxon material; therefore, this theoretical approach has not had much impact, thus far, on the understanding of the Anglo-Saxon period (Gowland, 2002; Lucy, 2005).

2.2.8. Incorporating Osteology:

Until the end of the twentieth century funerary archaeology was overwhelmingly focused on grave goods. Burials were interpreted as caches of cultural artefacts, with scant attention paid to their occupants. However, due to the advances made in osteological research and the efforts made by some researchers to incorporate both skeletal and cultural data this has begun to change (Lucy, 2000; Gowland, 2002). Not all of these forays have been entirely successful. Early attempts to integrate osteobiographical information into cultural analyses suffered from a lack of nuance or were based on erroneous interpretations of the evidence that renders their conclusions dubious. The inferences made cannot be supported by the data on which they are founded. Härke (1990), for instance, used age categories and pathological indicators to demonstrate that not all of the individuals provided with weapons in death could have used them in life; while he is correct in assuming that infants, aged approximately twelve months, would be unable to wield a spear, his assumption that the congenital condition spina bifida occulta would cause a significant disability is incorrect (Härke, 1990; Sutherland et al., 1995; Härke, 2004; Aufderheide et al., 1998; Johnston and Borzyskowski, 1998). As well, he uses several skeletal indicators, both stature and post-cranial non-metric traits, that are significantly impacted by environmental factors to infer genetic relatedness between populations within cemeteries (Härke, 1990; 2004; Gowland, 2002; Beavan and Mays, 2013). While Härke's work provided the important perspective of weapon burial as a rite signifying social identities, rather than simply a profession, the argument for an ethnic basis for that social identity founded in inaccurate interpretations of osteological data has proven persistent. However, as bioarchaeology continues to grow as a discipline, the integration of human remains into the understanding of mortuary rites continues (Williams, 2011; 2014).

Investigations of burial positions have often been undertaken by mortuary archaeologists with minimal integration of skeletal data; however, recent research has also begun to include both more detailed bioarchaeological analyses and more advanced chemical analyses (Lucy, 2005; Mui, 2018). Generally, the preferred burial position appears to have been supine and extended during the Anglo-Saxon period

(Lucy, 2000; Crawford, 2007). In a study of inhumation burials from the fifth to the eight centuries that included 3,053 burials from 32 cemeteries Sian Mui found that 76% of burials were supine, 60% with their legs extended (2018). Similar proportions were found by Karen Brush in an earlier study (1993). However, Mui also found burial position to be significantly influenced by region: Kent showed high levels of uniformity, with 90% of burials adhering to the standard burial position, while in the North of England only 50% of burials were found in this position; see figure 2.4 for standard positions (Mui, 2018). Burial position may have been informed by age and sex in some areas, as at West Heslerton where non-adults and adult females were more likely to be flexed than adult males (Lucy 2002). Higher rates of crouched burial among infants and young children may have been influenced by a physiology instead of representing an intentional symbolic practise; the spinal curvature of an infant produces a natural flexed posture that may be reflected in burial posture (Mui, 2018). Infrequently, Anglo-Saxon burials have been found in seated or prone positions. Prone burials are often interpreted as deviant or live burials. Notably, Worthy Park burial 78 and Sewerby burial 41 have been subject to these imaginative interpretations; however, several prone burials have no indications of 'deviance' beyond unusual posture (Hawkes and Wells, 1975; Hirst, 1985; Lucy, 2000). Margaret Faull proposed both prone and crouched burials as a British burial practise that indicated the survival of a native population in Anglian areas of England (1977). Montgomery and colleagues (2005), however, found that the $^{87}Sr/^{86}Sr$ ratios, indicative of geological area of origin, of inhumed individuals at West Heslerton showed no correlation with burial position.

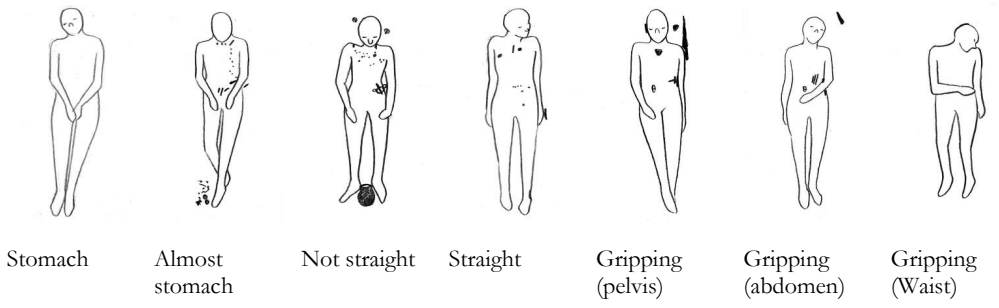


Figure 2.4: Seven main burial positions found by Mui (2018, p. 103).

Multiple burials were not the norm, but neither were they exceptional. Across England the rate of multiple burial in Anglo-Saxon cemeteries was approximately 4%, with considerable variation by region – the East Midlands showed the highest rate at nearly 6% while in the North of England there were relatively few cases at less than 2% (Mui, 2018). The majority, approximately 89%, of these interments consist of two individuals; however, burials have been found with up to six individuals at both Stowting in Kent and at Argyle Avenue in Luton (Lucy, 2000; Mui, 2018). Most instances of multiple interments appear to have been deposited concurrently, but a minority appear to have been re-opened suggesting two stages of interment (Williams, 2011; Mui, 2018). One interpretation of multiple burial is the interment of individuals who died naturally and coincidentally. Incidents of disease or accident, or in the particular case of women and infants obstetric issues could easily lead to the concurrent deaths of multiple individuals (Crawford, 2007). However, there are burials that suggest alternate explanations. At Great Chesterford grave 83 contained the remains of six individuals between the ages of 36 and 40 weeks, the most probable explanation for this configuration is that the burial was repeatedly opened for interment of stillborn fetuses (Crawford, 2007). A more brutal interpretation is that in some cases individuals may have been provided with companions or servants in death, accompanied in their burials by individuals whose deaths were not necessarily natural. No definitive evidence of this type of sacrifice has been found from Anglo-Saxon contexts. There are, however, a number of burials where the relative wealth of individuals or variations in their burial positions have been used to argue this possibility (Crawford, 2007).

Anglo-Saxon populations were healthy relative to their predecessors (Roberts and Cox, 2003; Lee, 2011). Roman Britain was characterised by a number of social structures that led to poor health outcomes: urbanisation and crowding increased transmission of disease, social hierarchies involved significant inequalities, and there was significant evidence of malnutrition in several populations (Roberts and Cox, 2003; Walther, 2017). Conversely, the population shift away from urban centres, as occurred during the Anglo-Saxon period, provided some protection against the transmission of diseases such as cholera, dysentery, typhus, and tuberculosis (Redfern and Roberts, 2005). Osteological evidence shows that early Medieval

populations have lower frequencies of enamel hypoplasia, cribra orbitalia, and tibial periostitis – all non-specific indicators of health insult (Arce, 2007; Klingle, 2012; Walther, 2017). Enamel hypoplasias are caused by disruption in the secretion of enamel by ameloblasts during the formation of the dentition. Cribra orbitalia is a condition in which the diplöe of the orbit expands through the overlying cortical bone, visible as a series of small holes. This process is the result of marrow formation in order to upcycle red-blood cell production. This process is indicative of either hemolytic or megaloblastic anemia (Walker et al., 2009; Gowland and Western, 2012). Deficiencies of either B_{12} or B_9 may lead to megaloblastic anemia, arising either from malnutrition or parasite loading (Walker et al., 2009). Periostitis is an inflammatory reaction of the tissue overlying the bone cortex, or periosteum, visible as layers of new bone formation (White et al., 2012). These reactions are most often found on the tibiae and can have either infectious or traumatic etiologies with diffuse, bilateral, and chronic conditions interpreted as infectious expressions (Roberts and Manchester, 2007).

Metric analyses, both overall stature estimation and relative indices, have been used as indication of health status in past populations, with shorter statures being related to either poor nutrition or disease. Early Anglo-Saxon populations were statistically taller than the preceding Romano-British populations; this is particularly evident among male individuals (Roberts and Cox, 2003; Klingle, 2012; Beavan and Mays, 2013; Walther, 2017). However, stature also has a genetic component. Previous research has used stature data comparisons between Anglo-Saxon and Romano-British cemeteries as evidence of an influx of Continental immigrants, though later investigations suggest this difference was more likely due to environmental factors (Härke, 1992; Beavan and Mays, 2013). Specific metric indices reflecting relative body proportions have been related more specifically to environmental factors, especially those reflecting the proportions of the lower limb. The male populations from the Anglo-Saxon period show an increase over the earlier populations in terms of lower limb indices (Walther, 2017). In comparison to the late Roman period, the early Anglo-Saxon period provided a number of health advantages: smaller, self-sufficient settlements decreased the spread of infectious disease and may have reduced the incidence of food shortages; reduction of industry

decreased the potential for continual exposure to pollutants; less complex social hierarchies led to less inequality in the provision of basic necessities (Roberts and Cox, 2003; Redfern and Roberts, 2005; Lee, 2011; Walther, 2017).

This is not meant to suggest the Anglo-Saxons were entirely free from pathology. As with most cemetery populations Anglo-Saxon cemetery populations show high rates of joint disease and dental pathologies (Roberts and Manchester, 2007; Lee, 2011). Osteoarthritis and degenerative changes to the vertebral bodies are the most commonly observed pathologies among Anglo-Saxon populations, with 8.8% of individuals suffering from osteoarthritis (628/7122) and 6.1% showing degenerative changes in the spine (436/7122) (Roberts and Cox, 2003). Individuals from the Anglo-Saxon period also often show significant tooth wear, likely related to the coarse-milling of their bread (Roberts and Cox, 2003). Dental calculus rates were higher than the Roman period, though dental caries decreased (Roberts and Cox, 2003). Rates of maxillary sinusitis, an inflammatory reaction of the mucous membranes related to poor air quality, rose to 4.7% (93/1992) during the Anglo-Saxon period from 1.8% in the Roman period (36/2013) (Roberts and Cox, 2003). Osteological evidence can provide direct evidence of specific infectious diseases, in some cases. Poliomyelitis has been observed at sites including Raunds Furnells and Worthy Park (Lee, 2011). Leprosy has been observed in Anglo-Saxon sites, famously in the wealthy bed burial found in grave 16 at Edix Hill, but also at Broughton Lodge, Nottinghamshire; Burwell, Cambridgeshire; Cannington, Somerset; Marina Drive, Bedfordshire; and Eccles, Kent (Crawford, 2007; Beavan and Mays, 2013). There are no pathognomonic lesions to indicate malaria in the skeleton. However, research into patterns of distribution of cribra orbitalia compared against geographical and topographical risk factors, as well as historical information on outbreaks of 'ague' and distributions of mosquito (*Anopheles atroparvus*) populations suggest the condition was endemic during the Anglo-Saxon period (Gowland and Western, 2012). The 10th century *Leech book of Bald,* one of the only medical texts available from Anglo-Saxon England mentions the 'spring ailment fever', which has been interpreted as malaria (Roberts and Cox, 2003). Most of the recommended treatments are herbal or mystical in nature, though some of the former treatments have some scientific merit including the treatment of wounds with onions, garlic,

and honey all with proven antimicrobial properties (Roberts and Cox, 2003). Some evidence of surgical intervention exists as well with two cases of healed amputation and 24 examples of trepanation (Roberts and Cox, 2003).

One area of Anglo-Saxon studies that remains highly contentious is migration – both the quantification and characterisation are widely debated (Lucy, 2000; Thomas et al., 2006; Richards et al., 2008). The influx of Germanic people into England during the early Anglo-Saxon period was, in the past, quantified and mapped through a simplistic interpretation of material culture, particularly artefacts excavated from cemeteries. The ethnic identity of an individual was read directly from their associated grave goods (Lucy, 2000; Loveluck and Laing, 2011). The application of these interpretations provided a variety of interpretations of the movement of peoples in the fifth and sixth centuries – from an invasion and mass migration that entirely replaced the previous inhabitants of the island to an incursion by a small, elite force followed by the acculturation of a significant surviving population of native Britons (Loveluck and Laing, 2011). However, the entire suite of interpretations was founded on the understanding of material culture being defined directly by a shared ethnic identity (Lucy, 2000). The character of the migration was influenced less by evidentiary changes than by changing political attitudes. Thus, the Victorians saw a glorious conquest over primitive people, antebellum scholars believed their Teutonic ancestors had provided them with superior genes relative to the inferior Celts and following the second World War when the appeal of the Germanic had lost its lustre, as an incursion of barbarous pirates (Lucy, 2000). However, towards the end of the twentieth century this interpretation was gradually challenged in multiple ways (Lucy, 2000; Loveluck and Laing, 2011). Ethnicity was beginning to be understood as a constructed identity that evolves over time (Lucy, 2000). Furthermore, the agency of material culture was recognised as a means of actively constructing identity rather than simply reflecting it, especially in the context of an intentional deposition such as a burial (Richards, 1995). With the growth of these understandings archaeologists began to consider material evidence with more nuance; these studies did not negate the idea of an Anglo-Saxon migration but shifted the majority of researchers towards an elite dominance model presuming only small numbers of migrants (Higham, 1992; Thomas et al., 2006;

Loveluck and Laing, 2011). Finally, techniques were arising that would potentially allow for the direct quantification of population movements – DNA and isotopic analyses (Loveluck and Laing, 2011). To clarify, these analyses do not provide evidence of cultural changes, only relatedness or movement of peoples.

DNA analyses are varied. Analyses of DNA from modern samples can provide evidence of relatedness between populations and can speak to the magnitude of exchange between them but cannot determine the timescale over which the exchange occurred (Leslie et al., 2015). These data are interpolated onto past populations in order to infer migrations; early research of this kind used Y-chromosome haplotypes to infer the contribution of the Anglo-Saxon migration to the modern English genome, estimating the contribution at between 50-100% in East Anglia (Weale et al., 2002). Late Roman Britain was estimated to have a population of approximately one million people; even the highest estimates of population movements for the Anglo-Saxon period are not believed to have involved many more than 200,000 individuals (Richards et al., 2008). In order to explain this discrepancy, some researchers suggested an 'apartheid-like' social structure that allowed a relatively small population of Anglo-Saxon males to disproportionately influence the genetic structure of later generations (Thomas et al., 2006). However, a later more comprehensive study of Y-chromosome haplotypes placed the likely contribution of the Anglo-Saxon migration at a more expected 40%, with significant regional variation (Capelli et al., 2003; Richards et al., 2008). Furthermore, neither of these estimates were able to separate 'Anglo-Saxon' contributions from those of 'Danish Vikings' (Richards et al., 2008). In a more recent study of single nucleotide polymorphism (SNP) from a diverse sample of British and Continental participants Leslie and colleagues were able to propose a fine-scale population structure for Britain (2015). Their research showed the most distinct populations were found in the Orkneys, followed by Wales. Scotland and northern England could then be separated from southern and central England, with southern and central England consisting of a remarkably uniform genetic cluster. The genetic separation of the Orkneys reflects a recent admixture with Norwegian populations. There was evidence of another admixture event involving genetic contributions from France that appear to predate the Saxon migrations. A third admixture event of genetic

material from northern Germany and Denmark corresponds chronologically to the Migration Period and accounts for approximately 35% of the genome of modern populations from southern and central England (Leslie et al., 2015). Research has also been done on ancient DNA samples; however, the role of this research has been limited by issues of preservation and contamination (Richards et al., 2008). These studies have been able to show definitively that genetic relatedness cannot be read as ethnicity with individuals from both the Anglo-Saxon period and the earlier Roman Period appearing culturally indistinct despite genetic evidence of varied origins (Martiniano et al., 2016; Schiffels et al., 2016).

In the case of isotopic analyses, evidence of the geographic origins of an individual can be provided by strontium and oxygen isotope ratios. These analyses cannot confirm local identities, but they can be used to eliminate potential areas of origin, although only among isotopically distinct regions (Sealy, 2001). The ratio of $^{18}O/^{16}O$ varies with temperature, altitude, precipitation, and distance from the ocean (Sealy, 2001). Human values reflect local drinking water $\delta^{18}O$ values, though mediated by fractionation. Studies of $\delta^{18}O$ values from enamel sampled from individuals (n=615) excavated from archaeological sites dating from the Neolithic through the 18th century showed a mean if 17.7‰ ± 0.7‰ (Evans et al., 2012). Higher $\delta^{18}O$ values are found in areas of higher rainfall, mean 18.2‰ ± 1.0‰ (n=40), while lower $\delta^{18}O$ values are found in areas of lower rainfall, 17.2‰ ± 1.3‰ (n=83) (Evans et al., 2012). There is also variation in the average $\delta^{18}O$ values over time related to variations in climate (Evans et al., 2012). The analysis of strontium involves comparing levels of ^{87}Sr, formed through the radioactive decay of rubidium (^{87}Rb), to levels of ^{86}Sr, which is not radiogenic. The half-life of ^{87}Rb is 49 billion years; thus, $^{87}Sr/^{86}Sr$ levels in the lithosphere are influenced by formation times and by the initial content of rubidium present (Sealy, 2001). Biosphere mapping of $^{87}Sr/^{86}Sr$ ratios correlated to specific lithologies has been undertaken in Britain using modern samples of water, plants, and animal bone as well as archaeologically derived bone and dentine samples (Evans et al., 2010). The range of $^{87}Sr/^{86}Sr$ ratios established for the British biosphere was between 0.7070 and 0.7222 (Evans et al. 2010). Seawater, also a major influence on strontium ratios in coastal areas has been established at 0.7092 (Evans et al., 2010). Strontium isotope values observed from

human enamel in Britain show a narrower range, between 0.7078 and 0.7165, than biosphere data; likely due to the averaging effect of humans incorporating strontium from a variety of dietary sources (Evans et al., 2012). Combining oxygen and strontium isotope analyses provides better resolution than relying on a single indicator of mobility (Montgomery et al., 2006; Hughes et al., 2014; Hughes et al., 2018). Though the data set for the Anglo-Saxon period remains small at this time, there have been some interesting parallels between them. None of the mobility studies utilizing isotope evidence from the Anglo-Saxon period have shown a majority population of immigrants (Montgomery, 2002; Montgomery et al., 2005; Montgomery et al., 2006; Hughes et al., 2014; Hughes et al., 2018). Though these analyses would only provide evidence of first-generation migrants, most have selected samples intentionally from earlier phases within cemeteries in an attempt to characterise the migration period (Hughes et al., 2014; Hughes et al., 2018). Furthermore, in each case both local and non-local isotope signatures were found throughout the timespan measured, suggesting that migration was a continual process during the early Anglo-Saxon period (Montgomery, 2002; Montgomery et al., 2005; Montgomery et al., 2006; Hughes et al., 2014; Hughes et al., 2018). In several cases, the demographics of the non-local population did not reflect an elite-dominance migration. Typically, non-local groups contained both males and females and their burials showed fewer grave furnishings; weapons especially were not correlated with the non-local groups (Montgomery, 2002; Hughes et al., 2014; Hughes et al., 2018). Finally, in several cases analyses showed evidence of internal movements of individuals from other areas of Britain indicating that population mobility was not confined to immigration from the Continent (Montgomery et al., 2005; Montgomery et al., 2006; Hughes et al., 2014; Hughes et al., 2018). Taken together, the isotope evidence and the latest DNA evidence of population movements during the early Anglo-Saxon period do not support either a mass-migration or elite-dominance model. Instead, the model proposed to explain the evidence is that of chain migration; in this model, successive generations of migrants follow family members or seek out areas with familiar social systems, resulting in an ongoing trickle of immigrants to an area over time (Montgomery, 2002; Montgomery et al., 2005).

2.3 Dating the Anglo-Saxons

Establishing the chronological sequence of finds is fundamental to archaeological analyses. Further theoretical interpretation of artefact suites and burial strategies is derived from an accepted temporal structure. Unfortunately, dating material from early Anglo-Saxon cemeteries by archaeological methods is problematic. Stratigraphic relationships are nearly absent in Anglo-Saxon cemeteries (Lucy, 2000; French, 2017). Burials are spread over wide areas with a paucity of overlying or intercut features that could be used to infer a sequence, although at both Cleatham and Spong Hill there are burial groups that allow for limited phasing of both cremation and inhumation burials; see figure 2.5 (Leahy, 2007; Hills and Lucy, 2013). Attempts have been made to map the horizontal development of these cemeteries, from earlier central burials to later interments spreading outward. However, in England, this has proved ineffective as several cemeteries developed polyfocally (Lucy, 2000; Leahy, 2007). Burials are instead dated primarily through two means: artefact typologies of associated grave goods and radiometric dating (French, 2017).

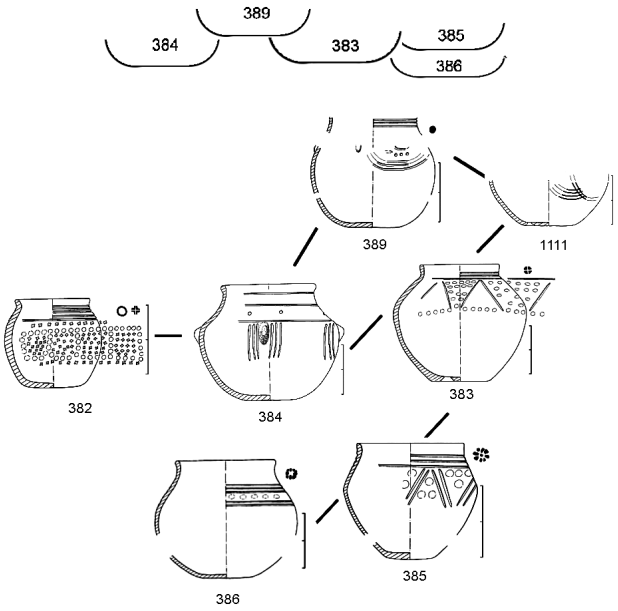


Figure 2.5: Group of seven inter-related cremation burials from Cleatham cemetery. This burial group was one of 422 associated burials used to create a chronological sequence at Cleatham (Leahy, 2007, p.70).

Artefact typologies are based on variations in form, composition, and decoration within a similar functional group. Many artefact typologies were developed through a culture-historic understanding of Anglo-Saxon archaeology. For instance, Swanton evaluated over 2,000 spearheads and sorted them into twelve types based on the profile of the spearhead, the shape of the cross-section, length of the blade and the ratio between the blade length and socket length (Swanton, 1973). The types are then sorted into a sequence via frequency seriation or occurrence seriation. Frequency seriation assumes that types of artefacts are initially rare, become popular and then decline in frequency again. The prevalence of the item can then be plotted on a curve. The peak popularity of artefact types can then be arranged into a relative order. This method requires large data sets. Occurrence seriation removes the prevalence curve from the equation. Artefacts are tabulated to compare context against type; diagonals in the table are considered to represent a chronological relationship (Geake, 1997). Correspondence analysis takes occurrence seriation further by comparing data on multiple axes to find the characteristics that best describe chronological developments in artefact types. Once the two most significant characteristics are identified, they can be plotted in two dimensions with a chronological relationship displayed as a parabola (Hakenbeck, 2013). These analyses assume that no later disturbance has occurred and that all finds are accompanied by an excavation context. Unfortunately, these assumptions cannot be applied to many collections of Anglo-Saxon artefacts, especially those from earlier excavations. Additionally, all three types of analysis assume that time is the primary factor in the evolution of artefact types – ignoring regional variation, or associations with gender, age, or status. Another complication is the 'heirloom effect' – precious or sentimental items retained and included in a later burial. This effect is of particular concern with artefacts, such as brooches, that are both durable and constructed of valuable materials. These dates are also relative, and the typologies cannot determine the rate of change in artefact types; therefore, these dates are without absolute reference or scale (Hakenbeck, 2013). Finally, existing typologies are often complicated, involving a long history of development and adaptation by a series of researchers; as a result, these methods have been applied without nuance or ignored by later researchers (Dickinson, 2011).

Typologies can be tied to reference points via associated absolute dates. On the continent there are burials of known individuals that have been excavated and used as a reference for the typologies of associated artefacts. The burial of Childeric I, identified by his signet ring, is dated circa 482, as are, therefore, the artefacts found among his burial treasure. A similar ring surmounting a glass bottle identified the burial of Queen Arnegunde and dated the associated artefacts between 565 and 570 (Werner, 1964). However, as yet, no early Anglo-Saxon burials have been securely identified. Though arguments have been made that Mound 1 at Sutton Hoo held Rædwald, King of East Anglia, no specific insignia was found (Chadwick, 1940). Coins may be used to establish a *terminus post quem* for associated finds. However, early Anglo-Saxon English cemeteries are largely barren ground for the numismatist as there was no domestic currency until the adoption of the sceatta in the later 7th century (Welch, 2011). There are examples of Roman coins in Anglo-Saxon burials, but most show evidence of being converted to jewellery. Rarely, there are also continental coins found in Anglo-Saxon burials; however, the rate at which these coins arrived in England is unclear. Lacking these more secure reference points several of the established typologies rest on the *adventus Saxonum* as established by Bede. Despite the questionable historical accuracy of Bede's record several typologies continue to base their analyses on his work; see Appendix 1 regarding Bede (Scull and Bayliss, 1999; Hills and Lucy, 2013).

Radiocarbon dating can provide absolute dates scientifically. Unfortunately, this method has limits as well. Firstly, only material containing carbon can be radiocarbon dated. Secondly, the testing is destructive. While accelerator mass spectrometry has allowed for the radiocarbon dating of small samples, the creation of high precision calibration curves requires 150 g to 200 g of material (Bayliss et al., 2013). Thirdly, due to a plateau in the radiocarbon calibration curve between 425 AD and 550 AD calibrated radiocarbon dates from the 5th and 6th centuries can only be dated to a 150-year period with 95% probability (or 100 years with 68% probability) (Bayliss et al., 2013). As such, radiometric dating has had little impact on early Anglo-Saxon chronologies. However, high precision radiocarbon dating, correspondence analysis and dendrochronology have been combined via Bayesian statistical modelling in a project designed as a comprehensive refinement of early

Anglo-Saxon chronology (Hines and Bayliss, 2013). Samples of human bone were used for radiocarbon analysis, selected from high-status burials from 17 sites that included grave goods often used in artefact typologies (Beavan and Mays, 2013). These artefacts were then reassessed into revised typologies and chronologies (Hines and Bayliss, 2013). This project has significantly influenced the chronological interpretation of late 6th and 7th century burials; however, the model could not be extended before 570 AD due to a lack of material and did not include cremation burials or pyre goods in the analysis (Hines and Bayliss, 2013; French, 2017). At Spong Hill the combination of correspondence analysis of pottery and grave goods and stratigraphic relationships between burial groups has allowed for the division of the cemetery into three phases of use from circa 400 AD through circa 550 AD (Hills and Lucy, 2013). However, the methodology used at Spong Hill may not be applicable to other cremation cemeteries with fewer inter-related burial groups (Hills and Lucy, 2013). Thus, chronology remains a significant problem in the interpretation of early Anglo-Saxon archaeology (Dickinson, 2011).

2.4 Cremation Burial

Cremation burial was a popular funerary rite in early Anglo-Saxon England (Lucy, 2000). Well over eleven thousand cremation burials have been excavated from this period, predominantly (68%) from Norfolk, eastern Lincolnshire, and Yorkshire (French, 2017). This distribution is biased by the existence of several large cremation cemeteries: Sancton, Yorkshire (n=330); Elsham, Lincolnshire (n=569); Cleatham, Lincolnshire (n=1009) and Spong Hill, Norfolk (n=2384) – Spong Hill alone accounts for 20% of cremation burials recovered from the early Anglo-Saxon period (Squires, 2012; French, 2017). However, despite these large data sets, cremation burials were largely ignored until the final decades of the 20th century (McKinley, 1994a; Worley, 2008; Squires, 2011, 2013, 2016). Archaeologists preferred to study the decorated cinerary urns and associated grave goods, many considering the cremated human remains to be without academic value (Hills, 1980; Lucy, 2000; Williams, 2003; Worley, 2008). In some cases, the cremated bone was simply discarded; for instance, over two hundred cremation burials excavated from South

Elkington in Lincolnshire were lost before any analysis was conducted, while the published report focused on the associated urns[1] (Hills, 1980; McKinley, 1994b; Lucy, 2000; Squires, 2011). Calvin Wells produced the earliest study of Anglo-Saxon cremations with his work on the cemetery at Illington in Norfolk (1960). Wells also provided the osteological analysis of both the cremated and inhumed remains from Caistor-by-Norwich for the site report published in 1973 (Squires, 2011). This work did not immediately provoke further investigations of Anglo-Saxon cremations, with the next analyses conducted by Mary Harman on the cremated remains recovered from the cemeteries at Elsham and Newark in Nottinghamshire, though only the Newark report was published, in 1989 (Squires, 2011). Not until Jacqueline McKinley conducted a detailed and extensive analysis of the vast quantities of cremated material at Spong Hill did archaeological investigations of Anglo-Saxon cremation truly begin to flourish (McKinley, 1994a; Squires, 2013, 2016). This publication, and the 1993(a) publication of McKinley's osteological assessment of the cremated remains at Sancton cemetery, challenged the understanding of cremation burials as the 'poor relation' of inhumation burials (McKinley, 1994a). Calculations of the investment of time and labour involved in the building of the cremation pyre, collection of the remains and later burial along with detailed analyses of the accompanying pyre and grave goods, and the significant investment reflected in the animal bone remains found in many cremation burials showed that these burials represented a disposal of wealth on par or in excess of contemporary furnished inhumations (Bond, 1994; McKinley, 1994a; Bond, 1996; Williams, 2003; Bond and Worley, 2006; Squires, 2011, 2013; Williams, 2014; French, 2017). While there is a dearth of the archetypical Anglo-Saxon 'warrior' burials accompanied by weapon sets among the cremation burials of this period there is a wealth of information regarding the mechanisms of their disposal, the material culture they chose to be cremated and interred with, and the social identities these choices sought to create and signify.

[1] The urns excavated from South Elkington cemetery have been retained and are held at the Lincoln Museum, Lincolnshire.

2.4.1 The Funeral Pyre

Pyre sites are rarely recovered in England. From the Anglo-Saxon period there are only three tentatively identified pyre sites: at Sancton, Yorkshire; at Snape, Suffolk, and at Asthall Barrow, Oxfordshire. At Sancton the possible pyre feature includes an area of burnt clay with associated finds of charcoal and bone. However, the area measures only 30 cm by 60 cm and is therefore unlikely to represent a pyre site (Squires, 2011). At Snape charcoal, pottery sherds, cremated bone, burnt flint and copper-alloy fragments were found in the soil layer. This scatter of finds was confined to one feature, 'Area A', and only one piece of charcoal was discovered outside of this feature; however, there were no clear indications of a pyre structure (Pestell, 2001). Finally, at Asthall Barrow along with finds of cremated bone, charcoal, charred timber, and pottery sherds there were post-holes discovered. These post-holes are similar to those found at pyre sites at the German mixed rite cemetery of Libenau, suggested to have been involved in support of pyre structures. Reassessment in 1992 suggested this feature was instead similar to the 'houses of the dead' discovered at Apple Down, West Sussex. Less convincing cases of potential pyre sites have been proposed as explanations of features at Chavenage, Gloucestershire and Little Wilbraham, Cambridgeshire (Lucy, 2000). None of these pyre sites are securely identified and therefore they cannot be used as evidence of the constructions of Anglo-Saxon pyres (Squires, 2011; French, 2017).

There are several elements of pyre construction that can be inferred from the observation of cremated remains and their accompanying artefacts. Jacqueline McKinley has suggested that Anglo-Saxon pyres were constructed along 'log-cabin' forms – that is, rectangular assemblies of timbers at right-angles, potentially in-filled with brush wood to provide additional fuel (1994a). The deceased would then be laid out supine and dressed on top of the pyre accompanied by pyre goods and animal remains, as shown in figure 2.6. Calvin Wells has suggested instead that the Anglo-Saxons employed pyramid-style pyre constructions in which the deceased was laid out and the fire constructed above them; however, evidence suggests McKinley's hypothesis is more likely (Wells, 1960; Wells, 1993; Williams, 2004; Squires, 2011). Observations of burning intensity across individuals from Anglo-

Saxon cremation cemeteries suggest a highly efficient oxidation process, though not necessarily complete calcination of the entire skeleton. Elements that were exposed to lower intensity burning conditions include: vertebrae, os coxae, proximal femora, petrous temporals, and portions of the occipital (McKinley, 1994a; Squires, 2011). The pattern suggests the posterior surface of the body was less exposed to intense heat, indicating the body lay in a supine position against the structure of the pyre which restricted oxygen flow to the posterior regions of the body. This gradient of burning intensities has been observed at Elsham, Lincolnshire; Cleatham, Lincolnshire; Sancton, Yorkshire; Snape, Suffolk; and Spong Hill, Norfolk (Squires, 2011). Furthermore, several bone fragments have been found with adherents of glass or copper-alloy material, suggesting pyre goods in contact with the bone during cremation and subsequent cooling (McKinley, 1994a; b). These adhesions are most commonly found on temporal bones, but also on bones of the hand, arm and less frequently on the ribs. These finds reinforce the interpretation of cremation in a supine position, as other body positions would likely cause these pyre goods to fall from the body prior to fusion with the bone. Furthermore, their presence suggests that there was little movement of the deceased during cremation – as this would likely dislodge the pyre goods before they cooled sufficiently to fuse to the bone surface. Therefore, it would appear that stoking or tending of the cremation pyre was not a common practise in Anglo-Saxon England (McKinley, 1994a; b).



Figure 2.6: Cremation pyre diagrams. Left: superior view showing the deceased in a supine position, dressed, and accompanied by animals. Right: ¾ view of funeral pyre showing 'log-cabin' construction. Figure by author.

The primary fuel used in Anglo-Saxon cremation was wood and several analyses of charcoal from possible pyre sites and cinerary urns have been conducted to determine whether there were preferred tree species utilized in these rituals (Squires, 2011). At Spong Hill, Norfolk and Mucking, Essex the predominant species was found to be oak, while at Snape, Suffolk pine was predominant, though oak and hazel were also commonly found (Squires, 2011). In a study of Norwegian tree species, beech was found to be the most efficient fuel source, producing most heat (kcal/kg). Ash, pine, and oak were also found to be relatively efficient sources of fuel, with lime, spruce, and birch gradually producing fewer calories by weight (Holck, 1986; McKinley, 1994a). However, fuel efficiency was not likely the sole, or even the predominant, influence on the Anglo-Saxons when choosing wood for the construction of a pyre. The choice of wood was likely heavily influenced by availability (McKinley, 1994a; McKinley, 2006). Ritual considerations cannot be ruled out: oak has associations with strength, power and energy in Norse and Germanic cultures, pine with immortality and protection, and ash with the god Odin (Squires, 2011). Furthermore, wood may have been chosen on the basis of its scent. In modern India sandalwood is preferred for pyre construction due to its perfume; there are ethnographic sources suggesting conifer, cedar, pine, mango, and wood-apple have been selected for similar reasons (McKinley, 1994a, Squires, 2011).

The amount of wood used to create the cremation pyre has been tied to social status or rank (Squires, 2011). Ethnographic sources support this; for instance, in the Iliad Homer records that the pyre built for Patroclus was 100 square feet (McKinley, 1994a). Similarly, in a study of Hindu customs and ceremonies Dubois and Beauchamp (1906) reported that the king of Tanjore was cremated on a pyre of sandalwood measuring up to 15 square feet, while a Brahmin was provided a pyre measuring only six by three feet (McKinley, 1994a). Holck (1986) estimated that the amount of fuel required to cremate a human body would be approximately 146 kg of pine; however, this was based on a comparison between the amount of gas used in modern cremation and the equivalent energy produced by wood fuels (McKinley 1994a). This calculation does not account for the heat lost to the atmosphere in an

open pyre; in modern India pyre construction typically involves between 300 kg and 500 kg of wood (McKinley, 1994a). From accounts written between 1850 and 1900 the amount of fuel required per individual for heating and cooking was estimated at '1-2 entire large tree trunks' annually (Høilund Nielsen, 2009). Given that a tree measuring 56 cm in diameter at breast height produces approximately 1000-2000 kg (based on oak and pine) of dry wood, the wood required for a cremation pyre therefore represents between one quarter and one half of the yearly supply used by a living individual (McKinley, 1994a; DeWald et al., 2005).

To aid in the ignition of the pyre accelerants may have been introduced during Anglo-Saxon period cremations; there is evidence that the Romans used perfumed oils and in modern India ghee and scented oils are often used (Squires, 2011). If the Anglo-Saxons employed accelerants these would likely have been butter or animal fats, possibly clarified or rendered into more efficient fuels (Squires, 2011). The maximum temperatures reached by Anglo-Saxon pyre cremations were in excess of 1000°C, as demonstrated by fragments of bronze artefacts that were found to have melted – the melting point of bronze is 1084°C (McKinley, 1994a; Squires, 2011). This indicates cremations were taking place at temperatures in line with modern crematoria (500°C – 1000°C), well in excess of the kindling point of subcutaneous fat (250°C – 350°C) or the temperatures required to oxidise leather, hair, fur, or wool (212°C – 600°C) (Squires, 2011). However, temperatures were not consistent across the pyre. The centre of the pyre will have been the hottest region throughout the cremation process, with the periphery relatively cool depending on the prevailing winds and weather (McKinley, 2000). Bones, such as the distal phalanges, and pyre goods that fell away from the body and into the wood-ash at the base of the structure will have been protected from further heat exposure (McKinley, 1994a). Though most of the artefacts recovered from cremation burials show evidence of burning, suggesting these goods were placed on the pyre with the deceased, these artefacts also show exposure to a range of temperatures; from melted bronze artefacts, suggesting temperatures above 1084°C, to lightly charred bone or antler combs suggesting temperatures below 300°C (McKinley, 1994a).

In modern crematoria the oxidation of the soft tissue is achieved after approximately 45 minutes, with the skeleton fully oxidized in under 90 minutes

(McKinley, 1994a). Once raked out, bone fragments cool sufficiently to be handled within 10-15 minutes (McKinley, 1993b). However, pyre cremations are subject to several variables influencing both the oxidation of the deceased and the ability of the mourners to collect the cremated remains. Accounts of cremation times vary. In modern India at highly prized cremation sites, such as those in Varanasi, pyres are allowed to burn for three to four hours before the remains, still hot, are removed to the Ganges thus vacating the pyre site for the next cremation. However, at other sites where demand is not so high, pyres are allowed to burn down overnight before scattering the cremated remains in the river (McKinley, 1994a). Early medieval literary sources record that cremations could take seven to ten hours to complete, suggesting that collection of the remains took place in the following days (McKinley, 2006; Squires, 2011). The occurrence of glass beads and fragments of bronze adhering to the bone, discussed above, suggests that the remains of the pyre and the deceased were left to cool *in situ* (McKinley, 1994b). In experimental pyre reconstructions, allowing pyres to burn out naturally in this way took approximately ten hours (McKinley, 1994a).

2.4.2 Collection of Remains

After cooling, the collection of the remains would have taken place by hand, though possibly aided by sticks, rakes, tongs, or shovels. This responsibility likely fell to the relatives or friends of the deceased, a task that has been estimated from ethnographic sources as requiring three hours of labour if conducted by a single individual (McKinley, 1994a; Squires, 2011). The weight of cremated remains recovered from Anglo-Saxon cremation urns is highly variable. For instance, at the Anglo-Saxon cremation cemetery at Elsham in North Lincolnshire the largest cremation held 5406 g of cremated bone, while the smallest only held 0.3 g. These values highlight a problem, however, as several of the Anglo-Saxon cremations contained multiple individuals or significant contributions of animal bone. Indeed, the large cremation burial referred to, EL75PH, held the remains of three individuals as well as some sheep bones. At the nearby cremation cemetery at Cleatham the largest cremation weight discovered was 4470 g, but this burial, MT84GB(b), was

primarily composed of horse bone with only a single cranial fragment from a human individual. There were 21 cremation burials recovered from these two sites that weighed 2000 g or more, most of which included some faunal remains (Squires, 2011). This complicates the interpretation of cremation weights as indications of labour expenditure. The mean weight of cremations recovered from Elsham was 523 g, but the weights do not follow a normal distribution and the median weight recovered is only 382 g; a similar pattern was observed at Cleatham (Squires, 2011). The average weight collected for cremation from eight early Anglo-Saxon cremation cemeteries was 438g, with results from individual cemeteries displayed in figure 2.7 (Squires, 2016).

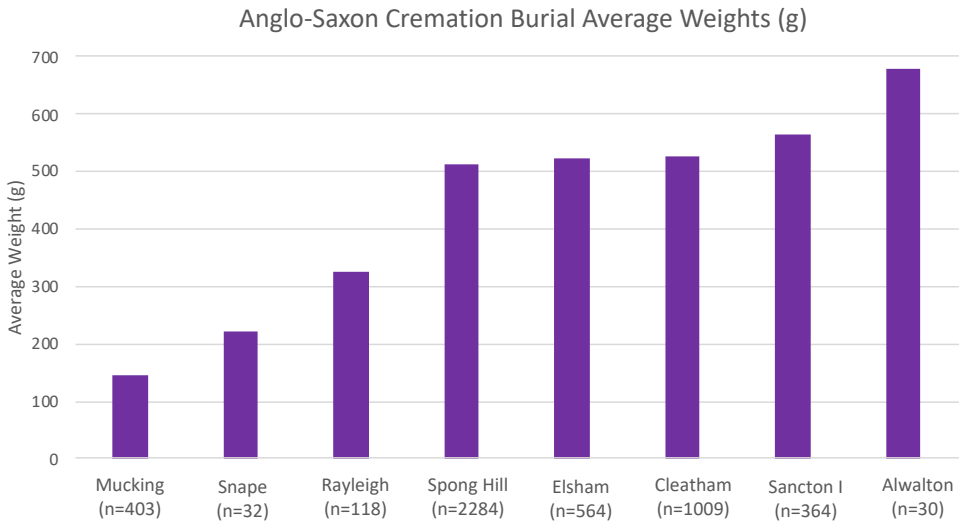


Figure 2.7: Average cremation weights from Anglo-Saxon cemeteries, with number of burials included below each site (data from Squires, 2016).

While it is difficult to interpret these results in terms of relative status, it is clear that the Anglo-Saxons were not concerned with collecting all of the skeletal remains left by the pyre. Jacqueline McKinley observed modern cremations to determine the average expected weight for a cremated adult individual; she proposed that only the fragments remaining on the 2 mm sieve should be included in this estimate as smaller fragments would be unlikely to be recovered or to survive the burial environment. She found that the adult remains ranged from 1002 g to 2423 g, with a mean of 1626 g (McKinley, 1993b). Thus, it is clear that in most cases the Anglo-Saxons were collecting less than half of the expected total weight of an

adult human skeleton. However, it also does not appear that the Anglo-Saxons were biased towards the collection of specific areas of the body. Analyses of the proportional weight allocated to the cranium, axial elements and limbs at Sancton, Spong Hill, and Elsham suggest that elements from each category were included and in approximately the proportions expected when compared against the weight of a dry skeleton – i.e. cranium 20%, axial elements 25% and limbs 55% (McKinley, 1994a; Silva et al., 2009; Squires, 2011). McKinley cautions that some bias towards the cranium is expected, not due to the collection of the mourners, but due to the identification bias of the archaeologist (McKinley, 1994a). While the Anglo-Saxons do not appear to have been invested in the complete collection of the skeleton, neither does it appear that they were careless or cursory in their collection of remains from cremation pyres. The urns recovered from these cemeteries contain cremated human bone, cremated and occasionally unburnt animal bone, pyre or grave goods but surprisingly little charcoal, slag or pyre debris (McKinley, 1994a; Squires, 2011). Furthermore, the collection of the small bones such as the distal phalanges or at Spong Hill even a portion of gall stone suggest that collection was meticulous, if dictated by a standard other than exhaustive collection of remains (McKinley, 1994a; Squires, 2011). The combination of cremation weights representing only a token portion of the physical remains and the inclusion of miniscule elements has led researchers to suggest that a portion of the cremated remains may have been retained by the mourners, either as tokens or for inclusion in later burial rites; however, it is difficult to prove the fate of these remains from their absence alone (McKinley, 1994a; 2006; Williams, 2004; Squires, 2011; Squires, 2016).

2.4.3 Cremation Urns:

Cremated remains from Anglo-Saxon cremation cemeteries were predominantly recovered from ceramic vessels (Lucy, 2000; Williams, 2014). All pottery from the early Anglo-Saxon period appears to be hand-made and largely coil-built, though some vessels are of a consistent thickness that suggests they were thrown on a low-speed wheel (Richards, 1987; Perry, 2013; Williams, 2014). The

majority of Anglo-Saxon pottery has a black, reduced appearance, but there are often patches of oxidization that instead appear buff or brown in colour (Leahy, 2007). Potters appear to have used local clays with a wide variety of inclusions; at Illington in Norfolk, for instance, from 314 pottery samples 123 distinct fabric types were identified (Richards, 1987; Russell, 1993). Similarly, at Cleatham in Lincolnshire while local clays were used two or more additives were found in 44.8% of the ceramic samples, but there was such variety that no patterns could be identified (Leahy, 2007). This variety in the fabric used to create cremation urns suggests that manufacturing was done on a small scale by many individuals, rather than by a small number of specialists (Russell, 1993; Perry, 2013). Concentrations of specific tempers suggest that local groups followed habitual beliefs regarding appropriate materials. While some of these may be tied to local availability of raw materials, others, such as the use of dung, would have been available to all potters but was used only by specific groups (Perry, 2013). There is little evidence of the production process, though the finished urns indicate firing at temperatures below 1000°C, possibly on a bonfire or simple kiln, such as those discovered at Purvell Farm, Cassington (Richards, 1987; Williams, 2014).

There is a debate among researchers regarding whether cremation urns were made specifically as funerary vessels or were made for domestic use and repurposed (Richards, 1987; Leahy, 2007; Perry, 2013). Those who argue that cremation urns must largely have been made specifically to contain human remains cite the specific forms and high levels of decoration found among cremation urns. In a study of 2440 cremation urns from 18 early Anglo-Saxon sites, Julian Richards found that these vessels had an average height of 19.5 cm and that when comparing the mean height of urns between sites there was a range of only 2.7 cm. The clustering of the means from these sites suggests there may have been a shared ideal, at least in size, of a cremation urn. In the same study, considerable variation of urn forms was observed in terms of: maximum width, constraint of the 'neck', diameter of the opening, or presence of a distinct 'shoulder'. However, none of the vessels could be construed as a flat platter or cup – typical pottery forms found at domestic sites. Furthermore, of the 2440 urns studied, approximately 80% showed some form of decoration: the most common type being incised decoration, with stamped and plastic decoration

on less than half of the urns examined (Richards, 1987). Comparatively, in a multi-site study of pottery from Anglo-Saxon settlement sites in East Anglia Russell found that, on average, only 7.5% of pottery sherds were decorated (Leahy, 2007). These observations, however, are more typical of the large cremation cemeteries of eastern England. In southern and central England cremations are more often found in undecorated urns (Williams, 2014). Furthermore, soot deposits on urns have been seen as an indication of domestic use prior to burial, although these deposits are found on only a minority of cremation urns. At Cleatham only 35 urns (3%) showed evidence of soot; at Mucking 16 urns (3%) showed similar evidence (Leahy, 2007; Perry, 2013). However, researchers who argue that cremation urns are more likely repurposed domestic wares point out that there is no difference in the ceramic fabrics found at cemetery sites and adjacent settlement sites. Additionally, while there are more decorated pots found in cemetery assemblages, the motifs used to decorate pottery sherds recovered from settlement sites are similar (Perry, 2013). Additionally, deposits of soot would only be expected on pots used in cooking, while other functions of ceramic vessels would produce different signs of use. In a study focused on Cleatham and Elsham cemeteries, Gareth Perry found that abrasion on the exterior basal surface, reflecting movement of the urn against a surface, and internal pitting, reflecting contact with an acidic substance, were particularly evident among cremation urns (2013). The proportion of Cleatham urns that showed evidence of prior use, when these additional indicators were evaluated, rose from Leahy's 3% estimate to 51% - this figure rises further, to 71%, when only complete urns are considered (Leahy, 2007; Perry, 2013). However, criticisms of these indicators question whether they suggest domestic use or use during funerary rituals. Abrasions of the exterior basal surface reflect only the movement of the urn, not a specific use and the internal pitting, while related to contact with acidic liquids, may instead relate to use during funeral feasting (Perry, 2013). Perry argues that the amount of pitting observed on cremation urns is too extensive to have been acquired during funerary feasting alone (2013). However, his assumptions are also predicated on the deceased being buried soon after cremation (Perry, 2013).

Whether the urns were made specifically as funerary vessels or chosen from a selection of domestic wares, there does appear to have been a culturally dictated

category of pottery that was considered acceptable (Richards, 1987; Perry, 2013; Williams, 2014). These distinctions were not consistent among all cremated individuals. There is a link between age and the height of the selected vessels, with older individuals found in taller urns. This relationship was recorded in Richards' multi-site study, but was also found independently at Cleatham, Elsham, Sancton, Spong Hill, and Mucking (Richards, 1987; McKinley, 1994a; Squires, 2011; Hills and Lucy, 2013; Squires, 2013). Non-adults, especially infants, were found to represent a markedly different group of urns compared with the adult population with a higher proportion of undecorated pots of smaller than average size (Richards, 1987; Squires, 2011; Hills and Lucy, 2013; Squires, 2013). However, this population of non-adults was also afforded a similar range of grave goods to the adult population, suggesting that while vessel decoration and size may be linked to the attainment of adult status, the distinction was not necessarily an economic one (Richards, 1987). A less universal link has also been found between urn forms and biological sex (Richards, 1987; Squires, 2011). In Richard's multi-site study he found that female remains were more often found in urns with wider rims (Richards, 1987). These types of vessels would be more suited to preparing or serving food and drink, rather than fermentation or storage, which has been interpreted as relating to expected gender roles (Perry, 2013). However, this link has not been as universally reported; in Richards' study the link was more tenuous than that between biological age and urn height. Similar patterning was found at Cleatham and Mucking, but at Elsham and Sancton this link was not significant (Richards, 1987; Squires, 2011). These associations are also questionable due to the small proportion of remains for which it was possible to estimate biological sex (Squires, 2016). At Cleatham for instance, a comparison between biological age and urn height was possible for 337 individuals, while a comparison between biological sex and rim diameter was only possible for 81 individuals (Squires, 2011). Further, this population included older non-adults and those for whom sex estimation was possible but not certain; when the population was limited to only adults for whom sex estimation was secure, statistical significance was not achieved (Squires, 2011). However, the selection of cremation urns was clearly intentional and conformed to Anglo-Saxon conceptions of death and

relative social status, whether we, as archaeologists, are able to read the intentions or not (Richards, 1987; Squires, 2013; Williams, 2014; Squires, 2016).

2.4.4 Pyre and Grave Goods:

As with inhumation burials in the early Anglo-Saxon period, a substantial proportion of contemporaneous cremation burials were interred with grave goods. In his multi-site study, Richards found that 48% of cremation burials (n=1170) contained grave goods; however, there was a considerable range between sites, as at Spong Hill approximately 70% of cremated individuals were afforded some type of grave good (Richards, 1987; Lucy, 2000). Richards believed that his inter-site estimate should be considered a minimum as at certain sites, such as Lackford where only 21% of cremations were recorded with grave goods, there were distinct issues of preservation and recording that affected these data (1987). There is some evidence that the Anglo-Saxons drew distinctions between pyre goods that were placed with the deceased on the cremation pyre and therefore burned, and grave goods, placed either in or around the urn before burial (McKinley, 1994a; b). Glass artefacts, for instance, nearly always show some signs of being exposed to the cremation pyre; conversely, combs, made of bone or antler, rarely show clear signs of burning (Richards, 1987). While this is an important distinction, and one that holds potential to reflect Anglo-Saxon attitudes towards the cremation rite, unfortunately it is not one that has always been made by researchers (McKinley, 1994a; Squires, 2013).

One of the most evident distinctions between the assemblages of grave goods found with Anglo-Saxon cremations compared with inhumations from the same period, and in some cases from the same cemeteries, is the lack of 'gendered' artefacts. The typical dichotomy of females buried with dress accessories and jewellery and males buried with weapons is not found in cremation burials (Richards, 1987; McKinley, 1994a; Lucy, 2000; Williams, 2003; Squires, 2013). The majority of grave goods are found with both males and females; the only exclusive associations are typically with objects that are found in such small numbers that they cannot be used as evidence of a sex-linked association (Squires, 2013). For instance, at

Cleatham the only artefact found exclusively with males were decorated strips, with only two examples recovered, while buckles and whetstones were only found with females, each of which were represented by a single example (Squires, 2011). Some common items were found to have distributions that could be linked to biological sex. Spindle whorls, beads, rings, and brooches have been found in higher numbers among female cremations at Elsham, Cleatham, and Spong Hill cemeteries (Squires, 2013). The fact that this female bias is also found in the burial assemblages of Anglo-Saxon inhumations strengthens the assumption that this reflects a gender-based identity in death. However, there have been no parallel male biased artefact groups discovered among cremation cemeteries that reflect the male inhumation rite (Squires, 2013). Correspondence analyses and cluster analyses have been used to identify potential sex-linked groups of artefacts among cremated populations. Richards identified three artefact groups: group one associated with miniature toilet items was a male dominated group, group two associated with glass beads and ivory was a female dominated group, and group zero had no associated grave goods and appeared more strongly linked with age. Importantly, none of these groups could be shown to have exclusive associations (Richards, 1987). Ravn (2000) evaluated the burial assemblage from Spong Hill using correspondence analysis and found three male dominated groups and one female dominated group of grave goods. However, at Cleatham and Elsham neither correspondence analysis nor cluster analysis showed statistically significant sex-links among the grave goods discovered at these sites (Squires, 2013).

Overall, early Anglo-Saxon cremations do not show the clear sex-linked patterning expected from research on inhumations from the same period. However, a number of caveats must be understood when considering this distinction. Firstly, sex can be difficult to determine from cremated remains. At Elsham of 564 identified individuals, only 182 (32%) retained any indicators of biological sex and only 63 individuals (11%) could confidently be assigned as either male or female; a similar proportion was found at Cleatham where only 328 individuals (33%) of 1009 retained indicators of biological sex, 90 (9%) of whom were able to be assigned a sex with confidence (Squires, 2011; 2013). Therefore, conclusions based on artefact associations, or lack thereof, among cremated remains must be interpreted with

caution. Secondly, among inhumation burials grave goods have, in the past, been taken as directly indicative of biological sex – in some cases even when osteological assessments suggest conflicting sex estimations (Davidson et al., 1993; Lucy, 1997; Knüsel and Ripley, 2000; Leahy, 2007). Therefore, the strength of the trend of sex-linked distributions of grave goods among inhumed Anglo-Saxons is based, in part, on a circular argument. Thirdly, while complete preservation of grave goods is not expected in burials regardless of funerary rite, cremations particularly may not reflect the full suite of grave goods initially provided to the deceased. Organic materials may have been consumed by the pyre, though these materials rarely survive in the burial environment of inhumations as well. Additionally, during the collection of the remains for burial, pyre goods may not have been collected; considering the cremation weights at Anglo-Saxon cemeteries suggest that collection of only a portion of the remains was considered necessary, it is likely that some grave goods may also not have been collected (McKinley, 1993b; 1994a; Williams, 2003; McKinley, 2006; Squires, 2011).

After glass beads, combs are the most frequently found grave goods associated with cremation burials. When considering only undisturbed contexts 19% (39/211) of cremation burials at Sancton contained combs, 22% (267/1212) at Spong Hill, 29% (281/960) at Cleatham and 34% (15/44) at Newark (Williams, 2013; 2015). The highest rate of inclusion of combs within cremation burials was at Alwalton, where 58% (16/28) of urns contained combs (Williams, 2015). Outside of eastern England combs are a less common inclusion in cremation burials, though the inclusion of pyre or grave goods is generally less common among cremation burials in southern and central England (Williams, 2011; 2015). Combs were manufactured from bone or antler, with antler combs being the most common (Williams, 2003; Squires, 2013). While the materials were common and inexpensive, the ornamentation afforded to these combs suggests that their production would have involved considerable skill and time investment (Williams, 2003). These implements were included in burials of both males and females and have been found in all age categories, with some variation – miniature combs, for instance, are most commonly found with infant burials (Williams, 2003; Squires, 2013; Williams, 2015). Interestingly, combs are relatively rare among the grave good assemblages that

accompany inhumation burials in the early Anglo-Saxon period; none of the inhumation burials at Cleatham were furnished with combs (Williams, 2003; 2015). The most common pyre/grave goods found in association with combs are toilet implements, shown in figure 2.8, including: tweezers, shears, razors, ear scoops, and blades. These implements were made of iron or bronze, were included as full-sized or miniature items and were sometimes kept on a ring as a set (Williams, 2003; McKinley, 2006; Squires, 2013). The inclusion of non-functional miniatures suggest that there was more to the inclusion of these items than a practical deposition of personal items or items polluted by the contamination of death (Williams, 2003). Instead, these items were considered a necessary symbolic inclusion for a sub-set of the population that were cremated in death. The relatively high number of grave goods found in cremation burials that include combs suggests that these were potentially high-status burials (Williams, 2003).

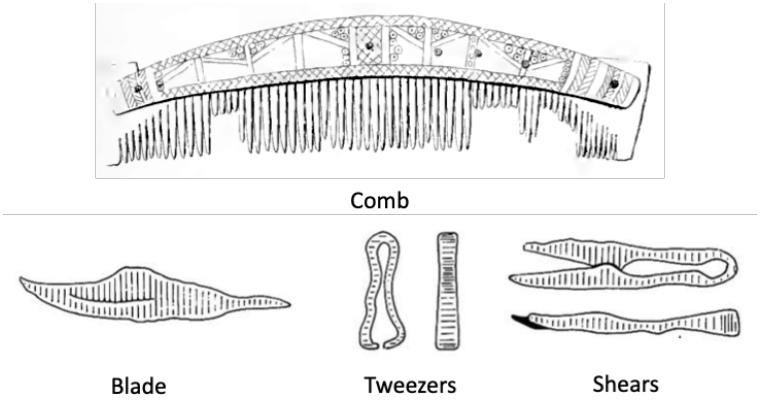


Figure 2.8: Decorated comb, ivory, or bone, Grave 53 - Kingston Downs (Faussett, 1856, plate 13). Toiletry set, iron, Urn 71 – Cleatham (Leahy, 2007, p. 224).

Another distinguishing feature of Anglo-Saxon cremation burials is the common inclusion of faunal remains; see figure 2.9 (Williams, 2003; Williams, 2014; Squires, 2016). In eastern England, where the majority of large cremation cemeteries are located, 20-40% of cremation burials contained multiple species (McKinley, 1994a; Squires, 2011; Squires, 2013; French, 2017). Cremation burials in southern and central England are less likely to contain faunal remains (Williams, 2014; French, 2017). However, only a select few Anglo-Saxon cemeteries have been

subject to comprehensive osteological analyses and fewer still have benefitted from the expertise of a zooarchaeologist (McKinley, 1994b; Bond, 1996; French, 2017). The two most common species found accompanying cremated individuals were sheep/goat and horse. At most sites, sheep/goat is the most common inclusion (French, 2017). These remains often show signs of butchery associated with dismemberment and may have been placed on the pyre as joints of meat rather than as whole animals (Bond, 1994; Bond, 1996). Age estimates on these animals also suggest that most were killed between one and three and a half years of age, suggesting these animals were raised for meat (Bond, 1994). The incidence of sheep/goat in cremation burials is not surprising when compared against animal assemblages derived from settlement sites where sheep/goat remains are also the most common when counted either as a minimum number of individuals (MNI) or number of identified specimens (NISP) (Crabtree, 1990; French, 2017). Sheep/goat remains may also be found as collections of astragali, likely intended as playing pieces, with examples of these types of deposits found at Spong Hill, Caistor-by-Norwich, Loveden Hill and Cold Eaton, Derbyshire (Lucy, 2000). Richards (1987), in his multi-site study, found that sheep/goat remains were the most common faunal inclusion in cremation burials and were present in the burials of both males and females and in all age categories. Cattle are also a relatively common inclusion among cremation burials, though at a lower rate than expected when compared to their representation within settlement sites (Crabtree, 1990; Bond and Worley, 2006; French, 2017). Few of these remains show butchery marks, but most are under three and a half years of age, suggesting they were reared for meat production (Bond and Worley, 2006). Pigs were a less common finding but appeared to fall into two groups: young pigs with butchery marks and neonates cremated as whole animals. Both practises suggest these animals may have represented food offerings (Bond, 1994; Bond and Worley, 2006). Occasional inclusions of domestic fowl, goose and fish may have been included as food offerings as well (Bond and Worley, 2006; French, 2017).

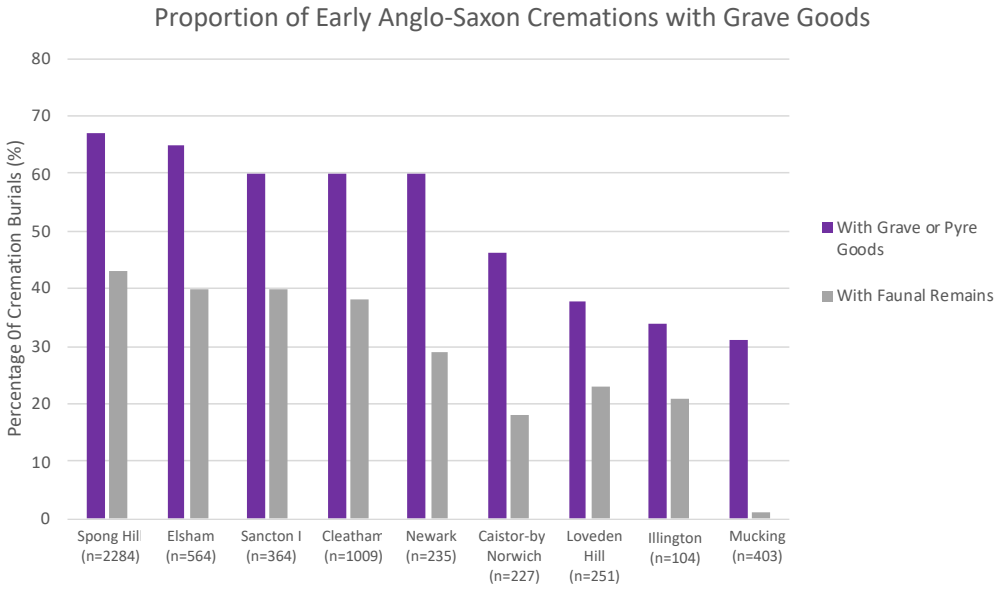


Figure 2.9: Proportion of cremation burials with pyre or grave goods, in purple, and faunal remains, in grey, from early Anglo-Saxon cemeteries. Grave good data from McKinley, 1994a; data on faunal remains from Bond, 1996; Cleatham, Elsham and Mucking data from Squires, 2016.

At three sites horses are the most common species included with cremation burials: Spong Hill, Sancton I, and Snape (French, 2017). However, this may be an underestimate as research has shown that fragmentary bones from larger mammals are difficult to distinguish from human remains when comingled (Bond, 1996). If zooarchaeological analyses are conducted on cremated remains from more Anglo-Saxon sites, additional sites may be found with higher proportions of horse remains than previously understood (Bond, 1996; Bond and Worley, 2006). The horse remains that have been recovered rarely show butchery marks and the completeness of the assemblages typically found suggest that horses were cremated whole (Bond, 1994; Bond 1996). Most horses appear to have been over three years of age, but secure age-at-death information is complicated by the absence of teeth in most burials (Bond, 1994). Pathology indicators on four of the animals found at Spong Hill suggest these may have been draught horses (Bond, 1994). Preservation of the horse remains may appear to represent a 'head and hoof' inclusion; however, this more likely reflect a bias in the recognition of these skeletal elements and their resistance to taphonomic factors rather than a ritual selection by the Anglo-Saxons (Bond, 1994; Bond, 1996). Lack of butchery marks, completeness, ages-at-death,

and pathological indicators suggest that these animals were not being included as food offerings. Instead they have been interpreted as indicators of status or wealth, companions in death or as psychopomps (Bond, 1994; Bond, 1996; Bond and Worley, 2006; French, 2017). When horse remains are found with Anglo-Saxon inhumations they occur either alone, not associated with a human burial, or with burials of adult males (Lucy, 2000; Williams, 2011). Among cremation burials horse remains are largely found with adults, including both males and females (Bond and Worley, 2006). Another domestic species unlikely to have been included as a food offering is the dog. None of the cremated examples show any evidence of butchery, most were adults at death and most appear to have been placed on the pyre as whole animals (Bond, 1994; Bond and Worley, 2006, French, 2017). The animals vary in size from terrier-sized to wolf-sized dogs. The only case where more than one individual of the same species can be identified was urn 1725 from Spong Hill, this identification was possible due to the size variation between the two dogs (Bond, 1994). Similar to horse burials these animals appear to have been companions in death. Dogs may also have been indicators of status. Transferring ownership of trained dogs can be ineffective, reducing their value as working animals once their owner is deceased (Bond and Worley, 2006).

A further category of faunal remains found with Anglo-Saxon cremations are those that do not appear to be food offerings, nor are they present as whole animals (Bond and Worley, 2006). Some of these inclusions could represent furs or pelts; the only skeletal element of brown bears found with Anglo-Saxon cremations are terminal phalanges, likely representing bear skins imported from the Continent (Bond, 1994; McKinley, 1994a; Bond, 1996; Squires, 2013). Similarly, of five examples of fox remains associated with cremations at Spong Hill, four contained only mandibles – potentially these animals were included as pelts (Bond, 1994; 1996). Other inclusions appear to have been amulets or pendants (Bond and Worley, 2006; French, 2017). Some raptor claws and bear claws have been found that were pierced to allow them to be strung (Bond, 1994; McKinley, 1994a; Bond, 1996). One pig carpal was found with a similar modification, its apparent use as an amulet suggests this bone instead derived from a boar (McKinley, 1994a). Several cremation burials also contained varying quantities of unworked antler, one at

Millgate in Nottinghamshire contained 300 g of antler. Examples have also been observed at Spong Hill, Sancton and Caistor-by-Norwich (Bond, 1996). The purpose of these inclusions is unclear, but antler was an important material for the early Anglo-Saxons used to make combs, beads, rings, and spindle whorls (Richards, 1987; McKinley, 1994a; Lucy, 2000; Williams, 2014).

2.4.5 Burial:

The last archaeologically visible stage of the funerary ritual characterized as cremation was burial. The majority of cremated remains from the Anglo-Saxon period are recovered from individual pits, with most contained within an upright pottery vessel (Lucy, 2000). Urns may also be placed in groups of up to eleven urns, most of which appear to be contemporary interments, perhaps involving the burial pit remaining open for a period of time (McKinley, 1994a; Leahy, 2007; Williams, 2014). However, in some cases cremation burials have clearly intercut earlier interments, with related matrices of up to seven associated burials (Leahy, 2007). Studies of Anglo-Saxon inhumation burials have suggested a cemetery layout that is polyfocal and not segregated by age, sex, or wealth determinations. During her investigations at Sewerby in East Yorkshire, Susan Hirst was the first to suggest that this distribution likely reflected the clustering of individuals from a household or farmstead (1985; Squires, 2013). This long-held theory has been more recently subjected to analyses via statistical modelling of GIS maps of Anglo-Saxon cemeteries; the evidence supports the idea of household clusters of approximately twelve living individuals leading to a burial population over 150-200 years of circa fifty interments (Sayer, 2010; Sayer and Wienhold, 2013). In the few analyses of cremation cemeteries, this household clustering interpretation is also found (McKinley, 1994a; Ravn, 2000; Squires, 2011; Squires, 2013). Correspondence analyses have suggested some discrete clusters may be pulled from the general populations; however, the lack of precision in the phasing of cremation burials has frustrated the interpretation of these patterns thus far (Squires, 2013).

Another avenue of research has begun to suggest that these clustered burials were designed to create a cumulative memorial landscape (Wessman and Williams,

2017; Emery and Williams, 2018). Long reported as only incidental variation in burial structure, evidence of mortuary structures has just begun to be studied in their own right (Lucy, 2000; Emery and Williams, 2018). Cremation burials have generally been interpreted as small burial pits that, when filled, would have resulted in a flat cemetery landscape (Emery and Williams, 2018). However, cremation burials have been found in stone lined cysts, surrounded by ring-ditches, under barrows and among the remnants of wooden structures (Lucy, 2000; Williams, 2014). Researchers have often remarked that the rarity of intercutting between cremation burials suggests some form of above ground markers were left in place after the infilling of the grave (McKinley, 1994a; Leahy, 2007). Furthermore, the patterning of cremation deposits suggests that there may have been above-ground monuments visible for an unknown period; the discovery of cremation burials in rows or curves suggests these monuments would have created a cumulative mnemonic effect for the burial community (Wessman and Williams, 2017). Large barrows, such as those found at Sutton Hoo, appear to be confined to the late sixth and early seventh centuries; smaller mounds over individual cremation burials have been indicated at Earsham in Norfolk and Merrow Down in Surrey (Wessman and Williams, 2017). Ring-ditches that might indicate the previous existence of small barrows have been found at Apple Down, Essex; Portway Andover, Hampshire; Springfield Lyons, Essex; Collingbourne Ducis, Wiltshire; and Tranmer House, Suffolk (Lucy, 2000; Emery and Williams, 2018). Evidence of wooden structures have been found at Apple Down; Alton, Hampshire; Alwalton, Cambridgeshire; Berinsfield; Oxfordshire; Butler's Field, Gloucestershire; Collingbourne Ducis; Croydon, Surrey; Morningthorpe, Norfolk; Star Hill, Kent; Tranmer House and Spong Hill (Lucy, 2000; Emery and Williams, 2018). These wooden structures vary in form and some researchers have interpreted them as remnants of pyre structures; however, re-examination has shifted the consensus towards the interpretation of these finds as mortuary houses (Dickinson and Speake, 1992; Squires, 2011; Wessman and Williams, 2017). The evidence left by these structures consists of collections of post-holes, post-lines, and gulleys delineating areas from one to over two metres squared (Lucy, 2000; McKinley, 2006; Emery and Williams, 2017). The precise function of these structures is unknown but researchers have suggested they may have been used as grave markers relating to a

particular sub-set of individuals, stages for post-cremation ritual treatment of remains, physical foci for post-funeral commemorative events, or as columbaria (McKinley, 2006; Emery and Williams, 2017; Wessman and Williams, 2018). Perhaps these interpretations may be whittled down as further attention is given to these funerary monuments.

2.4.6 Summary:

The assessment of cremation burial as the 'poor relation' must be discarded; certainly, in terms of the investment of wealth and labour by the Anglo-Saxon burying community and, increasingly, in terms of the potential data available to the modern-day archaeologist (McKinley, 1994a; 2006). We have very little evidence of the preparation of the corpse for burial, save that the deceased was cremated before the soft tissue had decomposed (McKinley, 2006; Squires, 2017). Further investigations into this aspect of the ritual would require advances in the understanding of mechanisms of cremation as related to the condition of the body's soft tissues, though further evidence may also be provided by studies of literary references. There is a wealth of indirect evidence for pyre construction (McKinley, 1994a; b; Squires, 2011). However, as yet no pyre sites have been discovered to provide direct evidence for confirmation (Squires, 2011). Burial weights and fragmentation provide some indication of the collection of human remains (McKinley, 1994a; b; Squires, 2016). Extensive analyses have been undertaken on the pottery vessels used to contain most cremations (Myers, 1969, 1977; Richards, 1987; Perry, 2013). The associated artefacts placed within the cremation urns or buried alongside them have begun to be appreciated, with increasing awareness of the role of animal bone among them (McKinley, 1994a; Bond, 1996; Bond and Worley, 2006; Squires, 2013; French, 2017). However, very few cremation cemeteries have been analysed to this level; inclusion of further analyses is essential if we are to understand regional patterns in the use of pyre and grave goods (Bond and Worley, 2006; Squires, 2013). We may never have evidence of the intervening period between cremation and burial of the cinerary urn, as periods of retention may not leave distinctive use indicators (Williams, 2011; 2014; Perry, 2013;

Wessman and Williams, 2017). The burial portion of the cremation mortuary ritual is only beginning to be studied, but initial investigations suggest this may be a fruitful area of study (Squires, 2016; Wessman and Williams, 2017; Emery and Williams, 2018).

2.5 Mixed Rite Cemeteries

Mortuary rites in early Anglo-Saxon England are characterised by heterogeneity (French, 2017). Mourners chose between inhumation and cremation rituals, furnished burials with a multitude of grave or pyre goods, and buried their dead in a variety of positions with an array of grave structures (Lucy, 2000). There have been 692 cemeteries discovered from the early Anglo-Saxon period that utilise only the inhumation funerary rite. Another 70 cemeteries from this period utilise only cremation, while 175 cemeteries utilise both rites (Lucy, 2000). However, cremation cemeteries or 'mixed' rite cemeteries where cremation was the dominant rite tended to be much larger than those where inhumation dominated (Squires, 2011). These large cremation-dominated cemeteries were concentrated in eastern England, in an area that included Norfolk, eastern Lincolnshire, and Yorkshire (Hills and Lucy, 2013; French, 2017). Of these, only Spong Hill has been fully excavated yielding a population of 2482 cremation burials and 57 inhumation burials, as well as several hundred urns removed before formal excavations began (Hills and Lucy, 2013). At Cleatham most of the boundaries of the cemetery could be established, yielding a population of 1009 cremated individuals and 62 inhumed individuals, although Leahy estimated that the full population would be 1528 cremated individuals and 128 inhumed individuals (Leahy, 2007). Loveden Hill has yielded over 1000 cremation burials and 20 inhumation burials, with estimations suggesting a population of approximately 1700 individuals (Leahy, 2007; Squires, 2011). Several other cemeteries, such as Elsham and Mucking II, have yielded hundreds of cremated individuals and a smaller proportion of inhumed individuals (Squires, 2011). Elsewhere in southern and central England cremation and inhumation were also practised contemporaneously, though without the large concentration of cremation burials found in the East. Examples of these cemeteries include Alwalton,

Cambridgeshire; Apple Down, Sussex; Great Chesterford, Essex; Sprinfield Lyons, Essex; and Wasperton, Warwickshire (Williams, 2014). While most of these cemeteries were in use from the 5th through 7th centuries, detailed phasing of the burials at Spong Hill suggests that 68% (n=1686) of the cremated individuals were interred between 400-490 AD (Squires, 2011; Hills and Lucy, 2013). Moving into the later 6th century inhumation became the dominant mortuary rite and smaller local cemeteries became the norm (Lucy, 2000; Leahy, 2007). However, both cremation and inhumation rites were practised contemporaneously for a considerable period (Lucy, 2000; Leahy, 2007; Williams, 2011 Hills and Lucy, 2013; Squires, 2013; Williams, 2014). Internal organisation of these cemeteries appears to have been polyfocal, with clusters of burials of varied age, sex, and wealth. These have been interpreted as household units (Squires, 2013). However, these households are not equivalent to a nuclear family or kin group, but instead to a group of individuals of potentially diverse origins that formed the basic social and economic unit of the early Anglo-Saxon period including the primary descent group, their kin, labourers, and slaves (Stoodley, 2000; Williams, 2014). Within these household clusters both inhumation burials and cremation burials can be found that were interred at broadly contemporary dates, suggesting that even among the smallest social units of the time, the use of these two mortuary rites was not exclusive (Squires, 2013; Williams, 2014). The location of cemeteries within the geopolitical landscape of early Anglo-Saxon England was significant. Several cemeteries, including Cleatham, West Keal, and South Elkington, were located along parish boundaries (Leahy, 2007). Many are located on geographically prominent areas such as hilltops or escarpments, including: Spong Hill, Hall Hill, Loveden Hill, West Keal, Lackford, and Sancton I (Hills and Lucy, 2013). Cleatham, South Elkington, West Keal Elsham and Loveden Hill have each been associated with soke centres and folk moots, Anglo-Saxon centres of administration and politics (Leahy, 2007; Green, 2020). Furthermore, many cemeteries were focused around ancient earthworks, such as Bronze Age barrows, that lent these newly founded cemeteries an ancient and sacred connotation (Lucy, 1998; 2000; Leahy, 2007). However, as these large cemeteries fell out of use in the 6th century these prominent settings became less important (Lucy, 2000; Leahy, 2007).

The interpretation of these mixed rite cemeteries has changed over time as the dominant theories applied to archaeological evidence developed. The Victorians viewed cremation as the more primitive, pagan and 'Germanic' practise that evolved into the later, Christian, civilised practise of inhumation. Early 19th century culture-historical researchers noted the regional concentration of large cremation cemeteries in 'Anglian' areas and understood cremation as an ethnic signifier (Lucy, 1998). Processualist archaeologists observed the apparent lack of high-status grave goods in cremation burials and interpreted these burials as belonging to a poor or low status group within early Anglo-Saxon communities (McKinley, 2006). Recently, there have been more nuanced interpretations of the contemporaneous use of cremation and inhumation at early Anglo-Saxon cemeteries. The social and geographical prominence of early Anglo-Saxon cemeteries suggests that these cemeteries were not only used for the disposal of human remains but were also important centres of both socio-political and sacred activities (Lucy, 1998; 2000; Williams, 2011; 2014; Green, 2020). The significance of each cemetery would have increased over time through the accumulation of burials and the repetition of mortuary rituals (Williams, 2014). These cemeteries served a regional area that were negotiating their communal and individual identities through mortuary rites (Lucy, 1998; Williams, 2011; 2014; French, 2017). These identities involved gender, sex, age, status, political allegiances, and ethnic associations and they were expressed not by the deceased but by those who mourned them (Lucy, 1998; Williams, 2011; 2014; French, 2017). Choices made in commemorating the dead established and cemented social identities and relationships between mourners (Williams, 2011). These choices were constrained by the expectations of the deceased and the living audience, which included the family, friends, and community of deceased, as well as ritual specialists (Williams, 2011). Through repetition these choices became a shared tradition that bound diverse individuals into a cohesive community (Lucy, 1998; Williams, 2011; 2014; French, 2017). The juxtaposition of early Anglo-Saxon cemeteries with ancient earthworks has been interpreted as part of this process of ethnogenesis, serving to lend legitimacy to these forming societies and to reinforce their territorial claims (Lucy, 1988; 2000; Leahy, 2007; Williams, 2011; 2014). However, as kingdoms coalesced and stabilised moving into the 6th

century these performative symbols of regional social cohesion may no longer have been considered necessary and burial practises shifted to smaller local cemeteries (Lucy, 1998; Williams, 2011; 2014; French, 2017). The shift toward inhumation with fewer grave goods, that became more common in multiple regions at this time, also appears to reflect the dwindling importance of expressing regional identities in death (Lucy, 2000). The rise of high-status burials in the 7th century, such as Asthall, Oxfordshire and Sutton Hoo, Suffolk, further suggests that status, rather than regional distinction, became the dominant identity expressed in funerary rites (Williams, 2011; 2014).

Despite their short-lived predominance, these large mixed rite cemeteries were clearly an important aspect of socio-political life during the early Anglo-Saxon period. From the investments of time, labour, and tangible wealth expended in both furnished inhumation and cremation burials it would appear that the identities expressed in death were significant to those mourning the deceased. These identities were undoubtedly expressed in life, as well as in death. Dietary choices have been shown to relate to ethnic affiliations, gender, age, status, and religion (Twiss, 2012). Whether diet can be correlated with choices or mortuary rite during the early Anglo-Saxon period will be investigated by the experiment discussed in Chapter 7.

2.6 Conclusion

The amount of variability in Anglo-Saxon burial rites may suggest that these practices were individual and thus not indicative of societal norms (Lucy, 2000). However, it is important to recognize that these choices are not random (Thompson, 2015). Funerary rites reflect cultural beliefs about death, physical bodies, and social identities (Graham, 2015). The traditional interpretation of the transition of funerary rites in the fifth century is that these burials are Germanic in tradition and therefore the individuals who practised them were Anglo-Saxons (Lucy, 2000). The increase in these practices in the sixth century can be interpreted in three ways: continued migration from the continent, natural increase of population, or the adoption of Anglo-Saxon rites by native Britons (Campbell, 1982). Funerary rites,

and rituals in general, are a means of presenting beliefs in such a way as to maintain or create social identities (Hedeager, 2000; Theuws, 2000). Cultures are often assumed to have been homogenous; thus, archaeologists consider Anglian, Saxon, Jutish, or British norms rather than considering the interplay between these cultures during a period of considerable upheaval and transition. However, the evidence supports a spectrum of funerary rites between areas of Anglian or Saxon control rather than a clear delineation (Williams, 2014). The range of mortuary treatments, coupled with the uncertain nature of budding Anglo-Saxon societies can be interpreted as ritual used to distinguish local groups and create a sense of shared identity rather than a ritual imported and copied from the continent (Theuws, 2000; Williams 2014). Cremation, especially because of its sensational visual nature, would have been effective in this role. Mixed rite cemeteries may seem not to fit this interpretation of shared identity established and expressed through ritual; however, it is important to recognize that a belief system can account for a variety of mortuary rites without contradiction as in modern Hinduism (Thompson, 2015). Thus, these cemeteries may be comprised of individuals from the same society with differing beliefs or roles within society that affected their treatment after death. The premise of this study is that these cultural differences may be observed in a dietary reconstruction of one of these mixed rite cemeteries.

Chapter 3: General Cremation Research

3.1: Introduction

This chapter provides background on cremation research within archaeology and forensic science. The chapter begins with a brief literature review, showing the progression of studies on burned bone over time. The basic thermodynamics of fire are discussed, followed by an outline of the thermal alterations that occur in soft tissue and bone. Finally, methods used to investigate burned bones are explored. An important distinction in this field of research is the difference between cremation and other burning events that may lead to the exposure of human remains to fire. Cremation refers to a symbolically loaded, culturally determined mortuary ritual that involves the transformation of human remains through fire (Thompson, 2015a). Burning events include experimental, accidental, or criminal applications of fire to human remains. Other terms used to indicate physical and chemical changes rather than ritual significance are heat-treated, thermally-altered, or fired (McKinley and Bond, 2001; Thompson, 2015a). Pyrolysis is a scientific term, referring specifically to the transformation of molecular compounds via heat (Thompson, 2015a). Experimental, forensic, and archaeological research conducted on burned bone and archaeological or ethnographic investigations of cremation rituals are all included within the umbrella term of "cremation research". Several studies in this field include both experimental and archaeological components, or rely on observations from modern crematoria; thus, separating 'purely' scientific studies from culturally focused studies would introduce a false dichotomy.

3.2: History of Cremation Research

Cremated human remains were not deemed worthy of consideration by antiquarians. This view prevailed into the 20th century with cremated material discarded from British archaeological finds as late as the 1960s (McKinley, 2015). European archaeologists recognized the value of cremated remains earlier than their British counterparts (Wahl, 2015). In Germany, publications of osteological analyses

of cremated remains from archaeological sites date to the 1930s (Wahl, 2015). Distressed by the proposition by Carl Magnus Fürst that cremated remains should be eliminated from Stockholm museums, Nils-Gustaf Gejvall published guidance on the estimation of sex, age, and minimum number of individuals (MNI) from cremated human remains in 1947 (Worley, 2008). European cremation research continued along these lines during this early period of research, assessing the effect of thermal alterations on osteologial methods used to estimate age, sex, stature, and ancestry (Gejvall, 1969; Mayne, 1990). In British archaeology, Calvin Wells (1960) provided the pioneering study of archaeological cremation burials, investigating fracture patterns among cremated remains and bemoaning the lack of available comparative studies. Other researchers in the United Kingdom, faced with the analysis of cremated remains found at archaeological sites, turned to previous research by Gejvall for guidance (Lisowski, 1955; Spence, 1967; 1968).

American cremation research began with forensic applications. Wilton Krogman (1943) discussed the variation in thermal alterations seen in fresh and dry bone referring to colour change, fracture patterns, and surface alterations, as published in the law enforcement bulletin of the Federal Bureau of Investigations (FBI), United States (Symes et al., 2015). His research was then used by William Webb and Charles Snow (1945) to compare Adena and Hopewell mortuary practises from evidence found at sites in Ohio; the earlier Adena tradition, developing circa 800 BCE, transitioned, circa 1 CE, into the Hopewell tradition that flourished until circa 400 CE. These researchers estimated from fracture patterns that the Adena culture cremated their dead as fleshed bodies, while the later Hopewell culture defleshed their dead before cremation (Webb and Snow, 1945; Ohio History Central, 2021a; 2021b). Raymond Baby (1954) attempted to verify these fracture patterns through observations of fleshed and defleshed cadavers cremated in a modern furnace; however, he found that the fracture patterns found on both the Adena and Hopewell cremated remains were better represented by those observed on the fleshed cadaver (Symes et al., 2015). For much of the early to mid-20th century cremation research continued in this disjointed pattern: cremation studies were

rare, experimentation was minimal, and archaeological cremated remains largely continued to be ignored (Mayne Correia, 1997; Symes et al., 2015).

Cremation research gained greater attention from the 1970s when experimental research began to flourish (Worley, 2008). By 1987 Lange and colleagues were able to list 636 sources from 229 periodicals in their 'Bibliography of Cremation'. Notable research from this period includes Herrmann's series of investigations into methods of study for cremated remains (1970, 1973a, 1976, 1977a). Specifically, Herrmann investigated thermally induced shrinkage and found that the majority of shrinkage occurred at temperatures over 1000°C and that the variation of shrinkage observed between different skeletal elements related to the mineral content of bone and the distribution of trabecular and lamellar bone (1976, 1977b). He also investigated the potential of histology for the evaluation of cremated remains (1973b, 1977c). Shipman and colleagues (1984) also produced important research during this period, still commonly cited in modern research, that established four categories of thermally induced change defined by bone colour, microscopic morphology, crystal structure, and shrinkage. Wilson and Massey (1987) were among the first to specifically observe thermally induced changes in teeth, specifically describing visual and microscopic changes that occurred in enamel and dentine between 200°C and 1000°C. These foundational experiments continue to be relevant to modern research, but consensus among studies was rare, due, in part, to a lack of conventional terminology and variations in experimental methodology – neither of these problems have truly been solved, but instead continue to plague cremation research in both archaeological and forensic fields (Mayne Correia, 1997; Symes et al., 2015).

Moving into the 1990s, experimental research began to shift focus from observing thermally induced changes to trying to understand the underlying nature of these changes and their implications for archaeological research (Thompson, 2015a). The interaction between soft-tissue and bone during combustion has been investigated by observations at modern crematoriums and through open-air experiments including interactions with various fuels or structures and attempted

reconstructions of prehistoric pyres (McKinley, 1989; 1997; DeHaan et al., 1999; Bohnert et al., 1998). Increasingly, microscopic examinations of burned bone have been conducted to evaluate the changes to both the mineral and organic structure of bone due to heat exposure (Nelson, 1992; Holden et al., 1995; Koon et al., 2003; 2010; Carroll and Squires, 2020b). Furthermore, in the last two decades exploitation of technologies such as X-ray diffraction (XRD) and Fourier Transform Infrared Spectroscopy (FTIR) have facilitated a shift from qualitative to quantitative analysis of the thermal alteration of bone (Surovell and Stiner, 2001; Rogers and Daniels, 2002; Piga et al., 2008; Thompson et al, 2009; Thompson et al., 2013; Ellingham et al., 2015a). These methods produce data that can be evaluated statistically to investigate burning conditions experienced by bone samples burned in experimental, forensic, or archaeological contexts (Ellingham et al., 2015a). Much of this research has been conducted for forensic applications, but increasingly these methods are being applied to archaeological cremations as well (Thompson et al., 2016). The excavation of and publication regarding Anglo-Saxon sites with large numbers of cremated individuals, Spong Hill and Sancton, have fostered renewed interest in cremation research specifically among British archaeologists (McKinley, 1993a; 1994a; Squires, 2011). Research designed to address archaeological questions related to cremations has been conducted, including observations from modern crematoria to determine the expected weight of cremated individuals (McKinley, 1993b), the relationship between the size of cremated bone fragments and the pyre technology employed in the cremation ritual (McKinley, 1994c), and the influence of taphonomy on the preservation of cremated remains (Nicholson, 1993). These experiments have been bolstered by the ethnographic sources providing context for ritual aspects that are absent from forensic research (McKinley, 1994a; McKinley and Bond, 2001; Ward and Tayles, 2015). Finally, the increased interest in cremation research in both forensic and archaeological fields has led to the production of reviews and commentaries on the existing literature (Mayne Correia, 1997; Ubelaker, 2009; Kujit et al., 2014; Schmidt and Symes, 2015; Thompson, 2015b; Gonçalves and Pires, 2016).

3.3: Fire Dynamics

A basic understanding of the mechanics of fire and heat transfer can help to explain patterns in the thermal alteration of bone. Fire, in chemical terms, is an exothermic, oxidation reaction. The basic reactants are a fuel and an oxidizer, which together generate enough heat to self-sustain a reaction yielding heat and light (DeHaan, 2008). Fire represents two basic reactions: a gas phase reaction producing flames as a visible product where a gaseous fuel burns in the presence of oxygen, and a slower solid-gas reaction known as smouldering that occurs on the surface of a solid fuel exposed to oxygen (Quintiere, 1998; DeHaan, 2008). The majority of fires involve flaming combustion, including those involved in the alteration of human tissue; the gas jets of a modern cremation furnace and the logs of a pyre both reduce human remains via flames (Drysdale, 1999; McKinley, 2015). The physical state and distribution of the fuel may influence the manifestation of the fire more than the chemical nature of the fuel (Drysdale, 1999). Fuel in a solid or liquid form must be converted to a vapour for flaming combustion; this occurs through sublimation, melting and evaporation, or pyrolysis. Thermal decomposition or pyrolysis is the splitting of molecules via heat. The products of this decomposition are of low enough molecular weight to volatize at the fuel surface (Drysdale, 1999). The energy produced by the fire may be insufficient to sustain the pyrolysis of fuel and without adequate heat the fire will extinguish itself (DeHaan, 2008). Gaseous fuel vapour can be pre-mixed with oxygen before ignition, as in internal combustion engines, or can mix with oxygen by diffusion, combusting only in regions with a suitable proportion of fuel to oxygen. Most natural fires are diffusion flames and can take either laminar or turbulent structure; see figure 3.1. Molecular diffusion is responsible for the ordered layers of laminar flames; however, in larger flames the erraticism of natural fluid mechanics interferes with this order creating turbulence (Quintiere, 1998). Turbulent flames experience rapid temperature fluctuations when measured at any given point, increasing to 400°C or even 800°C within five minutes (Sandholzer, 2015). This variation can be difficult to characterize and so most temperatures reported are average temperatures as with campfires in the 400°C – 700°C range, housefires somewhat higher between 700°C – 900°C and the majority of fuels burning in air between 800°C – 1000°C (DeHaan, 2008; Sandholzer,

2015). Temperature estimates in archaeological studies of cremation report maximum temperatures, rather than average temperature exposure; ancient cremations have been reported as exceeding 1000°C (McKinley, 2015). It is important to recognize, however, that the chemical and structural changes brought about by heat are influenced by duration as well as temperature (DeHann, 2008). This is especially important when temperature fluctuations are extreme; for example, prairie fires reach maximum temperatures of 700°C, but temperatures above 65°C are only recorded for up to 10 minutes (Shipman et al. 1984).

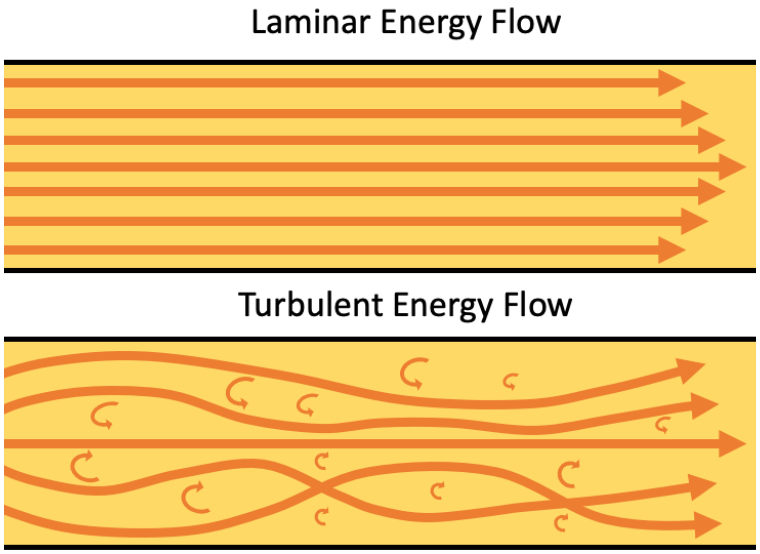


Figure 3.1: Above: laminar energy flow, typical of small fires, more consistent temperatures. Below: turbulent energy flow, typical in larger fires, more significant temperature fluctuations. Figure by author.

Understanding the temperature fluctuations of fires is not enough to gain an understanding of the processes of thermal alteration to human remains. In a burning experiment Buikstra and Swegle found that an oak fire burning at 900°C took over two hours to heat the flesh of a dog carcass to 650°C. Normal campfires may provide sufficient heat to raise objects, such as flints, to 550°C, with improvised pits and ovens allowing ceramics to reach 900°C (Shipman et al., 1984). Interpretation of burned human remains must consider not only the thermal potential of the fuel source but also the mechanics of heat transfer from the flames to the flesh and then to the bone. Heat transfer occurs via three processes:

conduction, convection, and radiation. These processes occur at the same time but one or another may be predominant at different stages of a fire (Drysdale, 1999). Conduction is the heat flow through solid or fluids and the rate at which heat is conducted is dependent upon the material in question. This accounts for minimal heat transfer in a pyre, but when objects come into contact with smoldering coals the heat transfer is primarily conduction and is sufficient to calcify bone (Ubelaker, 2009). Convection is the heat transferred from a liquid or gas as it flows over a solid; the rate of heat convection is related to the buoyancy of the hot liquid or gas (Drysdale, 1999). This has implications for the application of modern crematoria studies to archaeological cremations as the retention of heat in a modern oven represents a significant difference from pyres in the open air (McKinley, 2000). Radiation is the propagation of thermal energy via electromagnetic waves and does not require an intermediate medium for heat transfer (Drysdale, 1999). Understanding the general mechanics of fires and heat transfer helps researchers to predict patterns of thermal alteration and recognize aberrations in the pattern. Clothing and pyre goods may insulate a body from the flames and interfere with heat transfer by all three processes (Quintierre, 1998; McKinley, 2015). Wind direction and strength will influence the temperatures reached by a body and the duration of exposure by interfering with heat transfer by conduction (McKinley, 2015).

3.4: Reaction of Human Remains to Fire

3.4.1: Soft Tissue

An environment that is often ignored by researchers is the body in which bones are burned (Symes et al., 2008). Flesh impacts the alteration of bone in significant ways. The position of the body on the pyre will influence exposure to heat and the dispersion of bone elements in the remains of the pyre, which in turn may influence whether an element is collected for burial or not. Tissue shielding will affect heat exposure. Bones with little overlying tissue will be exposed to heat before those with more flesh coverage, see figure 3.2. However, it is important to remember that, at higher temperatures, fats will act as an accelerant and will

increase heat exposure in the nearby bone (DeHaan, 2012). Additionally, the biomechanics of thermal fracturing and warping are dependent on muscle tissue, tendons, and ligaments (Symes et al., 2008).

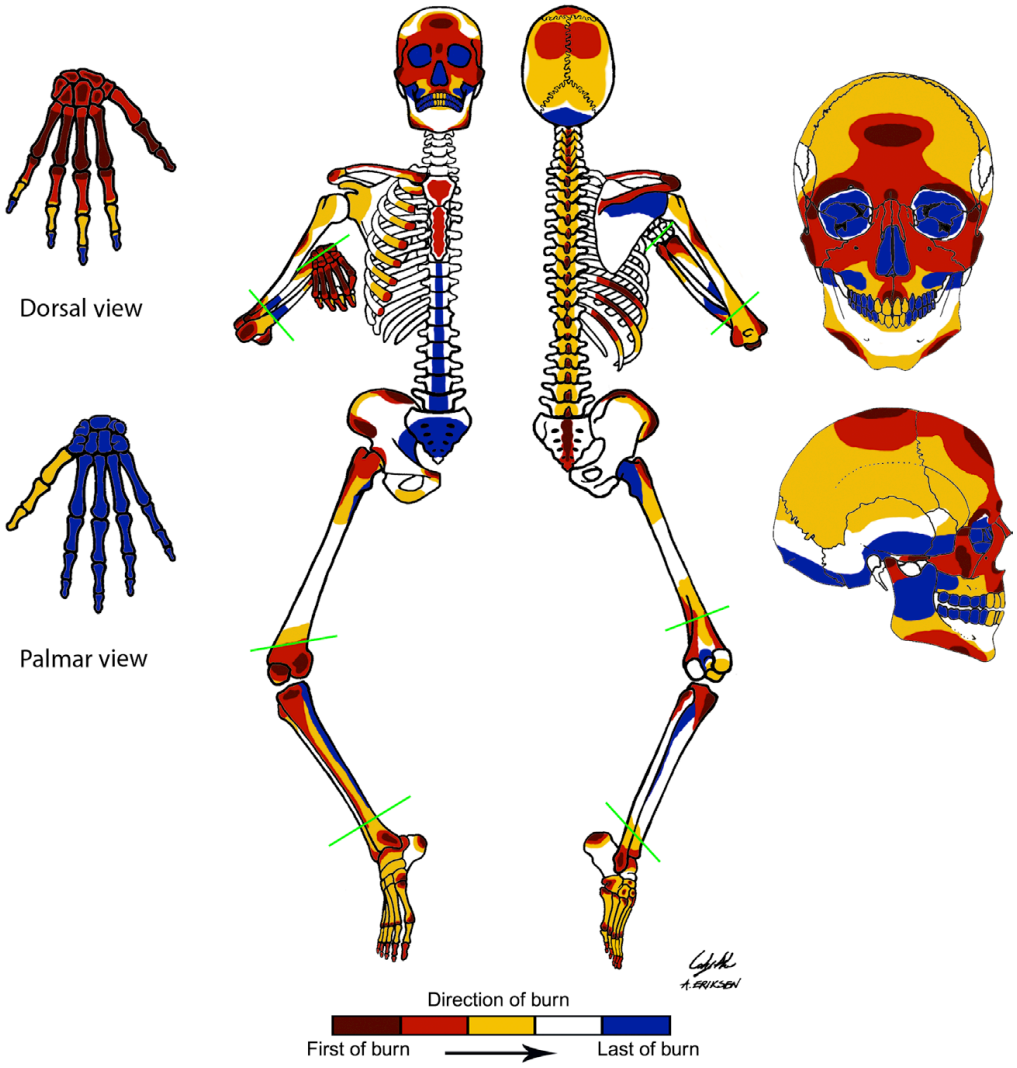


Figure 3.2: Image showing the progression of thermal exposure in human remains. Dark red areas burn first due to minimal tissue shielding, blue areas burn last due to tissue shielding and protection offered by pugilistic posture. Green lines indicate common sites of heat-induced fracture (Symes et al., 2015 p. 36).

Human remains do not represent ideal conditions for maintaining flames. The body is a wet mass of tissues and only the fat represents a source of fuel; however, fat is not a ready fuel and must be rendered before it can provide energy to a fire, see table 3.1 (DeHaan, 2008; McKinley, 2015). The first changes to a cadaver are superficial – hair scorches, skin burns and splits, and water begins to

evaporate (Mays, 1998). For the skin to split and fat to begin to melt an external flame must be introduced to the body for five to ten minutes (DeHaan, 2008). The muscles and ligaments dehydrate as they are exposed by splitting skin (Mays, 1998). Muscles contract via dehydration and protein denaturation; this process is universal, but the bulkier flexors generally exert more force than the extensors (Ubelaker, 2009).

Table 3.1: Describing in general terms the fuel potential of human body tissues (reproduced from DeHaan, 2012).

Fuel Potential of Human Body Tissues	
Dermis	Proteinaceous, thin and easily separated at 54° or above
Epidermis	Thicker, higher water content, minimal contribution to fuel
Subcutaneous Fat	Highest heat combustion (32-34 kJ/g), low melting point, burns as viscous fluid
Muscle Tendons	Proteinaceous, moderate water content, poor fuel (4-5kJ/g)
Internal Organs	Proteinaceous, high water content, no contribution to fuel
Bone	Mineral and organic content, fat-rich, contribution to fuel only when large bones split from external heat

The imbalanced force of contraction flexes the body into a 'pugilistic pose' or boxing stance. However, as combustion progresses destroying tendons the force exerted by contracting tissues is no longer translated to the bone and posture relaxes (Symes et al., 2008). There are records of rituals practised by Theravāda Buddhists in northern Thailand in which the tendons are sliced to prevent the movement of the limbs during cremation (Anusaranasasanakiarti and Keyes, 1980; Ward and Tayles, 2015). Liquids drain from the body as the skin and muscles split, water continues to evaporate and liquid fat pours from the body (Bohnert et al., 1998). Rendered fat has a high flash point and is unlikely to ignite without a wick that is rigid and porous to increase its volatility (DeHaan et al., 1999). Given an external flame sufficient to render fat and an appropriate wick, liquid animal fat can burn at an average of 700°C – 800°C and can support combustion for 6-7 hours (DeHaan, 2012). Over time, given the right conditions, flame will reduce human remains as fluids drain out or evaporate and muscle tissue burns (DeHaan, 2008). Flames will be concentrated over areas where the liquid fat has pooled, typically corresponding to the areas of highest fat concentration in the body. The torso, pelvis and upper legs will burn best while the hands, feet, head, and lower legs burn

less readily (DeHaan, 2012). Aside from bone, ligaments and brain tissue are the longest surviving tissues during cremation (Mays, 1998).

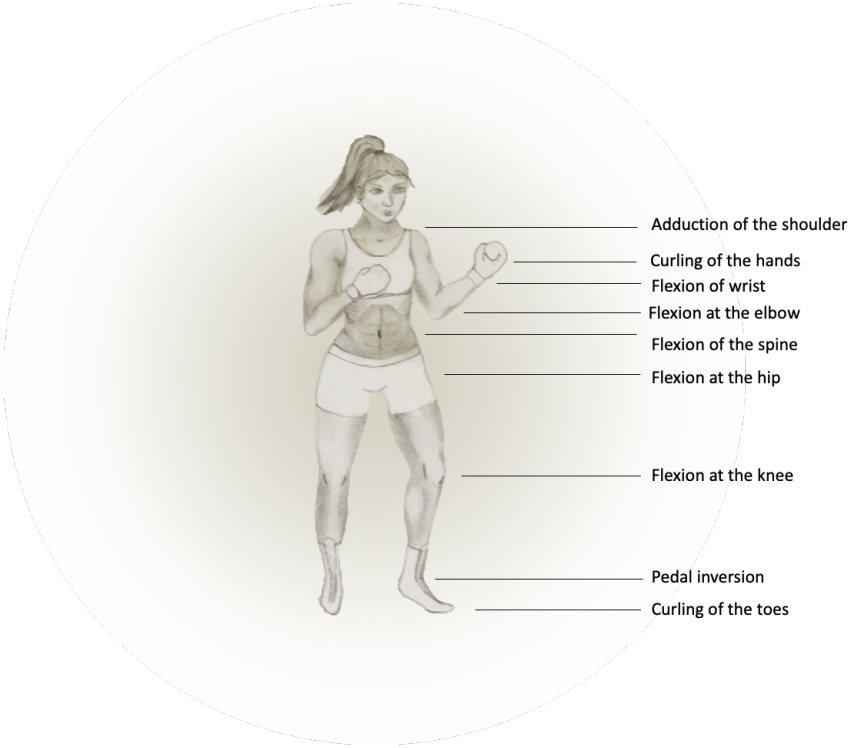


Figure 3.3: Boxing stance representing the 'pugilistic posture' adopted by fleshed human cadavers that are exposed to heat. Figure by author.

3.4.2: Thermal Alteration of Bone

As the overlying tissue disintegrates the bone is exposed to heat (Symes et al., 2008). Heat-induced changes to bone can be divided into primary-level changes and secondary-level changes. Primary-level changes are those that directly alter the composition or structure of the bone, whereas secondary-level changes are macroscopic changes that result from these more fundamental changes (Thompson, 2004). First, a brief explanation of bone structure is provided for clarity. Bone is a complex matrix of organic fibrous protein and inorganic crystalline mineral. By weight, the inorganic component accounts for 60% of living bone and 70% of dry bone. The organic component of bone accounts for a further 25% by weight with the remainder made up of water (Thompson, 2015c). Type I collagen, a protein common in the connective tissues of the human body, accounts for 85-90% of the organic matrix. There are over 200 other proteins present in bone but these account

for less than 10% of the organic portion and are often referred to collectively as "non-collagenous proteins". The organic matrix also contains minor contributions from lipids (Paschalis et al., 2001).

Collagen fibres contain smaller fibrils that consist of three polypeptide chains wound together in a helical pattern (Weiner and Wagner, 1998; Paschalis et al., 2001). Interwoven among the collagen fibrils are crystallites of inorganic material in the form of bioapatite, the chemical structure generally written as (Wopenka and Pasteris, 2005; Snoeck et al., 2014):

$$(Ca, Na, Mg, [])_{10}(\mathbf{PO_4}, HPO_4, \mathbf{CO_3})_6(OH, F, Cl, \mathbf{CO_3}, O, [])_2$$

Where empty square brackets indicate potential vacancies and bold text indicates the most common component molecules (Snoeck et al., 2014). However, in bone, the mineral is present in a poorly crystalline form and is characterized by extensive impurities and substitutions (Mkukuma et al., 2004; Thompson, 2015c). Calcium may be replaced by magnesium in up to 0.4% of cases, or strontium in up to 0.03% of cases (Pejović-Milić et al., 2004; Aaseth et al., 2012). In addition, carbonate ions are substituted for HPO_4^{2-} ions in up to 9% of molecules (Von Euw et al., 2019). The chemical and structural properties of bone will be determined by the specific substitutions in the lattice rather than mimicking stoichiometric hydroxyapatite (Rey et al., 2009). The crystals of apatite are small, anisotropic, and plate-shaped; this crystal structure is highly reactive because of its large surface area (Rey et al., 2009; Thompson, 2015c). Water is present in the gaps within and between fibrils and fibers of mineralized collagen (Weiner and Wagner, 1998). Primary-level thermal changes will affect these constituents of the bone matrix – the organic including collagen, lipids, and other proteins; the inorganic consisting of bioapatite but also crystals with substitutions; and water whether physisorbed or chemisorbed (Thompson, 2015a). The heterogeneity of the microstructure of skeletal tissue complicates the analysis of thermal alteration of bone, but there are some basic patterns that have been established.

3.4.2.a: Primary Changes

The primary changes occurring in bone can be divided into four theoretical stages popularized by Mayne Correia in a 1997 review of cremation literature from forensic sources. Proposed in 1984 by Shipman and colleagues, these categories were modified from those used in studies of ceramics. These stages correspond to the major primary changes that occur in bone as a result of thermal alteration, but there is some disagreement as to the temperatures at which each occurs.

The first phase involves dehydration. From 105°C – 300°C water in hydroxyl bonds is lost; above this temperature water bound in apatite is also lost and water is completely removed by approximately 600°C. The dehydration phase is the most consistently reported within the literature.

The second phase termed decomposition overlaps the first, as it begins at approximately 500°C with the pyrolysis of the organic content of bone; all organic material is lost around 800°C. However, later research has pushed the onset of this decomposition stage back to approximately 300°C (Thompson, 2005). Unmineralised collagen melts at around 60°C but bone mineral acts as a mechanical restraint and stabilizes the protein against denaturation and shrinkage with initial changes observed around 112°C (Holden et al., 1995; Etok et al., 2007). This begins as a localized unraveling of the fibril, which appears as a swelling or bead along the fibril. These beads under continued thermal exposure become breaking points along the length of the collagen fibril leading to a dumbbell appearance; see figure 3.2. Finally, the collagen denatures and no fibrous pattern can be detected (Koon et al., 2003). Younger individuals with a more random orientation of mineralized collagen fibres are more susceptible to this disruption of collagen structure, whereas older individuals with more ordered collagen fibres and a higher density of cross-linking are somewhat protected; individuals accrue these cross-links continually with age (Holden et al., 1995). However, organics are still present in the bone at this stage; they have simply lost their characteristic form. With further heating the carbonization of these proteins occurs and organics are lost (Thompson, 2005).

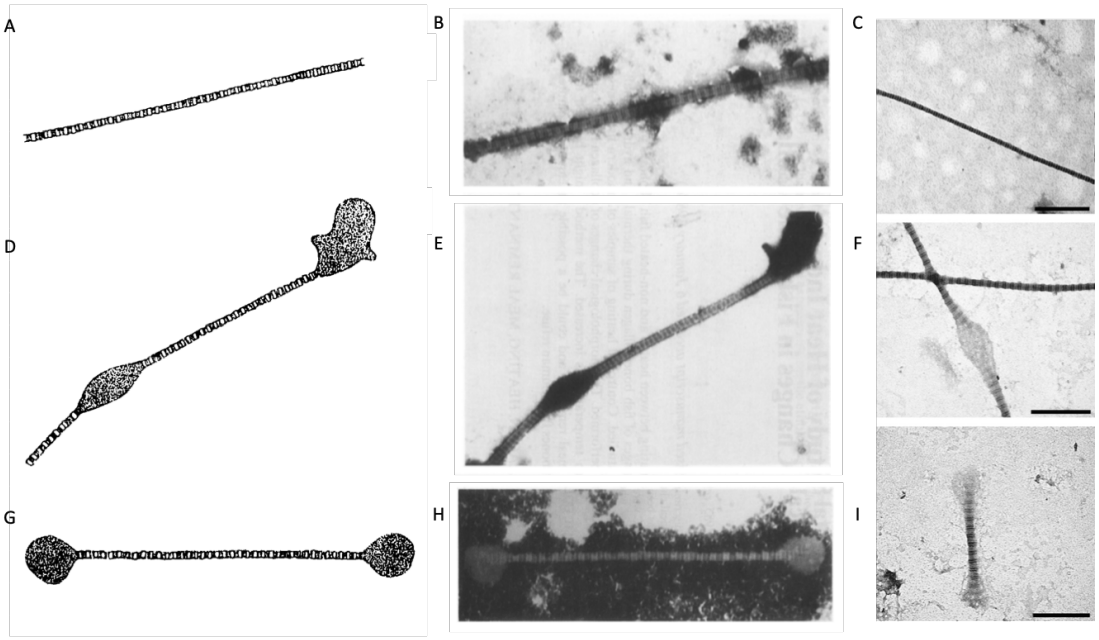


Figure 3.4: Transmission electron microscope (TEM) observations of thermally altered bone collagen. Images A, B, and C represent unmodified collagen. Image A) is a diagram from Richter, 1986 (p.478); image B) fish collagen enlarged 30,000 times from Richter, 1986 (p.478); image C) mammalian collagen, scale bar is 500 nm from Koon and colleagues, 2010 (p. 65). Images D, E, and F represent collagen fibrils in the 'beaded' stage of thermal alteration. Image D) is a diagram from Richter, 1986 (p. 478); image E) fish collagen enlarged 15,000 times from Richter (p.478), 1986; image F) mammalian collagen, scale bar is 500 nm from Koon and colleagues, 2010 (p. 65). Images G, H, and I represent the 'barbell' stage of thermal alteration. Image G) is a diagram from Richter, 1986 (p.478); image H) fish collagen enlarged 45,000 times (p.478); image I) mammalian collagen, scale bar is 500 nm from Koon and colleagues, 2010 (p. 65).

The third stage, inversion, takes place between 700°C – 1100°C; this is when carbonates are lost and large crystals of apatite form. Again, later research has pushed this threshold into lower temperatures with changes in crystal structure occurring from 500°C (Thompson, 2005). The inversion stage involves several changes to bone mineral, essentially conversion to a purer form of apatite. The plate-shape characteristic of unaltered bone apatite is lost as the crystals grow into larger isotropic crystals encroaching on the space left by the loss of organics. This growth is limited; overall crystals increase from 2.5 nm to approximately 10 nm, with the most significant changes occurring between 500°C and 700°C. Impurities such as carbonate are lost in this process. Thus, the bone mineral becomes purer, less reactive, and less porous (Thompson, 2005). New crystal phases may also occur; β-tricalcium phosphate and $NaCaPO_4$ have been recorded by some researchers (Etok et al., 2007).

Finally, crystals melt in the sintering or fusion stage at 1600°C or higher (Mayne Correia, 1997). In this phase, the disagreement in the literature is most significant with later research pushing the sintering stage as low as 700°C, for a visual comparison of the disagreements discussed see figure 3.2 (Thompson, 2005). Bone mineral heated above the sintering threshold will re-crystalise when cooled independent of the constraints of the, now absent, mineralized collagen structure (Holden et al., 1995).

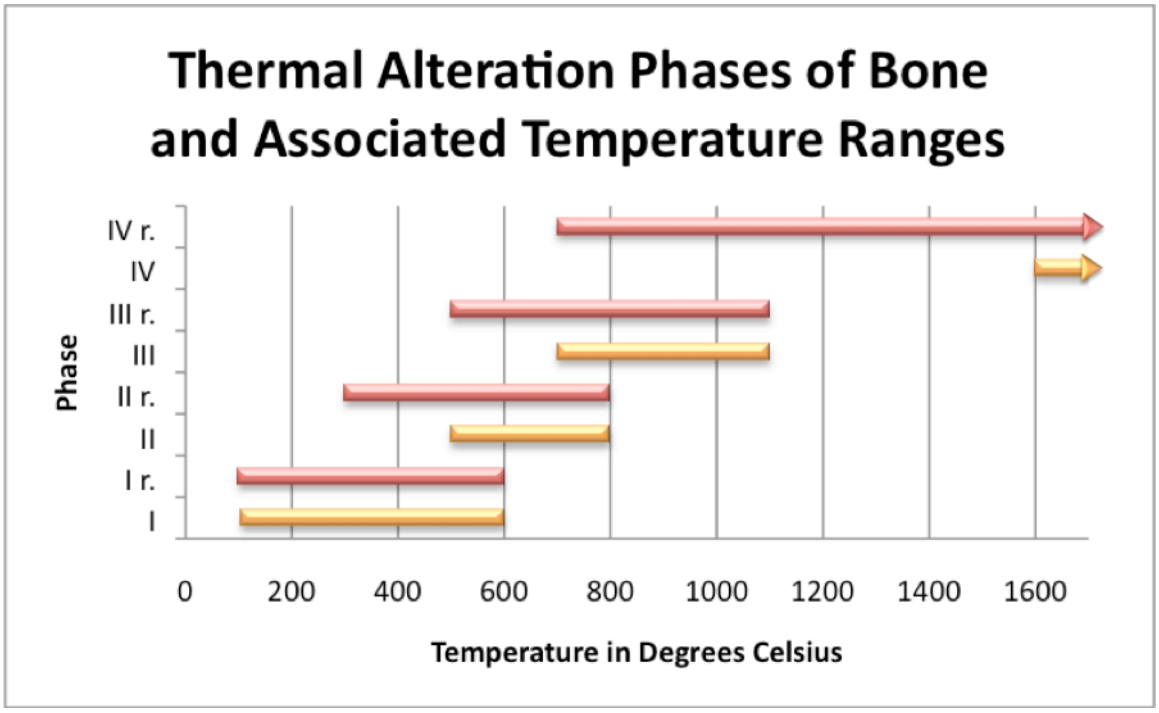


Figure 3.5: Demonstrating the shift in the temperature ranges associated with thermal alteration phases. The yellow bars and roman numerals refer to the initial phases as laid out by Mayne Correia in 1997. The red bars and roman numerals followed by "r." indicate the revised temperatures offered by Thompson in 2005. Phases are I: dehydration, II: decomposition, III: inversion and IV: fusion.

3.4.2.b: Secondary Changes

The macroscopic changes observed in bone can be tied directly to the four primary phases. These visible, secondary changes include colour change, weight loss, shrinkage, warpage, and fracturing. Colour changes relate to chemical changes in bone, or to chemicals present in the pyre environment. The typical progression for burnt bone is from its original buff or cream tone, to a brown or tan below 300°C, to a charred black appearance at 200°C – 300°C (Walker et al., 2008; Harbeck et al.,

2011). Schmidt and colleagues in studying remains from Herculaneum found instances of a "mottled" colouration where bone was whiteish tan with brown and grey spots, this was attributed to low temperature exposure of 0°C – 100°C (Schmidt et al., 2015). These lower temperature colour changes are associated with the combustion of the organic portion of bone (Mayne Correia, 1997). At 550°C and above the black colour fades as the char is oxidised (DeHaan, 2008). Bone then takes on a grey or blue-grey colour around 600°C that is associated with the pyrolysis of organic components, and finally a white or calcined appearance which is associated with the fusion of bone salts and is typical in temperatures of 800°C or above (Mayne Correia, 1997; Walker et al., 2008). Other colours are associated with environmental factors; browns have been related to the presence of haemoglobin or to soil staining, greens to copper inclusions, yellows to bronze, and pinks or reds to iron, zinc, or madder (*Rubia tinctorum*) plants (Mayne Correia, 1997). As well as environmental factors, colour may be affected by tissue coverage and duration of heat exposure (McKinley and Bond, 2001; Walker et al., 2008). Bones often present a gradient of colours relating to the maximum temperature exposure experienced at different loci or the presence of colour depositing components such as those listed above (Symes et al., 2008).

Weight loss occurs during the first three stages of thermal alteration and relates to the loss of water, organics, and carbonates respectively. In the third stage magnesium, if present, may also be lost (Mayne Correia, 1997). The majority of the weight lost is from water and organic components and occurs below 400°C but continues to a lesser extent above this temperature (Gonçalves et al., 2015). However, the weight of an archaeological cremation reflects the pre-depositional treatment and the excavation methods as well as thermal alteration (Gonçalves et al., 2015). Collection strategies following cremation in past societies ranged from nearly complete, as in Bronze Age Britain where average weight is 1525.7 g, to nominal collection, typical of Norwegian cremations where average weight of a single burial is 269.7 g (McKinley, 2000). Burial in urns or other containers will generally keep bone fragments together, reducing taphonomic losses, and easing excavation; however, some cultures favoured organic burial containers that do not

survive archaeologically (Gonçalves et al., 2015). Additionally, intentional fragmentation of remains in order to fit designated cinerary vessels may produce fragments easily lost before or after burial (McKinley, 2000). Experiments in modern crematoria suggest that thermal alteration alone produces remains of similar weight to a dry bone skeleton, on average 3000 g (McKinley, 2015).

Shrinkage has been extensively studied, with researchers attempting to quantify heat-induced dimensional changes since Malinowski and Porawski's study in 1969. For a summary of this early research see Mayne Correia (1997). While the overall amount of shrinkage expressed by bone has not been established, estimates range from less than 6% to 30% (Gonçalves, 2011). However, certain patterns have been established. First, there is agreement that the majority of the dimensional change to bone occurs at or above 800°C (Thompson, 2005). Low temperature exposures result in minimal, even negligible, changes in bone dimensions (Gonçalves, 2011). By relating this data to observations of bone microstructure during heating events, researchers have concluded that the majority of shrinkage occurs as a result of changes to the crystal structure of bone mineral; the minimal shrinkage observed at lower temperatures can be related to the loss of water and organics from the bone matrix (Thompson, 2005). Given sufficient temperatures to affect shrinkage, two other factors will influence the amount of shrinkage observed: distribution of trabecular and lamellar bone and the mineral content of bone (Mayne Correia, 1997). The literature regarding bone types and heat-induced shrinkage is conflicting. Gejvall reported that lamellar bone was more affected, while McKinley found that trabecular bone was more significantly reduced by heat (Gejvall, 1969; McKinley, 1994c) Thompson has proposed that this conflict is in reporting rather than observation; lamellar bone may be proportionally more reduced by heat, while trabecular bone shows more change in absolute dimensions (2005). Bone with a higher mineral content has been found to experience more shrinkage, this may introduce a sex related pattern of shrinkage as males tend to have a higher percentage of bone mineral (Mayne Correia, 1997). There have been attempts to produce regression formulae to allow metric analyses to be conducted on burned bones, however, due to the number of variables involved these have been

unsuccessful (Thompson, 2005). Furthermore, research has discovered that at low burning intensities bone may also experience heat-induced expansion; thus, any estimates of dimensional change will be dependent on accurate modelling of temperature exposure (Thompson, 2005).

To a certain extent warping can be predicted as, given similar firing conditions, bone will respond in relatively uniform ways (Symes et al., 2015). However, attempts to quantify degrees of shrinkage and deformation have not been successful (Wells, 1960; Mayne Correia, 1997). The mechanism of thermally induced bone deformation is poorly understood. The progression from an elastic deformation, with no lasting effect, to a plastic deformation, that will remain when bone cools, to failure or fracture at vulnerable points is evident, but the force responsible is unknown (Mayne Correia, 1997). Fleshed cremations tend to show higher levels of warping in bone than defleshed or dry cremations (Ubelaker, 2009). This has led researchers to theorize that warping is a result of muscle fibres pulling and twisting the bone as they contract with additional stress from the expansion of air within the medullary cavity (Thompson, 2005). However, these theories have not been supported by quantitative analysis. Alternative theories explaining bone deformation include the contraction of the periosteum or carbonized collagen exerting uneven forces due to its anisotropic structure (Thompson, 2005). Collagen can exert a contractile force sufficient to manipulate the mineral within its fibres; it is possible that in dry bone the weakening of collagen-apatite bonds prevents warping by eliminating this force. In a large cremation study using dry bone of individuals buried at least 5 years before burning, Gonçalves and colleagues found warped bone in four out of 61 individuals. They propose that flesh is not a causative agent in the thermally induced warping of bone but rather is correlated with good collagen preservation which explains why in a small proportion of dry cremations warping is still found; in these cases, collagen is still sufficiently bound to apatite to exert force on the bone mineral (Gonçalves et al., 2011).

Heat-induced fracture is a secondary process that results from the shrinkage of bone and the force exerted by soft tissues (McKinley and Bond, 2001). The

mechanical failure of bone can be predicted to an extent, following recognized patterns as determined by shared human anatomy (Symes et al., 2015). Symes and colleagues have suggested seven descriptive categories for the classification of heat-induced fractures: longitudinal, step, transverse, patina, splintering/delamination, burn line and curved transverse (2015). Longitudinal fractures are the most common. Failure along the grain of the bone parallel to osteon canals down the shaft of a long bone occurs as a result of evaporation, protein denaturing, and shrinkage of the bone matrix. Step fractures are typically associated with longitudinal fractures, extending transversely from the margin of one longitudinal fracture through the compact bone to another, transverse fractures follow the same direction but need not be associated with longitudinal fractures. Patina refers to superficial patterns of cracking analogous to old china often found on flat areas of postcranial bones, epiphyses, and cranial bones. Splintering and delamination are terms used to describe the splitting of cortical from cancellous bone, the separation of inner and outer table of cranial bones, or the exposure of cancellous bone at epiphyses. Burn line fractures separate areas of thermally altered and unaltered bone, due to the biomechanical difference between the altered and unaltered material. Curved transverse fractures produce a 'thumbnail' pattern; in fossae, or other areas of concentrated tissue, these may form concentric rings instead of curves (Symes et al., 2015). Controversy has followed the interpretation of fracture patterns from the beginning. Krogman published forensic articles in 1943 detailing fracture morphology and surface alteration as indicative of the pre-burning condition of human remains, that is, whether the body was fleshed or defleshed before burning, with patina fractures considered indicative of defleshed remains (Mayne Correia, 1997). However, in 1954 Baby contradicted Krogman's research and instead proposed transverse fractures and warping could suggest pre-burning conditions. Fleshed remains warped and produced curved transverse fractures when burned, while defleshed remains showed no warping and straight transverse fractures (Mayne Correia, 1997). This research was contradicted in 1989 by Buikstra and Swegle who found defleshed remains showed both warping and curved transverse fractures (Mayne Correia, 1997). Despite the lack of consensus in this area, research continues and in 2001 Whyte published an experimental study that

found dry bone showed less warping and less variation in fracture patterns than fleshed bone when heated (Ubelaker, 2015). Despite this uncertainty, a review of cremation literature published from 1995-2015 Gonçalves and Pires found that 69.6% of researchers estimated pre-burning condition on the basis of curved transverse, or "thumbnail", fractures (2016). Fracture patterns may, however, be used to provide information on other aspects of the cremation ritual, outside the preparation of the remains for the pyre (McKinley, 1994c). Heat-induced fractures begin when bone reaches an approximate temperature of 500°C, a temperature easily reached by cremation pyres (Thompson, 2005). However, if cremated remains show areas without fracture this may be an indication of temperature shielding that may indicate the presence of clothing or ritual goods on the pyre (McKinley, 2015). Furthermore, extensive fracturing may indicate practises of tending the pyre during cremation – either stirring the coals, quenching the fire, or raking of the remains during collection (McKinley, 1994c). However, caution must be exercised when attempting these types of inferences as the condition of bone analysed may not reflect the condition of bone buried; further fragmentation may occur *in situ* or during excavation (McKinley, 1994c).

3.5: Methods of Analysis for Burned Human Remains

3.5.1: Developing an Osteoprofile

Basic osteological analyses establishing minimum number of individuals (MNI), sex, age, stature, pathology, and status indicators are essential to archaeological study but are complicated for cremated remains. For the most part, researchers have applied methods developed on unmodified bone (Mayne Correia, 1997).

Minimum number of individuals is determined through duplication of elements or the presence of indicators of incongruous sex or age (McKinley, 2000). Distinction between multiple cremations and multiple burials may be drawn from the comingling of remains. When multiple individuals are cremated on the same pyre their remains will be interred in a comingled state; whereas, if individuals are

cremated separately but interred in the same context, there will be some stratigraphic separation of remains even within a single interment vessel (McKinley, 2000). Researchers have used overall weight of remains as an indicator of MNI but because of significant variation found in experimental studies this is not a reliable indicator (Gonçalves et al., 2015).

Morphological sex estimation methods for the skull and pelvis can be applied to remains burned in modern crematoria; however, in archaeological samples fragmentation and absence of diagnostic elements often necessitate the use of other methods (Mayne Correia, 1997; McKinley, 2000). The pelvis rarely survives cremation but the occipital ridge, supraorbital margin and portions of the mandible often survive and may show sufficient dimorphism for sex estimation (Mayne Correia, 1997). The petrous pyramid is often recovered and is somewhat sexually dimorphic. Two methods to estimate sex have been developed: one by Wahl and Henke in 1980 and the other by Schutkowski in 1983 (Mayne Correia, 1997). These methods are not commonly used in unmodified remains as there is some overlap of male and female traits and other morphological indicators are typically available. Estimation in burned bone is somewhat less effective, allowing correct sex determination in 67-73% of cases when tested by other researchers (McKinley, 2000). Metric methods of sex estimation are not recommended without due consideration of the effect of heat-induced shrinkage on relevant measurements. Either error margins must be increased or regression formulae must be employed to equate measurements to unmodified dimensions (Thompson, 2005). Metric methods have also been developed specifically for burned bone, but these may also be impractical with extensive fragmentation or incomplete pre-depositional collection (Gejvall, 1969; Van Vark, 1974; McKinley, 2000).

Age estimation for cremated remains can be achieved for non-adults using dental development, epiphyseal fusion, and long bone lengths (Mayne Correia, 1997; McKinley 2000). Erupted dental crowns fragment at high temperatures but development stages can be evaluated from unerupted teeth or the roots of teeth (McKinley, 2000). Cranial suture closure, in spite of reported unreliability, is the

most common method used to estimate age in adult cremated remains due to the frequent absence of other criteria. Dental attrition, pubic symphyseal surface, sternal rib ends, and auricular surfaces can be used if present, but these are rare finds in both archaeological cremations and forensic burned bone cases (Mayne Correia, 1997; McKinley, 2000). There is potential for histological assessment of age in burned bone (Holden et al., 1995). However, fragments of osteons may be difficult to identify in cremated remains. Shrinkage of thermally altered bone will also affect the number of osteons observed in an area, thus histological age estimates cannot be directly correlated to those for unburned bone (Absolonova et al., 2012). Furthermore, at high temperatures osteons may be obliterated entirely, though some researchers have found that microstructures persist up to temperatures around 1200°C (Hanson and Cain, 2007; Gonçalves, 2012). Generally, regardless of the method employed, broad age categories rather than specific age ranges may be more realistic for cremated remains (McKinley, 2000).

Interesting examples of pathologies, such as calcified lymph nodes, have been found from archaeological cremations, but palaeopathological analysis is rarely possible. The number of lesions recorded and their diagnoses require consistent complete representation of individuals from a population, which is simply not a realistic expectation from most archaeological cremation cemeteries (McKinley, 2000). In large cremation cemeteries, some palaeopathological analysis may be possible. For instance, at the Roman cemetery from Stettfeld rates of dental disease and spinal joint disease could be estimated. In the case of periapical lesions, vertebral osteophytes and intervertebral disc degeneration age related patterns of disease could also be observed. Sex related patterns of vertebral osteophytes were also observed. However, these observations must be taken with caution due to the influence of incomplete preservation (Wahl, 2015). However, in forensic research particular attention has been given to identifying perimortem trauma in burned bones. Sharp force trauma can be clearly distinguished even in fully calcined remains, while blunt force trauma may be more difficult to observe (Ubelaker, 2015). Where recovery is sufficient perimortem fractures can also be distinguished from those induced by heat (Mayne, 1990). Transverse fractures can be clearly

distinguished, but spiral fractures may mimic heat-induced longitudinal fracturing – distinguishing between these patterns is especially problematic if the fracture is comminuted (Mayne, 1990). Reconstructing comminuted fractures may be difficult but possible in experimental conditions, but extremely challenging in forensic or archaeological contexts where complete recovery of the remains cannot be assured (Mayne, 1990).

Cremation as a funerary option has been interpreted as the economical option and cremated individuals have been assumed to be of low status. This is based largely on the dearth of grave goods in certain cremation populations compared to their inhumation-favouring contemporaries (McKinley, 2006). However, these interpretations fail to consider the major investments typical in cremation rites. The first is the pyre itself, which would require in excess of 146 kg of pinewood or equivalent fuel, based on observations of modern crematoria furnaces (McKinley and Bond, 2001). The second is animal bone, commonly found among cremated remains. Various inclusions indicative of feasting, totems, animal companions in death, or clothing all represent significant investment. These elements may be overlooked without detailed osteological analysis leaving a mistaken impression of the status of an individual as established through grave goods (Bond and Worley, 2006). Finally, the labour required to build the pyre, collect, and inter the remains represents a significant investment. For nearly completely represented individuals, such as those found in British cremations during the Bronze Age, the collection alone represents four person-hours of labour (McKinley, 2000). Thus, status interpretation of cremation burials requires analysis of not just what is interred, but also the processes by which they came to be there.

3.5.2: Colour

Burned bone goes through a series of macroscopic changes as discussed above. While these changes can confound methods of osteological analysis, they can in themselves provide information on the burning conditions experienced by bone. Colour, for instance, can be used to estimate maximum temperature

exposure (Devlin and Herrmann, 2008). Observations of colour variation in cremated bone have been reported from the earliest publications on the subject, as with Baby's 1954 work on Hopewell funerary practises (Devlin and Herrmann, 2008). A recognized progression of bone colour change with increased temperature exposure was established as early as 1975, as Bonucci and Graziani presented in their investigations on burned bone from various contexts (Devlin and Herrmann, 2008). However, the first work to systematically assign colour values to temperature exposure ranges was by Shipman and colleagues in 1984. McCutcheon (1992) then simplified the classification of bone colour into three bands that correlated with increased thermal exposure (Devlin and Herrmann, 2008). Colour reporting remains an important aspect in the analysis of burned human remains. In a review of 84 articles from 1995-2015 Gonçalves and Pires found that 91% included colour description in their assessment of burned human skeletal remains; of these, 92% used colour to estimate maximum temperature exposure (2016). However, the change of colour reflects chemical changes in bone in response to burning intensity – not directly as a result of temperature (Thompson, 2015). Duration of exposure, oxygen availability, and the surrounding environment will also affect bone colour (Walker et al., 2008).

In order for colour descriptions to be comparable and repeatable, a standardized recording system must be used. The simplest of these are colour order systems, such as the Munsell Soil Colour Charts used by the researchers mentioned above (Shipman et al., 1984). This is a subsection of the Munsell Book of Colour meant to correspond to common soil colours; this is a commonly used colour order system in archaeology as the system does not require specialist equipment or extensive training (Munsell Soil Color Charts, 1994). Munsell Book of Colour describes colours using three components: hue, value and chroma. There are five principle hues – purple (P), blue (B), green (G), yellow (Y) and red (R), as well as five intermediate hues. Achromatic colours are scored as "N". Munsell value is equivalent to lightness, from black (0) to white (10). Chroma is the increase in hue content from 0 for neutral samples with increasing chromas having a stronger hue – or an increasing richness of colour. There is no set maximum for Munsell chroma.

These three components are incorporated into a score consisting of three symbols: a number and letter designation for hue, a score from 0-10 for value, and a score from 0-8 for chroma (Munsell Soil Color Charts, 1994). Fresh bone measured for this study had a Munsell designation of 0.4Y 8/2, that is a yellow hue close to the border between the yellow-red and the yellow hue designations that is very light in value and not far removed from neutral or achromatic. The Munsell Book of Colour is available as printed colour swatches. These colour swatches are then matched against a sample. This system provides an orderly arrangement of colours that can be easily referenced and allows precise description of observed colours. The Munsell Book of Colour was designed to be viewed under Commission Internationale de l'Éclairage (CIE) illuminant C, by CIE 1931 standard colourimetric observer (2°), on a middle grey (N5) background, with an illuminance level of 500 lux or higher. These conditions are not always met by researchers and variation from these standards will cause errors in the colour specification by Munsell value and these designations cannot be generalized to other viewing conditions. Furthermore, this type of subjective colour matching is susceptible to errors arising from physiological or psychophysical differences in observers, geometry and surface characteristics of the sample, influence of the surround, illumination geometry, and fading or discoloration of the sample swatches, among other issues (Fairchild, 2013)

Colour analysis studies have begun to move away from using colour order systems to using colour appearance models. Colour appearance models have two major advantages over colour order systems. The first is the ability to adapt to changes in viewing conditions in a manner that mimics the chromatic adaptation of the human visual system. Data can be adapted to estimate different viewing conditions by incorporating a predicted cone response signal expected for the new set of conditions – this calculation is referred to as a chromatic adaptation transform (CAT). Colour appearance models differ in the sophistication of the CAT they employ; an appropriate model for colour measurement is dependent on the experimental conditions and the data required from the results. One of the simplest colour appearance models, CIELAB, can predict lightness, chroma, hue angle, and colour difference. However, if cross-media applications are desired CIELAB is inappropriate

and a more sophisticated model must be used. The second advantage of a colour appearance model is that the colour specifications defined by the model relate mathematically to physically measureable values allowing statistical evaluations of colour difference (Fairchild, 2013).

CIELAB uniform colour space, also written as L*a*b*, was developed by the CIE in 1976 and proposed as a universal colour space. The system records colour stimuli as coordinates along three axes. The L* axis is a vertical range measuring lightness from black (0) to diffuse white (100). The a* axis ranges from positive values indicating red hues, through an achromatic neutral, to negative values indicating green hues. The b* axis ranges from yellow in the positive direction, to blue in the negative, also passing through a neutral grey at the zero point. These values are calculated from tristimulus values of a sample against tristimulus values of a reference white material. Colour stimuli are then designated as coordinates in an unambiguous three-dimensional colour space that can be understood as an absolute value and used in formulae to measure colour difference as Euclidean distance in this space (Fairchild, 2013).

Even the most sophisticated colour appearance models will not remove the issues that arise from the subjective observation of colour. Differences between observers, changes in the illumination, the influence of background, and surrounding colours are present regardless of the colour space used. A spectrophotometer eliminates these issues, measuring colour stimuli objectively. Photometers measure the intensity of light as a function of its wavelength. Spectrophotometers emit a calibrated beam of light that is reflected off a sample; the reflected light is measured by photometer to produce a spectral distribution of reflected wavelengths of light. The spectral distribution is represented as percentage reflectance compared against a reference material. This spectrum is then interpreted by software within the device to provide data in a recognized colour space. Modern spectrophotometers are capable of adjusting the illuminant to match a variety of CIE established standards and providing data in multiple colour spaces. These conditions, as well as the illumination area, observer, and specular component mode must be reported

with measurements made by spectrophotometer for the data to be useful. Spectrophotometers, designed specifically for colour measurement, have been on the market since 1928 (Hunter and Harold, 1987). However, archaeology, as a discipline, has largely failed to embrace this development. Few researchers utilize spectrophotometers for archaeological analyses preferring the simplicity of colour order systems, such as the Munsell Book of Colour. The objectivity and comparability of the data obtained by spectrophotometer is preferable for scientific research.

Given the precision that can be achieved by a spectrophotometer, care needs to be taken to not overstate the potential for colour analysis in the interpretation of burned human skeletal remains. Bone colour is simply used as a proxy measurement. Typically, the change in bone colour is related to maximum burning intensity. Bone progresses through expected colour phases when heated; in experimental conditions these can be related directly to temperature (Thompson, 2015a). A shift from ivory to yellow, through brown and then black relates to charring of the organic portion of bone. With further increase in the temperature, combustion removes the charred organic component and its associated colouration, leaving the bone grey. Alteration of the inorganic bone salts produces an achromatic white, distinct from the cream colour of fresh bone. Blue, blue-grey or purple tints have also been recorded in bone burned above 800°C (Devlin and Herrmann, 2015; Walker et al., 2008). This progression is well established in the literature, though the temperatures reported differ between publications – see table 3.2 below.

Table 3.2: Comparison of colour analyses on burned bone from previously published research. Temperatures in °C.

	Bone Colour Changes					
Temperature	Bonucci and Graziani (1975)	Shipman et al. (1984)	McCutcheon (1992)	Munro et al. (2007)	Walker, Miller and Richman (2008)	Wahl (2015)
100°		Pale yellow or very pale brown (below 285°)	Pale brown and black up to 340°	No Change	Gradual shift to dark brown	Yellowish white
150°						
200°	Ochraceous and brown			Dark Brown		
250°						Ivory, glassy light grey
300°	Black	Dominant colours: pink and black Secondary: very dark greyish brown and brown (285°-525°)		Black	Black to tan	Brown, dark brown
350°						
400°			Light brownish grey up to 600°			Black
450°						
500°				Taupe		
550°	Greyish	Light grey with brown and light brownish grey (up to 645°)				Grey
600°					Grey	light grey or blue grey
650°	White			Light blue		Milky white
700°			White dominant above 650°			
750°		Neutral white and light blue-grey (940°)				Mat cretaceous
800°				White		Old white cream-coloured brownish, greyish, ochre
850°						
900°						
950°						
		Above 940° neutral white and medium grey			1100° purple tint develops	

The association with temperature is often erroneously applied directly to archaeological or forensic material. As stated above, bone colour can more accurately be related to burning intensity – a combination of temperature, exposure time, and burning conditions (Thompson, 2015a). Furthermore, the observed changes represent a peak in temperature experienced for a period of time rather than an average exposure. By objectively measuring bone colour and relating this data to established experimental data, peak burning intensity can be roughly estimated (Ellingham et al., 2015b). Importantly, dental tissues do not follow the same colour progression as bone when burned, see Beach et al., 2015.

Burning is not the only process able to discolour bone; human skeletal remains from forensic or archaeological contexts may experience several processes leading to colour change before, during, or after burning. Soft tissues may stain the bone: hemoglobin leaves red or brown stains, haemosiderin and lipids leave yellow or brown stains, and decomposition of soft tissues may lead to a grey-red stain (Mayne Correia, 1997; Dupras and Schultz, 2013; Schafer, 2001). The normal yellowish or ivory colouration of bone is a result of lipids retained within the bone, when these lipids are lost bone shifts towards white or neutral grey – this colour change occurs whether lipids are lost due to high temperatures, ultraviolet exposure, or chemical bleaching (Dupras and Schultz, 2013). Adipocere will also cause a white discolouration but only as a waxy adherence external to the bone

(Dupras and Schultz, 2013). Soil staining can produce a wide variety of colours, unsurprisingly running the gamut of the Munsell Soil Colour Chart. The composition of the soil in the burial environment will affect the staining that develops on buried bone. Organic content, including tannins and humics, will produce a variety of browns from tan, through reddish tones, and black. Iron oxides in the soil will produce red hues, given adequate drainage. Manganese compounds can stain black, green, pink, or purple (Dupras and Schultz, 2013). Artefacts in the burial environment may also stain bone. Iron artefacts will stain red, orange, or brown – often with a remnant of the corrosion product adhered. Copper, or copper alloy, artefacts stain from yellow-green through blue-green and may preserve overlying cloth or soft tissue (Dupras and Schultz, 2013). Vegetation can also contribute to the colour profile of archaeological bone: green stains from moss or algae, red stains from madder plants, or purple from certain fungi (Dupras and Schultz, 2013; Mayne Correia, 1997; Cole and Waldron, 2016). Again, caution is needed when examining the dentition as differential staining relative to the skeleton is not uncommon, due to differences of both morphology and chemical composition of dental tissues (Dupras and Schultz, 2013). A chart showing the colours expected in burned human skeletal remains and alternative sources for similar colouring is presented below in table 3.3.

Table 3.3: Typical colour changes associated with burned bone and alternate explanations for similar discolouration. Temperatures in °C.

Colour	Temperature Exposure	Alternative Cause	Source
Ivory/Cream	-	Normal bone colour, lipid retention	Dupras and Schultz, 2013
Yellow	25°-300° (Shipman et al., 1984)	Haemosiderin or lipid staining Soil staining: organics Iron oxides	 Dupras and Schultz, 2013 Dupras and Schultz, 2013
Brown	175°-300°; 450°-600° (Munro et al., 2007)	Hemoglobin Soil staining: organics Iron oxides	Mayne Correia, 1997 Dupras and Schultz, 2013 Dupras and Schultz, 2013
Black	325°-425° (Munro et al., 2007)	Soil staining: organics or manganese compounds	Dupras and Schultz, 2013
Grey	600°-950° (Walker, Miller and Richman, 2008)	Soft-tissue decomposition Ultraviolet radiation Bleaching Soil staining	Dupras and Schultz, 2013
White	700°-900° (Munro et al., 2007)	Ultraviolet radiation Bleaching Adipocere	Dupras and Schultz, 2013
Blue/Purple	625°-675° (Munro et al., 2007)	Copper staining Soil staining: manganese compounds Fungi	Dupras and Schultz, 2013 Dupras and Schultz, 2013 Cole and Waldron, 2016
Red	-	Hemoglobin Soil staining: iron oxides Iron artefacts Madder plants	Mayne Correia, 1997 Dupras and Schultz, 2013 Dupras and Schultz, 2013 Mayne Correia, 1997
Green	-	Copper artefacts Algae or moss	Dupras and Schultz, 2013

Determining whether bone colour change has resulted from burning or other processes can be problematic. Correlation with other expected changes such as warping, fissuring, or fracturing would indicate that colour change has resulted from heat exposure. Another indication is the combination of high temperature characteristics on the exterior surface of a bone with lower temperature characteristics internally (McKinley, 2015). An example of this pattern of colour change is shown in figure 3.3. Still, colour change can provide only a rough estimate of the maximum temperature exposure of human skeletal remains. These estimates should be verified by other methods, such as the more precise temperature estimation methods present in the advanced methods section below.



Figure 3.6: Photograph of a rib fragment from burial EL75DX, Elsham Anglo-Saxon cremation cemetery showing characteristic colour patterning seen in burned bones. Note the white, calcined appearance of the outer surface and the black, charred appearance within. Photograph by Simon Hughes.

3.5.3: Weight

Cremation weights have been used to infer sex, age, MNI, completeness, and the representation of skeletal elements. The major advantage of cremation weight as an indicator is that it is not compromised by fragmentation, shrinkage, or warping (Gonçalves et al., 2015). In a bioarchaeology literature review comparing 84 articles on burned human remains published between 1995-2015 Gonçalves and Pires found that 87% of researchers used skeletal mass to estimate completeness and 16% used mass to infer MNI (2016).

Several experimental studies have established the range of weights to be expected from the burned remains of adult individuals. McKinley published observations from modern crematoria in 1993(b); she found that cremated human remains weighed an average of 1626 g, with a range of 1002-2423 g. She also found that males on average weighed more, 1862 g, than females, 1272 g – though the range of cremation weights overlapped significantly. All of these measurements excluded the fragments <2mm; this portion was excluded to better approximate archaeological cremation (McKinley, 1993b). In a European study of cremated cadavers the average sieved weight was 2095 g, with a range of 923-3805 g (Gonçalves et al., 2015). Cremation weight has been found to be influenced by sex, age, and BMI (May, 2011; Chirachariyavej et al., 2006). Males have been found to consistently produce higher cremation weights, though ranges overlap (May, 2011).

Sex has been estimated using cremation weight; however, this method is not recommended due to the overlap in sex specific weight ranges and the multitude of factors that may influence the weight of cremated remains recovered by archaeologists or forensic investigators (Gonçalves et al., 2015).

Cremation weight is negatively correlated with age. Researchers theorize this pattern relates to senescent and osteoporotic changes to bone density and may not be evident in archaeological populations where younger individuals are represented in higher numbers (Chirachariyavej et al., 2006; McKinley, 1993b). When non-adults are represented this trend is not observed; adult cremation weights have been found to represent approximately 3.5% of their pre-cremation body weight, while cremation of non-adults produces residual weights only 2.5% of pre-cremation body weights and in infants only 1% residual weights are recorded (Ubelaker, 2015). There is a suspected regional difference in cremation weights as well, although variations in methodology render this correlation suspect (Gonçalves et al., 2015).

Despite the significant variation discussed above, weight continues to be used to infer MNI of cremation burials (Gonçalves and Pires, 2016). However, weight can really only be used as an indication of an MNI >1, to be confirmed by assessing repetition of skeletal elements or incongruities of sex and age. Thus, if a set of remains believed to represent a single individual is found to weigh more than the heaviest recorded experimental weight of burned bone, likely the remains represent more than one individual. Detailed examination of bone fragments can then be conducted to determine whether multiple individuals or animal bone inclusions can be established definitively. Importantly, the opposite assumption cannot be made; multiple cremations may well weigh less than recorded experimentally burned individuals (Gonçalves et al., 2015).

If MNI is established via other means it may be possible to assess skeletal completeness by weight. This is currently the most common application of assessments of cremation weights (Gonçalves and Pires, 2016). Specifically, if few

fragments are identifiable, weight may be the only indicator of completeness available. However, as with MNI this is a unidirectional indicator. A low cremation weight indicates incomplete representation of skeletal remains, but a high cremation weight is not a guarantee of completeness (Gonçalves et al., 2015). Average cremation weights, as a proxy for skeletal completeness, have been used to infer collection methods among burial populations (Squires, 2015). These average cremation weights can be compared within populations to infer status, as estimated by the amount of labour invested in recovering the remains, or between populations to foster hypotheses regarding funerary traditions (Squires, 2015).

Finally, the relative representation of skeletal elements may be determined with the aim of detecting whether any preferential selection occurred during pre-depositional collection. The full identification of burned bone fragments is impossible but the sorting of fragments into bone types is more realistic. These types can be weighed and compared against expected proportions of total weight to determine if a pattern of inclusion or exclusion from deposition can be found. The approximate proportions by weight are 21% from the skull, 16% from the trunk, 18% from the upper limbs and 45% from the lower limbs (Gonçalves et al., 2015).

Weight can provide several rough indications to the archaeologist studying cremated bone, but a few further cautions are warranted. The weight recorded from archaeologically cremated remains can easily include unidentified animal bone fragments, dirt, charcoal, or ash, which will contribute to the weight and skew any inferences made from it (Gonçalves et al., 2015). Furthermore, the experimental burned bone weights are from cadavers fired in modern crematoria and thus represent a relatively consistent degree of thermal alteration that cannot be assumed for archaeological remains (Gonçalves et al., 2015).

3.5.4. Histology

Histology is the study of anatomy through a microscope. Light microscopy, scanning electron microscopy, and transmission electron microscopy have been used

to study the effects of burning on bone and its microstructures. The results of these studies are outlined below.

3.5.4.a: Light Microscopy

Light microscopy studies of cremated bone have largely focused on two aspects of thermal alteration. The first are changes to bone microstructures, observing changes to the osteons and Haversian canals. There has been little consensus achieved among these studies. Bradtmiller and Buikstra (1984) found that osteon dimensions increased with temperature exposure. Nelson (1992) found that while osteon dimensions decreased, Haversian canal dimensions increased. Squires and colleagues (2011) observed the same pattern in samples taken from individuals buried in Anglo-Saxon cremation cemeteries. Other researchers found that osteons decreased in diameter without an associated increase in Haversian canal size (Herrmann 1976, 1977; Hummel & Schutkowski 1993). Absolonova and colleagues (2012) found the dimensions of all microstructures were extensively reduced with high temperatures; however, these researchers also found that there was transient expansion of these structures at lower temperatures. The expansion of the microstructures observed around 600°C was referenced to explain the marked difference between these results and those found earlier by Bradtmiller and Buikstra in 1984. Finally, Nelson (1992) found a sex related pattern in the thermal deformation of osteons, with females showing elongation of osteons with higher temperatures resulting in an ovoid pattern.

The second major focus of these studies has been to characterise thermal changes in the bone surface. Castillo and colleagues (2013) describe four stages of thermal change: collagen deformation between 100°C – 300°C, crystalline formation between 400°C – 600°C, loss of homogeneity between 700°C and 800°C and finally granular surface appearance from 900°C and above. Other researchers have described a carbonaceous char that appears between 300°C – 500°C and polygonal cracking between 400°C – 600°C (Ellingham, 2015b; Nicholson, 1993).

3.5.4.b: Scanning Electron Microscopy

Scanning electron microscopy (SEM) employs a beam of electrons focused within a vacuum; the backscattered electrons are detected and used to produce a magnified image of the surface of a sample (Pijoan et al., 2007). Researchers employing SEM to burned bone have found the 1,000x to 10,000x range to be most useful for observing thermal modification of bone tissues (Shipman et al., 1984; Nicholson, 1993). Only highly localized images can be produced, showing a selected fraction of the bone sample used (Pijoan et al., 2007). Bone can be analysed either as thin-sections or whole bone samples (Nicholson, 1993). Thin-sections are stabilised in resin and cut to an approximate thickness of 60 microns; however, thermally altered bone often crumbles when subjected to this process (Squires et al., 2011). Whole bone samples are mounted in SEM stubs and coated in a thin film of conductive metal for analysis (Shipman et al. 1984; Nicholson, 1993).

SEM examinations of surface morphology changes and alterations to the shape and size of apatite crystals can indicate the temperature exposure experienced by a bone sample; see table 3.4. Temperature estimates based on these observations are accurate within 200°C (Absolonova, 2012). The pattern of crystal morphology has not been consistently observed, but there is consensus among researchers that bone mineral crystals increase in size with increased temperature exposure (Nicholson, 1993).

Table 3.4: Scanning electron microscope (SEM) observations of changes to the surface morphology of bone expose to various temperatures (°C).

Temperature Range	Description of Surface Morphology	Source
0° to 185°	Gently undulating Comparable to unheated controls	Shipman and colleagues (1984)
186° to 285°	Increasingly rough and granular	Shipman and colleagues (1984)
286° to 440°	Roughness became smooth and glassy	Shipman and colleagues (1984)
441° to 800°	Frothy appearance	Shipman and colleagues (1984)
800° to 940°	Frothy particles coalesce into smooth nodules	Shipman and colleagues (1984)
600° to 1000°	Spherical or hexagonal crystals that increased in size with temperature Holden and colleagues (1995) suggest that 'frothy' appearance seen by Shipman and colleagues (1984) were the same crystal forms viewed at lower magnification.	Holden and colleagues (1995)
1000° to 1400°	Hexagonal crystals show localized fusion Rhombohedral crystals observed	Holden and colleagues (1995)
1600° +	Bone mineral melts Cools to a featureless, glassy surface	Holden and colleagues (1995)

SEM analysis can be used to distinguish burned bone from bone discoloured by other diagenetic processes, as neither weathering nor fossilisation produce analogous changes to the internal structure of bone (Hanson and Cain, 2007). These analyses can also be used to produce a rough temperature estimate (Absolonova, 2012; Nicholson, 1993). Up to approximately 600°C bone microstructures are largely unaffected by either shrinkage or fusion allowing for age estimation below this threshold (Holden et al., 1995). However, most of the studies that have used SEM to analyse burned bone have been forensic in focus; more research is needed to determine how effectively these models can be applied to archaeological samples (Hanson and Cain, 2007).

3.5.4.c: Transmission Electron Microscopy

The major difference between scanning electron microscopy and transmission electron microscopy (TEM) is an eponymous one – while SEM images are produced from electrons that have rebounded from the surface of a sample, TEM images are produced by electrons that have passed through a sample (Pijoan et al., 2007; Fultz and Howe, 2012). As such, the samples prepared for TEM analysis cannot exceed 150 nm in thickness (Fultz and Howe, 2012). Samples are mounted within dedicated grids and efforts must be made to ensure the samples are flat and

to prevent the introduction of contaminants during sample preparation (Fultz and Howe, 2012). Burned bone applications of TEM analysis have focused on collagen, observing low temperature changes to individual collagen fibrils (Richter, 1986; Koon et al., 2003; Koon et al., 2010).

TEM studies of thermally altered collagen were concerned with attempting to distinguish between cooked and uncooked animal bone, focusing on heat-induced changes to collagen proteins that occur in bone that has not reached sufficient temperatures to char the surface (Richter, 1986; Koon et al., 2003; Koon et al., 2010). 'Char' recognized as the development of black colouration due to heat exposure occurs at approximately 300°C (Munro et al., 2007; Walker et al., 2008). Richter discovered in 1986 that collagen progressively degraded with increasing temperatures. First, the collagen fibril develops a "beaded" appearance – the typical fibril structure ending in a swollen break (Richter, 1986). Richter explained this morphological development as the "melting" of the collagen fibril; however, later research indicates instead that the fibril has become locally disorganised or "unpacked" (Richter, 1986; Koon et al., 2003). Next, the fibril takes on a "barbell" appearance characterised as short sections swollen at either end (Richter, 1986). Finally, the collagen become amorphous and disorganised (Koon et al., 2003). In an experiment using plaice (*Pleuronectes platessa*) vertebrae, Richter found that the collagen appeared "beaded" when subjected to 60°C and progressed to the "barbell" stage by 80°C (1986).

In a later experiment, humeri taken from sheep (*Ovis aries*) were experimentally heated and boiled to determine if a similar pattern of change could be found in mammalian collagen (Koon et al., 2003). The progressive disorganisation of the collagen fibril followed the expected pattern, but the rates of change were not equivalent – the collagen in the mammalian bone samples was less susceptible to thermal alteration (Koon et al., 2003). Samples from the sheep humeri heated to 60°C showed largely unaltered collagen fibrils. The proportion of "beaded" and "barbell" type fibrils increased with temperature, but some unaltered fibrils could still be seen in bone heated to 100°C (Koon et al., 2003). Koon and colleagues also

investigated whether these heat-induced changes could be distinguished from collagen lost through weathering processes, successfully discriminating between heated and unheated controls subjected to a variety of burial environments via TEM analysis (2003). In 2010, Koon and colleagues built on this research by attempting a blind study of bovine bone excavated from Coppergate, York. Bones were designated as likely cooked or likely unmodified by zooarchaeological and spatial evidence; these bones were then analysed by TEM and two clear groups were established. Only one bone sample from the 'likely cooked' was not identified as thermally altered by TEM analysis (Koon et al., 2010).

The success of this technique, though based on only a few studies, suggests that low-temperature burning events can be determined in archaeological or forensic contexts (Koon et al., 2010). The potential of this type of analysis has applications for the investigation of food preparation, site use, and funerary practises. Furthermore, non-culinary bone processing, such as glue production and fat extraction, could possibly be identified (Koon et al., 2010). While these techniques have been developed on animal bone, the method has potential for the analysis of human remains as well.

3.5.5: Crystallinity

The techniques discussed below have all been used to assess changes in the crystallinity of the bone matrix. Initial studies using these techniques were interested in diagenetic changes, but crystallinity measures were later correlated with increases in temperature as well (Piga et al., 2008). Fourier Transform Infrared Spectroscopy, X-Ray Diffraction and Raman Spectroscopy are methods that are used to observe changes in crystal structure; however, in the case of Fourier Transform Infrared Spectroscopy organic material can be observed as well.

3.5.5.a: Fourier Transform Infrared Spectroscopy

A Fourier Transform spectrometer emits a beam of light that is split and reflected by a pair of mirrors, one fixed and one adjustable. The second is used to create a difference in the optical paths of the two beams. The light is recombined

and measured in what is referred to as an interferogram. A detector measures the intensity of light relative to the position of the moveable mirror; the data represents the interference between the beams of light when recombined. The interferogram is a Fourier Transform of the spectrum of light absorbed. A second Fourier Transform, the inverse of the first, is used to produce a measure of the intensity at different wavelengths from the interferogram. Light sources and detectors can be varied to measure different spectral ranges, most often measurements are made in the infrared range (Barth, 2007).

The infrared spectral region extends from 0.78 µm to approximately 1000 µm, subdivided into the near-infrared from 780 nm to 2.5 µm, the mid-infrared from 2.5 µm to 50 µm and the far-infrared from 50 µm to 1000 µm (Barth, 2007). Spectra from FTIR spectrometers can be reported as absorption spectra or transmission spectra; conventionally in archaeology absorption spectra are used. Absorption spectra are reported as wavenumbers, which are the inverse of wavelength, in units of cm^{-1}. The infrared range expressed in wavenumbers runs from 12,820 cm^{-1} to 10 cm^{-1}, with the mid-infrared covering the 4000 cm^{-1} to 200 cm^{-1} range (Barth, 2007).

There are two methods of FTIR spectroscopy that are used in solid state analysis, both have been applied to bone samples. FTIR-KBr is the older method, wherein the powdered bone sample is mixed with a support medium, namely potassium bromide. Potassium bromide does not absorb mid-infrared radiation, meaning during these analyses the support medium is transparent. Bone and support medium are sintered via pressure, in the order of ten tonnes, and the resulting pellet is placed into the sample chamber of the spectrometer for analysis. Early FTIR research was mainly done using this method (Thompson et al., 2009). The FTIR-ATR method uses a crystal to produce an internally reflected infrared beam, referred to as attenuated total reflection (ATR). Infrared radiation is directed through the crystal, the internal reflectance produces an evanescent wave that extends a few microns beyond the surface. Given sufficient contact between the sample and the crystal, the sample will absorb specific wavelengths of the infrared spectrum producing an absorption spectrum. The ATR method is preferred over the

earlier KBr method as less variation is introduced during sample preparation (Thompson et al., 2009). Data produced by the two methods are not comparable but are similar enough to produce analogous trends (Ellingham et al., 2015b).

Using either method, wavelengths of infrared radiation are absorbed by the study sample yielding information about its chemical structure. The bonds between molecules are in motion – vibration, rotation, and twisting for example. The vibrational frequencies of these motions absorb infrared radiation at specific wavelengths. Functional groups can be inferred from the vibrational frequencies, as the frequency is affected primarily by the mass of atoms in a molecule and the strength of the bonds vibrating between them (Barth, 2007; Ellingham et al., 2015a). However, the vibrational frequency cannot be directly connected to the chemical structure because the absorption bands in the infrared spectrum overlap. Instead, the strength of infrared spectroscopy is in observing changes to the chemical structure of a substance (Barth, 2007).

Absorption peaks observed by FTIR spectroscopy, and indices calculated from them, can be used to examine thermal alteration in bone as compared to unaltered bone samples. The most commonly used measure is the Crystallinity Index (CI), sometimes also referred to as the 'splitting factor'. The CI is calculated by adding the absorption peaks at 605 cm^{-1} and 565 cm^{-1} and dividing by the minimum absorption found between them (Thompson et al., 2009). The equation given by the following, where A_x represents the absorbance at wavenumber x:

$$CI = \frac{\{A_{565} + A_{605}\}}{A_{595}}$$

The absorption peaks at 605 cm^{-1} and 565 cm^{-1} both relate to vibration bands of phosphate (PO_4). In fresh bone CI falls between 2.50 and 3.25. The value rises as absorbance at 605 cm^{-1} and at 565 cm^{-1} rises, and the absorbance at 595 cm^{-1} falls. This reflects a progression from small crystals, poorly ordered and under higher strain to larger crystals in a more orderly structure that experience less strain. Both

thermal alteration and diagenesis can affect this change (Thompson et al., 2011). Interpretations of CI are further complicated by the variation in crystallinity between trabecular and cortical bone. Additionally, pathological bone, entheseal growth, and age-at-death may affect measures of CI (Thompson et al., 2011). Recent research has suggested that the accuracy of temperature prediction by FTIR is increased significantly by the use of six additional ratios, as shown in table 3.5 (Thompson et al., 2013).

Table 3.5: Additional FTIR absorption peak ratios used in temperature estimation and their associated wavenumbers (reproduced from Thompson et al., 2013).

Ratio	Abbreviation	Wavenumber
Carbonate to Phosphate	C/P	1415 cm^{-1}/1035 cm^{-1}
Carbonyl to Phosphate	CO/P	1650 cm^{-1}/1035 cm^{-1}
Carbonyl to Carbonate	CO/CO_3	1650 cm^{-1}/1415 cm^{-1}
Carbonate to Phosphate	CO_3/P	900 cm^{-1}/1035cm^{-1}
Phosphate High Temperature	PHT	625 cm^{-1}/610 cm^{-1}
Phosphate Peak Line Width	FWHM at 1035 cm^{-1}	Full Width at ½ Maximum at 1035 cm^{-1}

Furthermore, absorption peaks relating to the organic components of bone can be observed in the region between 1800 cm^{-1} and 1200 cm^{-1}, as listed in table 3.6 below (Ellingham et al., 2015a). The amide I band gives the strongest signal mainly arising from the vibration between double bonded carbon and oxygen, with some contribution from the stretching motion between carbon and nitrogen. Amide II and III arise from the variable contribution of the in-plane bending of nitrogen and hydrogen and the stretching of carbon and nitrogen in the peptide linkages (Figueiredo et al., 2012). Absorption bands measured near wavenumbers 1415 cm^{-1} and 1450 cm^{-1} arise from the motions of both mineral, carbonate (CO_3), and organic, methylene (CH_2), covalent bonds (Figueiredo et al., 2012).

Table 3.6: FTIR absorption peaks associated with organic components of bone and their associated wavenumbers (reproduced from Ellingham et al., 2015a).

Absorption Band Name	Wavenumber of Band Peak
Amide I	1660 cm^{-1}
Amide II	1550 cm^{-1}
Amide III	1250 cm^{-1}

FTIR spectroscopy produces these results quickly and with a high signal-to-noise ratio (Barth, 2007). However, there are a few caveats. Most research using FTIR to determine thermal exposure has used dry bone and does not account for the effect of soft tissue. A study by Ellingham and colleagues in 2015 showed that below 400°C soft tissue protects bone from heat exposure; between 400°C and 700°C bone matrix is largely exposed and alteration is comparable to dry bone. However, above 700°C the soft tissue, particularly the fat, acts as an accelerant and contributes to the thermal alteration experienced by the bone (Ellingham et al., 2015a). Differences in collagen cross-linking associated with age or biomechanical loading may affect ratios of the absorption bands associated with the organic portion of bone (Vidal and Mello, 2011). Furthermore, there are known changes to bone mineral composition associated with diagenesis, aging, and pathological bone growth that must be taken into account when analysing samples with FTIR (Surovell and Stiner, 2001; Thompson et al., 2009).

3.5.5.b: X-ray Diffraction

X-ray diffraction (XRD) utilizes the constructive interference of a beam of x-rays diffracted by contact with a sample to characterize its atomic structure; however, only crystalline compounds can be analysed (Ellingham, 2015b; Pijoan et al., 2007). The method is based on Bragg's Law, defined as $n\lambda = 2d\sin(\theta)$, where λ refers to the wavelength of the x-ray, d represents the interplanar distance between atoms in the sample and θ refers to the angle of incidence of the x-ray on atoms within the sample (Ellingham, 2015b). The reflected x-rays are detected, and the angles and intensities evaluated, to produce a diffraction pattern that can be compared against reference standards (Pijoan et al., 2007).

Studies of bone apatite crystallinity are derived from experimental work on synthetic apatite by Termine and Posner, who calculated a ratio referred to as "percent crystallinity" that could be correlated with crystal size in their samples (1966). In 1975, Bonucci and Graziani found that the crystal size of apatite in thermally altered bone samples increased, a change that could be seen in the

sharpening of diffraction peaks in XRD analysis (Piga et al., 2008). Building on this observation, Shipman and colleagues observed diffraction patterns in experimentally heated bone (1984). They found that below 525°C all samples produced broad diffraction peaks characteristic of small crystal size, though crystal size gradually increased with temperature. Above 645°C diffraction patterns were distinctly different; the bone mineral became more crystalline and individual crystals of apatite significantly increased in size (Shipman et al., 1984). The "Crystallinity Index" (CI) is a ratio used to characterise the diffraction patterns produce by human bone samples. Barstiokas and Middleton proposed CI in 1992 as the ratio of the (300)/(202) line profiles of hexagonal apatite when using copper K alpha radiation in the angular range of 15° – 120° in 2θ (Piga et al., 2008). CI can also be calculated from FTIR data, based on the calculation developed by Weiner and Bar-Yosef in 1990. However, these indices cannot be directly compared, despite having been derived to represent the changes in bone mineral; the problem is a methodological one – FTIR produces data that is averaged by area, while XRD data is averaged by volume (Thompson et al., 2009).

Bartsiokas and Middleton developed their CI calculation not to estimate temperature exposure in burned bones, but to date recent and fossil bones – inferring age from the gradual increase in crystal size after death (1992). This introduces an equifinality that complicates the use of CI as an estimate of temperature exposure (Piga et al., 2008). However, the time period investigated by Bartsiokas and Middleton was on the scale of millions of years. XRD research on samples from the last 10,000 years can largely disregard the influence of diagenesis, although intensive weathering may influence crystallinity on a shorter time scale (Piga et al., 2008; Gonçalves, 2012).

Of perhaps greater importance is the issue of uncertainty in XRD studies of bone mineral. Anisotropy of the crystals in the bone mineral matrix accounts for some of this uncertainty. Small crystal size also contributes to the ambiguity of XRD data; small crystals produce broad diffraction maxima, thus the diffraction peaks used in XRD analysis overlap (Rogers and Daniels, 2002). Both of these issues resolve

at higher temperatures as crystals increase in size and become symmetrical in form (Thompson, 2015c). Thus, XRD analysis is more effective at differentiating high temperature exposures, above 700°C, than at distinguishing unaltered bone from low temperature exposures (Ellingham, 2015b).

3.5.5.c: Raman Spectroscopy

Another method for analysing crystallinity in bone is Raman spectroscopy. This method is commonly used by chemists, but thus far, rarely used in archaeology or forensic anthropology (King et al., 2011). Raman spectroscopy exposes a sample to a single frequency of radiation and records the difference in the energy between the incident beam and the radiation scattered by the sample. Inelastic scattering of photons, that is, a scattering process that involves a transfer of energy between the photon and the molecule it encounters, is referred to as Raman scattering – hence, Raman spectroscopy (Smith and Dent, 2005). Only a miniscule proportion of photons are Raman scattered, thus, these analyses require an incident beam with a high energy density (Smith and Dent, 2005). Analyses can be conducted in the ultra-violet, visible, or near infra-red spectra, though in Raman spectroscopy studies of bone most research has used deep red or near infra-red lasers to minimize tissue fluorescence (Ellingham, 2015b; Morris and Finney, 2004). Raman spectroscopic analysis is possible on solids, liquids, polymers, and vapours of both organic or inorganic material (Smith and Dent, 2005).

Both Raman spectroscopy and FTIR spectroscopy can provide data on changes in the chemical composition of bone; for instance, those changes gradually accumulated via diagenesis – the loss of organic components and increased crystallinity in the mineral portion. However, Raman spectroscopy can further provide data on specific mineral substitutions (King et al., 2011). This greater selectivity is possible for two reasons. First, the wide-spread use of Raman spectroscopy among chemists has provided a wealth of information regarding the specific peak positions found in Raman spectra (King et al., 2011). Secondly, large molecules produce clear bands in Raman spectroscopy while in FTIR spectroscopy

the presence of these must be inferred from a variety of possible bands (Smith and Dent, 2005). However, despite the potential of this technique, Raman spectroscopy has not yet been adopted in archaeological or forensic studies of burned bone (Ellingham, 2015b). The major reason for this dearth of research is the comparative availability of FTIR spectrometers (Ellingham, 2015b). Furthermore, FTIR spectroscopy provides a better signal-to-noise ratio in the data produced (Smith and Dent, 2005). There are also some compounds that do not produce strong Raman signals; therefore, the use of both FTIR and Raman spectroscopy in conjunction will produce the most complete results (Smith and Dent, 2005).

3.5.6: Other Methods of Analysis

Several other methods of analysis that have been used in the study of burned bones are briefly listed here. Thermogravimetry is a method by which the mass of a material can be monitored as its temperature is gradually increased within a controlled atmosphere; experiments on burned bone have been able to determine specific phases of weight loss and the temperatures at which they occur (Mayne Correia, 1997). Small-angle X-ray scattering (SAXS) measures inhomogeneities in a sample in the range of 1-50 nm, recording the size and shape of mineral crystals. This technique provides similar information to XRD or FTIR studies (Pijoan et al., 2007). Electron spin resonance (ESR) measures the nature of free radicals in a carbonized sample, reported as a *g*-value. This *g*-value can be strongly correlated with temperature exposure, while being largely unaffected by the duration of exposure. The method has been used mainly in the interpretation of carbonized plant remains but has also been applied to burned bones in order to garner information on the thermal exposure specifically of the organic content of bone (Schurr and Hayes, 2008). Some researchers have successfully extracted DNA from burned bones in both forensic and archaeological contexts (Ubelaker, 2009). Experimental research suggests that DNA can be extracted from bone exposed to temperatures up to 700°C (Harbeck et al., 2011). Trace elements within the bone matrix may provide data of lifestyle, diet, or health. The first to attempt this type of analysis was Herrmann, who attempted trace element analysis in 1972 in order to

separate commingled remains that had been burned accidentally (Grupe and Hummel 1991). Experimental investigations found that barium and lead content were affected above 800°C, and that calcium, phosphorus, and strontium content followed a linear relative increase with temperature; therefore, analysis of these elements should be possible if linear regression formulae are employed (Grupe and Hummel, 1991). Research into stable isotope analysis and radiocarbon dating of burned bone has also been conducted; this will be addressed in the following chapter. Producing an exhaustive list of the methodologies applied to burned bones is simply not possible, as new methods are continually being tested and refinements are being made to existing methods. Hopefully, in future, this wealth of methodology will be matched with consistency in experimental methods and reporting, leading to a more rigorous scientific understanding of the process of thermal exposure in burned bone.

3.6: Summary

This chapter has explored the current understanding of the thermal alteration of bone. First, in section 3.2, a review of the literature was presented to provide an appreciation for the history of the investigation of burned bone in both archaeological and forensic spheres; there is a progression from initial neglect, to isolated studies, through a flourishing of experimentation that was gradually refined, to the present wealth of methodology that includes advanced technology and ethnographic analogy. Fire was addressed in section 3.3 as a mechanism of energy exchange, especially the potential of various fuels and the temperature fluctuations that can be expected during burning events. The effect of fire on the body was then addressed in section 3.4 first focusing on soft tissue and then on bone. Soft tissue is often neglected in studies of burned bone but contributes to the burning environment by shielding the bone initially, providing a fuel source in some cases and as a mechanical force that may act on the bone when heated. Bone itself progresses through four stages when heated: dehydration, or loss of water content; decomposition, the pyrolysis of organics; inversion, the loss of carbonates and formation of large crystals of bone mineral; and fusion, where bone mineral melts

(Mayne Correia, 1997; Thompson, 2005). The stages account for the macroscopic heat-induced changes to bone colour, weight, dimension, and shape (Thompson, 2015a). Finally, section 3.5 outlined methods by which burned bones are analysed by archaeologists and forensic anthropologists. In general, studies of burned bone have failed to produce wide-spread consensus among researchers. Results of experimental studies are often incompatible due to variations in temperatures, durations of exposure, materials, or insufficient explanation of the methodology. The future of the discipline will rest on the development of consistent practises and terminology that allow for comparisons between studies (McKinley, 2015).

Chapter 4: Isotopic Studies:

4.1: Introduction

Isotope analysis provides direct, individual evidence for diet, mobility, and culturally determined practises such as weaning. Taking diet as the focus, analyses of coprolites and middens can provide a household or community wide view of dietary components. Parasites and animal remains found in middens or latrines can provide evidence of the types of foods available. Residues on potsherds or cooking implements provide evidence of meals accumulated over a number of days (Schoeninger and Moore, 1992). Paleopathological analysis can relate to deficiencies in diet such as scurvy or rickets, or to opulent diets relating to gout (Roberts and Manchester, 2007). Microwear analysis of teeth can also provide limited evidence of dietary components on an individual basis (Schoeninger and Moore, 1992). However, none of these methods of inquiry provide the potential for dietary reconstruction that is possible through isotope analysis. Isotope data can provide detailed dietary information at an individual level allowing comparisons between populations, sexes, age categories, socio-economic groups, or periods of occupation at a site. Nuanced dietary reconstruction using isotopic data can include not only the different foods that made up an individual's diet but also the proportions at which they were consumed (Schoeninger and Moore, 1992). The following chapter first outlines the basic terms used in stable isotope analyses, then discusses the materials used most often in these analyses. Detailed explanations are then provided for the three elements most often studied in relation to diet: carbon, nitrogen, and sulphur. An explanation of how these isotope analyses can be combined and interpreted to infer the diets of past populations is then given. The next section addresses how the light isotope composition of bone is affected by exposure to heat. A summary of dietary reconstructions that have been conducted on early Anglo-Saxon populations is then given to provide context for the $\delta^{13}C$ and $\delta^{15}N$ data presented in chapter seven.

4.2: Basic Terminology

The basis of the isotope analysis is the natural variation of atomic weight among atoms of an element. The term isotope was introduced in 1913 to refer to those atoms of an element that differ in nuclear composition (Gat, 1981). Taking carbon as the example, there are two stable isotopes and a third radioactive isotope (Mays, 2010). Carbon twelve, or ^{12}C, is the most common comprising 98.89% of naturally available carbon. The superscript number twelve refers to the number of protons, six, and neutrons, also six, in the nucleus of the atom. The other stable isotope form of carbon has an additional neutron in the nucleus and is therefore referred to as ^{13}C; this isotope comprises only about 1.11% of available carbon. With the addition of another neutron the atoms become unstable and subject to radioactive decay over time; this is the ^{14}C that is used in carbon-dating of organic materials (Katzenberg, 2000; Mays, 2010). Isotopes of an element react identically in chemical reactions, differing only in the rate at which these reactions occur (van der Merwe, 1982). Molecules incorporating atomically heavy atoms accrue in the most thermodynamically stable phase of a system, in liquid rather than gas, for instance. Similarly, the products of mass-sensitive biochemical or physical processes contain different proportions of the heavier isotope because of kinetic differences in the behavior of the heavier molecules in the reactants. The term for this effect is fractionation (Lee-Thorp, 2008). The relative difference in mass between reactants determines the extent of the fractionation effect, with the greatest effect occurring in molecules of lighter elements (Schoeninger and Moore, 1992). The concentration of reactants, the specific enzymes involved, and the speed of the reaction will also affect the magnitude of the fractionation effect (Arneson and MacAvoy, 2005; Lee-Thorp, 2008). Stable isotope ratios differ among molecular species, but the worldwide average ratio remains consistent (van der Merwe, 1982). Stable isotope analysis measures the ratio of two stable isotopes against a standard value expressed as a delta or "δ" value in parts per thousand, or per mille, symbolized as "‰". An example of the calculation using carbon can be seen in figure 4.1:

$$\delta^{13}C = \left[\left(\frac{\frac{^{13}C}{^{12}C}\ Sample}{\frac{^{13}C}{^{12}C}\ VPDB} \right) - 1 \right]$$

Figure 4.1: Equation for determining the delta value of carbon (Coplen, 2011).

The initials VPDB stand for Vienna Pee Dee Belemnite, which is the reference standard used for carbon (Mays, 2010). The material measured is either combusted or chemically volatilized to release gases, carbon dioxide for example. The mass spectrometer detects the concentration of molecules differentiated by mass in a volume of gas. In the case of carbon dioxide, the potential molecules may have masses of 44 (comprised of ^{12}C, ^{16}O, and ^{16}O), 45 (comprised of ^{13}C, ^{16}O, and ^{16}O), or 46 (comprised of ^{12}C, ^{18}O and ^{16}O); though other isotopologues of carbon dioxide exist they are rare and typically not recorded by mass spectrometers. The gas from the sample is compared against a laboratory standard, that has been calibrated against the international standard, VPDB for carbon (Schoeninger and Moore, 1992).

4.3: Sample Materials

Archaeologically, human bone, enamel, or dentine are the preferred materials for isotopic analyses, though other tissues such as hair may be used if they are preserved (O'Connell and Hedges, 1999). Collagen isolated from bone or dentine provides a source of carbon, nitrogen, oxygen, sulphur, or hydrogen. The type I collagen found in both bone and dentine is ideal for isotope analysis as it is stable, abundant, and easily isolated (Collins et al., 2002; Lee-Thorp, 2008). The high robusticity of bone collagen is a result of extensive linkages between the chains of the protein's triple helix structure (Schoeninger and Moore, 1992). Only when the hydrogen bonds linking the α-chains are broken do the individual fibrils begin to disintegrate into peptides; these may be leached from the bone and lost or remain as protein fragments in archaeological samples (van Klinken, 1999; Lee-Thorp, 2008). Collagenase is the only enzyme capable of hydrolyzing the collagen fibrils from the helix; however, once denatured the fibrils dissolve relatively quickly (Sellstedt et al.,

1966; Lee-Thorp, 2008). Two genera of bacteria are capable of producing collagenase: Bacillus and Clostridium (Sellstedt et al., 1966). The main influences in collagen preservation are moisture, pH, microbial attack, temperature, and time (Lee-Thorp, 2008). Arid conditions are especially hostile to collagen preservation (van Klinken, 1999). Acidic conditions may lead to the dissolution of the mineral phase of bone, leaving the collagen exposed to biodegradation; either extreme, alkaline or acidic, accelerates the hydrolysis of the collagen molecule (Collins et al., 2002). Elevated temperatures will also compromise the collagen molecule. Even in ideal conditions the slow loss of collagen occurs, with protein deterioration beginning before death via glycation reactions (Collins et al., 2002). However, isotope analysis of collagen has been possible for some Late Pleistocene (dated between 80 and 130 kya) hominin samples discovered in Europe where temperatures have been consistently low, potentially aiding collagen conservation (Bocherens et al., 1999; Lee-Thorp, 2008).

There are four possible outcomes for the isotopic analyses of degraded collagen. First, the degradation may not alter the isotope ratio of collagen; the loss does not bias the isotope ratio of the sample and sufficient protein survives for testing (van Klinken, 1999). Second, the degradation shifts the isotope ratio of collagen; the isotope values will be skewed in the sample relative to biogenic collagen but sufficient protein is available for testing. The component amino acids of collagen are not isotopically identical. Glycine, for instance, which accounts for 33% of collagen amino acids is enriched in ^{13}C and depleted in ^{15}N relative to bulk collagen values (Tuross et al., 1988; Hare et al., 1991). Third, the proportion of collagen in the sample is so low that background contamination present in the bone overwhelms the collagen isotope ratio. Fourth, insufficient collagen remains in the bone to allow for testing (van Klinken, 1999). A separate issue is the possibility of contamination by exogenous molecules; most often the contaminants that affect collagen samples are humic substances or melanoidins from the soil, or preservatives introduced by conservators. Contamination of bone collagen while *in situ* is more common in temperate regions (van Klinken, 1999). Preservatives can be

removed before or during collagen extraction if the nature of the consolidant used is known (Moore et al., 1989).

There has been significant research into collagen quality indicators to ensure that studied samples reliably reflect the original isotope ratios of bone collagen (Ambrose, 1990; van Klinken, 1999). Histological examinations or spectroscopy can indicate the presence of collagen within a bone sample before attempting extraction (Koon et al., 2010; Ellingham et al., 2015a). Collagen yields are the simplest indicator, falling from a fresh modern value of 22% by weight to 0.5% by weight indicating a likely breakdown of sample integrity. Amino acid composition can be used, but studies show that gradual changes in amino acid composition do not seem to occur; only samples with less than 0.5% collagen by weight showed depleted levels of glycine, alanine, proline, and hydroxyproline (van Klinken, 1999). The atomic ratio of elements in the collagen sample can indicate either degradation or contamination; the acceptable range for C:N has been calculated as 2.9-3.6 (DeNiro and Hastorf, 1985; Ambrose, 1990; van Klinken, 1999). The acceptable range for the atomic ratio of C:S has been defined at 300-900 and for N:S at 100-300; these ratios are specifically for mammalian collagen as there is a significant difference in the amount of sulphur found in fish collagen (Nehlich and Richards, 2009).

The isotope ratios measured from bone collagen are average values reflecting the entire period of tissue synthesis. Observations of femoral cortical bone provide a model for turnover rates of human bone collagen. In non-adults, this reflects the growth and remodeling of bone resulting in an overall turnover rate of 10-30% per year for those aged 10-15 years. Male turnover rates are higher under 20 years of age, but more data is needed for the modeling of collagen turnover in non-adults. Female collagen turnover rates fall from 4% per year at 20 years of age to 3% per year at 80 years. Males at 25 years average 3% collagen replaced per year falling to 1.5% by age 80. In adults, therefore, the bone collagen stable isotope values will reflect a long-term average of dietary protein (Hedges et al., 2007). Preferably, samples are taken from the same bone for all individuals included in a stable isotope study; however, this is not always possible in archaeological studies

(DeNiro and Schoeninger, 1983). Primary dentine is not remodelled, but reflects initial collagen synthesis, most adult crowns are formed before 10 years of age (White and Folkens, 2005). There is a minor contribution of secondary dentine formed in the pulp cavity with age, but this is not present before the age of 28 (Gustafson, 1950). The isotope ratio of collagen extracted from dentine is therefore representative of non-adult dietary protein, unless taken from 3rd molars, which form later in life. This can be compared against bone collagen to detect age related differences, or, using incremental analyses of dentine, to establish a timeline of isotope ratios. The consistent schedule of dental development coupled with the absence of remodeling allows for high-temporal resolution in these studies (Beaumont et al., 2015).

The mineral portion of bone and enamel, bioapatite, is also useful in isotope analyses. Carbonate molecules can be isolated for carbon and oxygen analysis, and phosphate molecules for oxygen analysis. Furthermore, substitutions of strontium ions for calcium in the biological apatite can be used for strontium analysis (Lee-Thorp, 2008). Lead accumulates in bone mineral by a mechanism that is not properly understood (Montgomery et al., 2000). Bone apatite is highly reactive because of the high number of substitutions and low crystallinity inherent to the mineral. Enamel apatite has fewer substitutions, higher crystallinity, increased density, and higher-order prismatic structures. Thus, enamel is more resistant to diagenesis (Lee-Thorp, 2008). The factors in preservation of bone mineral are similar to those affecting collagen: moisture, pH, microbial attack, and time. The exchange of ions with groundwater is a major mechanism of diagenetic alteration in bioapatite (Nelson et al., 1986). Acidic conditions have previously been mentioned as a factor in the dissolution of bone mineral. Microbial attack while primarily affecting collagen produces two complications for the preservation of apatite. The presence of collagen in bone stabilizes the bioapatite; when the organic phase of bone is lost this acquired passivity is also lost (Collins et al., 2002). Further, byproducts of organic decomposition create an acidic micro-environment around a decaying body (Pate, 1994). Bone apatite is more resistant to temporal degradation than collagen, though the decay of the organic portion of the bone matrix leaves a porous mineral

structure that is vulnerable to dissolution (Lee-Thorp, 2008). Enamel apatite remains dense and relatively inert in the burial environment and has been used to study the diet of australopithecines (Lee-Thorp, 2008). The ready interaction of bioapatite with surrounding soil of the burial environment has discouraged researchers in the past; however, there is some indication that this reputation is undeserved. The characterization of bone apatite as a mineral sponge may stem from early research expecting $\delta^{13}C$ values of collagen and apatite to be equivalent, rather than reflecting different portions of an individual's diet (Lee-Thorp et al., 1989). Additionally, the structural molecules of the apatite lattice are more stable than those adsorbed on the surface. Differential solubility allows for the separation of the surface molecules, removing potentially compromised mineral from that more likely to retain biogenic isotope ratios. However, no consensus regarding bone mineral quality indicators has been reached in archaeological isotope research (Ambrose and Krigbaum, 2003). As discussed above, carbon isotope ratios from apatite reflect the whole diet of an organism with a fractionation offset that relates to metabolism and dietary strategy (Lee-Thorp et al., 1989; Ambrose and Krigbaum, 2003). The turnover rate of bone mineral, similar to bone collagen, varies between bones with ribs experiencing a higher turnover rate than femora (Fahy et al., 2017). Enamel, like primary dentine, is laid down in non-adults according to a strict timeline. Thus, isotope ratios are unchanged and can be compared against adult values found in bone (Beaumont et al., 2015).

4.4: Carbon

Evidence of an isotope of carbon with an atomic mass of 13 was first reported by Arthur King and Raymond Birge in 1929, but it was not until 1939 that stable carbon ratios were first measured by Alfred Nier and Earl Gulbransen. Many of the early geochemical experiments were conducted at the University of Chicago; they chose a standard material that was convenient and abundant, PeeDee Belemnite. By historical accident this reference material was substantially enriched in ^{13}C relative to most biological samples, thus the $\delta^{13}C$ values of most biological samples are negative (Schoeninger and Moore, 1992). This reference material was

consumed and replaced by the Vienna PeeDee Belemnite referred to in section 4.2 (Coplen, 1995). Melvin Calvin and Andrew Benson first traced the photosynthetic pathway of carbon in 1948, using radioactive ^{14}C to trace the reactions used by algae, spinach, and barley (Calvin, 1961). Willard Libby developed the method of dating organic samples by the decay of radiocarbon in 1949 (Libby et al., 1949). P. L. Parker was first to publish the suggestion, in 1963, that the relative abundance of carbon isotopes could be used to trace dietary sources. In the 1960s a worldwide catalogue of the carbon isotope ratios of flora was built up as a reference standard for radiocarbon dates; the fractionation of carbon isotopes by plants during photosynthesis has a significant effect on ^{14}C dates. A 1% difference of $\delta^{13}C$ represents a 2% change in the abundance of ^{14}C, which when converted to radiocarbon age is equivalent to 160 years. Maize, and certain other tropical grasses, consistently produced young radiocarbon dates (van der Merwe, 1982). However, the photosynthetic pathway of these plants was not explained until 1966, by Davidson Hatch and C. R. Slack, experimenting on Hawaiian sugarcane. The first isotopic calculation of diet of an archaeological human population, by Vogel and van der Merwe in 1977, evaluated the significance of maize to the diets of four archaeological populations from the state of New York. In a controlled feeding study DeNiro and Epstein confirmed the assumption that the isotope ratio of an individual's tissue was determined by their diet in 1978.

The major reservoir of carbon is the non-biological oceanic carbon pool, held steady at natural abundance ratio of 98.89% ^{12}C to 1.11% ^{13}C. In terrestrial ecosystems carbon is fixed from the atmospheric pool of carbon dioxide, the cycling of carbon is demonstrated in figure 4.2 below. The current average of atmospheric CO_2 is -7‰, but prior to the exploitation of fossil fuels this value was likely between -6‰ and -5‰ (Schoeninger and Moore, 1992). Atmospheric CO_2 varies with latitude, season, and altitude but these deviations are minor. The average northern hemisphere $\delta^{13}C$ value is only 0.2‰ depleted in ^{13}C relative to equatorial latitudes. Seasonal differences in northern temperate zones average 0.5‰, with equatorial and southern latitudes more consistent. However, forest habitats can produce significantly different concentrations of ^{13}C. Amazonian rainforests have measured

$\delta^{13}C$ values of CO_2 at the forest floor 5‰ to 6‰ lower than those measured at the canopy. The decomposition of leaf litter releases CO_2 with a low $\delta^{13}C$ value and the density of the forest prevents the dispersal of the gas, creating a gradient between the forest floor and the relatively ^{13}C enriched open air. This canopy effect occurs to a lesser extent in all forests (Pate, 1994).

Among terrestrial plants exposed to the same atmospheric CO_2 reservoir $\delta^{13}C$ variations occur because of photosynthetic differences. The majority of plants use the Calvin-Benson pathway. The first step in this process fixes carbon dioxide from the air via ribulose biphosphate to produce a phosphoglycerate compound with three carbon atoms (Chisholm et al., 1982; van der Merwe, 1982). This compound lends the photosynthetic pathway and the group of plants that employ it the 'C_3' terminology used in most archaeological discussions of terrestrial plants (van der Merwe, 1982). The CO_2 uptake in the leaves of C_3 plants is slow and produces a large fractionation effect depleting plant ^{13}C levels relative to the atmospheric CO_2 reservoir (van der Merwe, 1982). A $\delta^{13}C$ range of -34‰ to -22‰ is typical of C_3 plants. This strong discrimination against ^{13}C is found in most terrestrial plants (Sealy, 2001). The majority of plants exploited as food by humans – barley, wheat, rice, beans, manioc, cassava, potatoes, and nuts – are all C_3 plants (Pate, 1994).

The initial product of carbon fixation in the photosynthetic process described by Hatch and Slack is an acid with four carbon atoms, thus 'C_4' plants (van der Merwe, 1982). The C_4 pathway is an adaptation to arid conditions or high solar radiation. Carbon dioxide is concentrated in the bundle sheath cells prior to carbon fixation. The fractionation effect is minimally expressed as all collected CO_2 is converted (Lee-Thorp, 2008). This conserves water at the expense of fixing a higher proportion of the heavier carbon isotope (van der Merwe, 1982). The less discriminate carbon fixation strategy results in a $\delta^{13}C$ range of -16‰ to -8‰ (Sealy, 2001). Tropical C_4 plants include maize, amaranth, sorghum, sugarcane, and some millets (Pate, 1994).

A very few plants are able to switch between pathways in response to environmental conditions, which is referred to as Crassulacean Acid Metabolism (CAM) (Sealy, 2001). When most CO_2 is fixed during the night these CAM plants fall into a $\delta^{13}C$ range of -14‰ to -10‰; when most CO_2 is fixed during the day the $\delta^{13}C$ range mimics C_3 plants from -30‰ to -24‰. These CAM plants are mostly succulents such as cacti and agave which have adapted specifically to xeric conditions (Pate, 1994). Agave, yucca, pineapple, and prickly pear are CAM plants that contribute to human diets (DeNiro, 1987).

While the overall oceanic carbon reservoir has a $\delta^{13}C$ of 0‰, the local ion exchange is a complicated interaction of dissolved bicarbonates, carbonates, and atmospheric CO_2 (Katzenberg, 2000; Sealy, 2001). Sea-grasses, kelps, and seaweeds growing in coastal areas are C_4 plants (van der Merwe, 1982; Schoeninger and Moore, 1992). Algaes use both C_3 ribulose biphosphate and C_4 phospheonolpyruvate carboxylase enzymes to fix carbon and depth is a factor in determining which pathway is followed (Chisholm et al., 1982; Sealy, 2001). Cold water plankton follow a C_3 pattern, but represent the most ^{13}C depleted of plankton species, which cover the range between C_3 and C_4 isotopic signatures (Schoeninger and Moore, 1992). Marine plants average $\delta^{13}C$ values of -17‰, with considerable variation following a gradient from relatively higher benthic values to pelagic and profundal values that are lower (Grupe et al., 2009). Grazing univalves, such as abalone, feeding on C_4 grasses reliably reflect this signature; bivalves feeding on plankton, such as oysters, will be closer to a C_3 signature (van der Merwe, 1982). This variation is less significant at higher levels of the food chain, as multiple food sources are averaged in carnivores (Schoeninger and Moore, 1992).

The photosynthetic pathways of producers and the impact of the oceanic versus atmospheric carbon reservoirs together account for much of the variation in the $\delta^{13}C$ values of animals; however, there is also a fractionation effect involved in the metabolism of carbon, referred to as a trophic shift. Trophic level shifts in carbon isotope ratios are small, on average only 1‰ higher with successive trophic levels between food and consumer (DeNiro and Epstein, 1978). The variation in

carbon reservoir and the method of carbon fixation divide carbon isotope ratios into three major groups: terrestrial C_3 fed mammals averaged around -21.5‰, terrestrial C_4 fed mammals around -7.0‰ and marine fed animals in between around -13.5‰. However, the range of values found in terrestrial mammals, -22. 0‰ to -11.9‰, and those found in marine mammals, -16.4‰ to -9.6‰, overlap significantly (Schoeninger and DeNiro, 1984; Pate, 1994). Dietary analysis of collagen can compare dietary contributions of C_3 plants relative to C_4 plants, provided the marine contribution to diet is negligible; or compare relative contributions of marine and terrestrial food sources, when no C_4 cultivars contribute significantly to the diet. C_4 photosynthetic $\delta^{13}C$ signatures and marine signatures cannot be untangled through the analysis of carbon isotopes alone (Lee-Thorp, 2008).

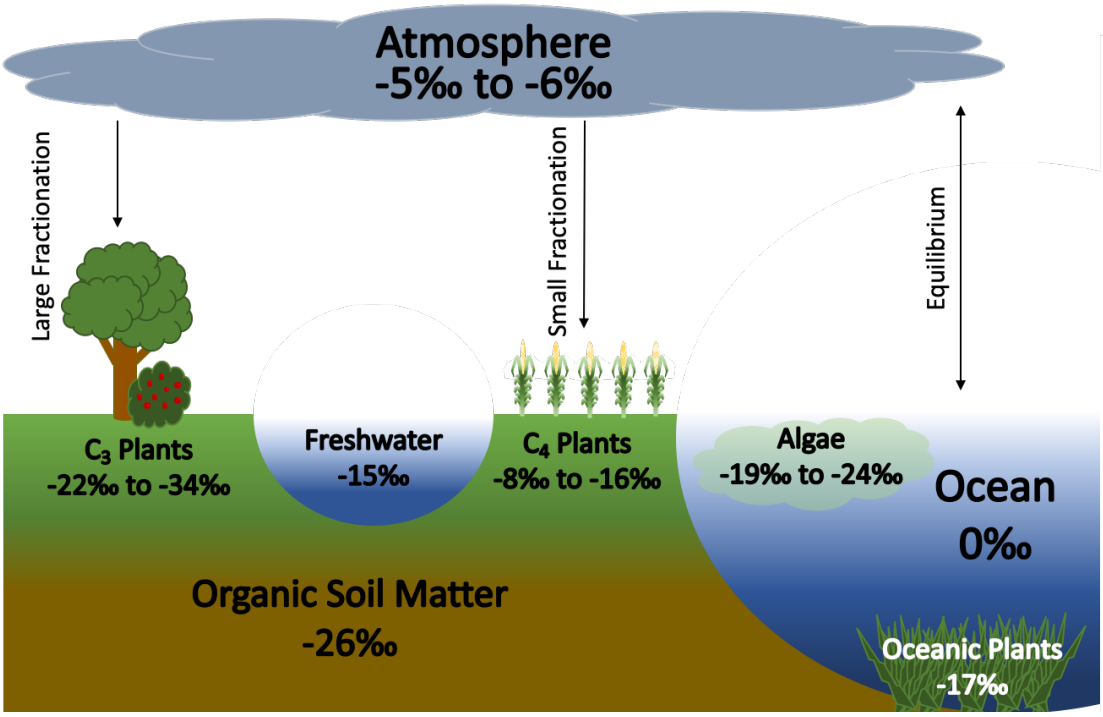


Figure 4.2: The Carbon Cycle: this figure shows the $\delta^{13}C$ values for natural carbon reservoirs and producers. Atmospheric value from Schoeninger and Moore (1992). C_3 plant, C_4 plant, and ocean values from Sealy (2001). Oceanic plant value from Grupe and colleagues (2009). Organic soil matter, freshwater and algae values from Peterson and Fry (1987). Figure by author.

4.5: Nitrogen

Nitrogen is essential to all living organisms. However, the abundant reservoir of nitrogen in the atmosphere is bound as N_2, which must be chemically or biologically reduced before being incorporated by living organisms. The depletion of

nitrogen from soils has been managed by farmers for centuries by cultivating a balance of crops capable of fixing N_2 and those incapable of fixing atmospheric nitrogen. This cycling empirically improved crop yields but the basis of the enrichment was not understood. The importance of nitrogen to agriculture led to discoveries regarding the fixation of nitrogen, predating chemical research into nitrogen as an element. In the 1830s Boussingault identified leguminous plants as those capable of fixing N_2, but this was contested in the 1860s by experiments in Germany, Great Britain, and France providing no resolution. However, in 1888 Hellriegel and Wilfarth published convincing evidence of localized fixation of N_2 in the root nodules of pea plants (Burris and Roberts, 1993). The agronomic application of their discovery led to the commercial inoculation of legumes with rhizobia, the symbiotic bacteroids discovered in the root nodules. Later research, Winogradsky's work with *Clostridium pasteurianum* in 1893 and Beijerinck's with *Azobacter chroococcum* in 1901, identified free-living prokaryotes capable of nitrogen fixation. The ability to fix nitrogen has since been identified in several more species of prokaryotes, including cyanobacteria responsible for N_2 fixation in marine environments (Burris and Roberts, 1993). Nearly a century after the identification of legumes as nitrogen fixers, S. M. Naude discovered nitrogen atoms with an atomic weight of 15 (1929). The dominant isotope ^{14}N represents 99.63% of naturally available nitrogen with 0.37% holding an extra neutron (Katzenberg, 2000). This discovery led to research into natural abundance levels, such as that by Hoering in 1955. Other researchers focused on tracking variations in isotope ratios through foodwebs; however, DeNiro and Epstein were the first to quantify the relationship between the nitrogen isotopic composition of animals and their diets through a controlled feeding study in 1981.

The international standard for nitrogen isotope analysis is AIR[2], thus the vast reservoir of atmospheric N_2 by definition has a $\delta^{15}N$ value of 0‰ as does dissolved N_2 in the ocean (Schoeninger and Moore, 1992). There are two processes that

[2] Often in archaeological literature AIR is said to be an abbreviation of 'ambient inhalable reservoir' but this is not used in other sciences.

produce bioavailable nitrogen compounds, the cycling of nitrogen is demonstrated in figure 4.3 below. The first, responsible for much of the research discussed above, involves organisms that are capable of fixing N_2. The Rhizobium bacteria discovered in pea plants by Hellriegel and Wilfarth lives symbiotically with other legumes as well, fixing nitrogen directly from the atmosphere (Burris and Roberts, 1993; Katzenberg, 2000). Legume $\delta^{15}N$ values average 1‰, with a range from -2‰ to 2‰ (Pate, 1994). Humans cultivate several species of legumes for food, including beans, peas, chickpeas, broad beans, pigeon peas, cow peas, lentils, lupines, peanuts, and soybeans. In modern dietary studies, legumes were found to account for 20% of worldwide protein. Other legumes – alfalfa, clover, and vetch – are agriculturally important as animal feed (Burris and Roberts, 1993). Some non-leguminous plants, such as alder, have symbiotic relationships with bacteria allowing for direct nitrogen fixation; however, none of these are significant contributions to human diets (Burris and Roberts, 1993). Other species of bacteria are capable of fixing nitrogen from the atmosphere but do so in the soil as free-living organisms (Burris and Roberts, 1993).

The second process producing bioavailable nitrogen is the decay of nitrogen species from organic matter by bacteria. This produces nitrates that are used by vascular plants. These nitrates are enriched in ^{15}N relative to atmospheric nitrogen (Schoeninger and Moore, 1992). Terrestrial plants without symbiotic nitrogen fixing bacteria draw nitrogen from the soil incorporating some ^{15}N enriched nitrates from decayed organic matter; the average $\delta^{15}N$ of non-legumes is 3‰ with a range of 0‰ to 6‰ (Pate, 1994). However, the modern use of nitrogen rich fertilizers has altered this ratio by providing bioavailable nitrogen at atmospheric $\delta^{15}N$. In the past, the average $\delta^{15}N$ for non-legumes would have been closer to 9‰ (DeNiro, 1987). Additionally, the fixation of nitrogen in legumes is a metabolically expensive process; when soils are rich in nitrogen there is evidence that these plants no longer fix nitrogen from the atmosphere further blurring the distinction between these plants (Schoeninger and Moore, 1992; Sealy, 2001). In marine and aquatic systems, cyanobacteria are the primary fixers of nitrogen (Schoeninger and Moore, 1992). Marine plants cannot fix nitrogen and depend on dissolved nitrates and ammonium with a resultant average of 7‰ that overlaps the terrestrial non-legume range

(DeNiro, 1987; Pate, 1994). Though the ranges overlap, marine $\delta^{15}N$ values are higher than terrestrial values. Both nitrification and denitrification take place in the ocean, processes that both select for ^{14}N and therefore leave behind an available pool of nitrogen enriched in ^{15}N. Run-off from terrestrial environments may further enrich marine environments in ^{15}N (Sealy, 2001). Thus, in terrestrial environments nitrogen is made bioavailable either by fixation of N_2 or through the decay of organic materials. In aquatic systems N_2 fixation can be accomplished by cyanobacteria, but marine plants depend on nitrogen present as dissolved bioavailable molecules.

The controlled feeding experiment by DeNiro and Epstein established the enrichment in ^{15}N of an animal over its diet. This trophic shift indicates there is a preferential incorporation of ^{15}N into an animal's tissues (DeNiro and Epstein, 1981). There is an average shift of 2‰ to 4‰ of a consumer over its diet (DeNiro, 1987). This trophic shift allows for the differentiation of protein sources. Terrestrial herbivores, including most livestock, average 5.7±2.2‰. Few marine plants or marine herbivores are consumed by humans; though seaweed may be used as both food and animal fodder (Kim et al., 2017). Marine mammals have much longer food chains and average $\delta^{15}N$ values are 15.6±2.2‰ (Pate, 1994). Thus, marine and terrestrial food sources can typically be distinguished despite overlapping ranges at the base of the respective food chains (DeNiro, 1987). Freshwater values are intermediate as nitrogen fixation by cyanobacteria is a greater influence in these systems; freshwater fish exhibit a range of 6.6‰ to 9.5‰ (Schoeninger et al., 1983; Grupe et al., 2009). Certain environments produce anomalous $\delta^{15}N$ values. Coral reefs, mangrove swamps, seagrass meadows, and salt marshes have nitrogen fixation rates higher than the general marine environment by a factor of up to 250. Animals from these environments are depleted in ^{15}N relative to the general marine signature (DeNiro, 1987). Thus, due to the large trophic level effect on $\delta^{15}N$ ratios, it is possible to determine the relative contributions of plants, terrestrial herbivores, terrestrial omnivores and marine proteins to the diet of individuals studied via nitrogen isotope analysis.

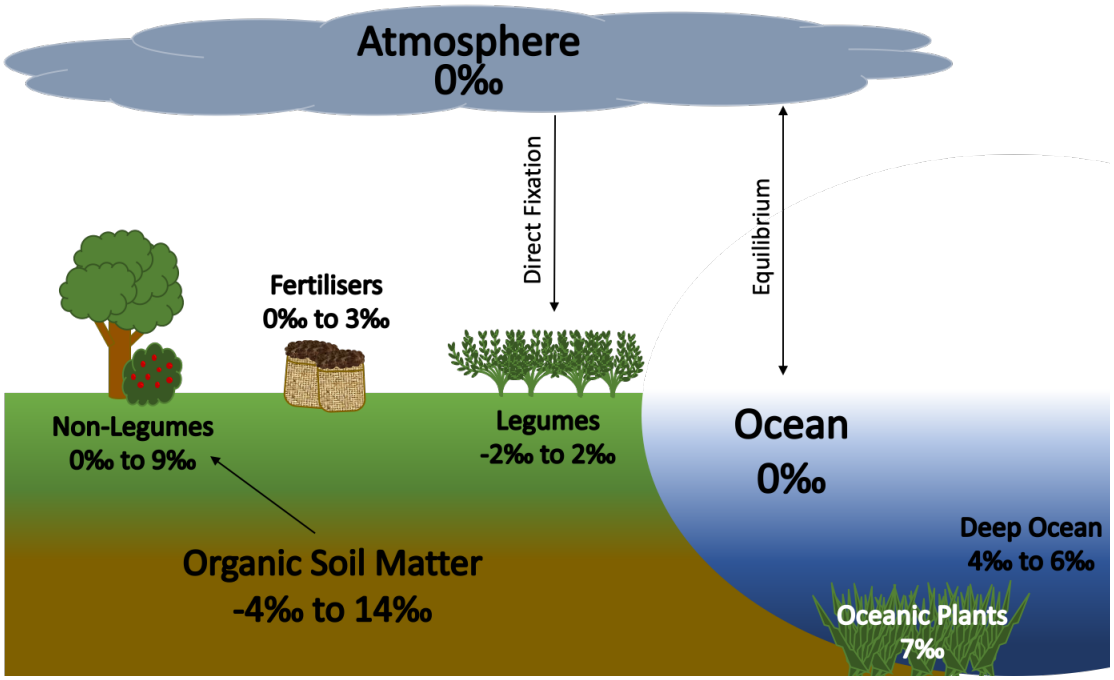


Figure 4.3: The Nitrogen Cycle: this figure shows the $\delta^{15}N$ values for natural nitrogen reservoirs and producers. Atmosphere, ocean, deep ocean and fertiliser values from Peterson and Fry (1987). Legumes, oceanic plants, and organic soil matter values from Pate (1994). Non-legume values from DeNiro (1987) and Pate (1994). Figure by author.

4.6: Sulphur

The discovery of radioactive isotopes elicited the theory that a variety of stable isotopes, as yet undiscovered, existed; in order to prove the theory J. J. Thompson began a series of experiments using anode rays to separate particles by atomic mass. His work was interrupted by the first World War but was resumed by his student Dr. Francis William Aston. Aston conducted his experiments using equipment that was a significant improvement on anode rays, the mass spectrometer (Downward, 2007). He discovered three of the four stable isotopes of sulphur – ^{32}S, ^{33}S, and ^{34}S in proportions of 96:1:3. Later experiments by Alfred Nier in 1936 proved the existence of a fourth stable isotope, ^{36}S (Nier, 1938). These are the four stable isotopes of sulphur known to modern science ^{32}S, ^{33}S, ^{34}S, and ^{36}S. The two most abundant ^{32}S at 95% and ^{34}S at 4.2% are most often analysed; the other two stable isotopes are considerably less plentiful ^{33}S at 0.75% and ^{36}S at only 0.02% (Thode, 1991). The $\delta^{34}S$ value represents the ratio between ^{34}S and ^{32}S compared against the Canyon Diablo Troilite standard (CDT); that is, troilite (FeS) inclusions from meteorites discovered in the Canyon Diablo region of Arizona (Thode

et al., 1961; Nehlich, 2015). Meteoric sulphur is distinguished from terrestrial sources by its sulphur ratio consistency, which is ideal for a comparative standard (Thode et al., 1961). However, when inconsistencies were found in the Canyon Diablo Triolite standard it was replaced by the Vienna Canyon Diablo Triolite (V-CDT) standard, a synthesized silver sulphide (Krouse and Coplan, 1997).

The oceans are a major sulphur reservoir, one that is relatively uniform due to the continual movement of water, with a modern average $\delta^{34}S$ of 20.3‰ (Nehlich, 2015). The major terrestrial reservoirs of sulphur are evaporites and iron pyrite (FeS_2) (Nehlich, 2015). Marine sulphate has over the last 400 million years varied between a low of 10‰ in the Triassic period and a high of 35‰ at the culmination of the Precambrian period; however, no deviation from the modern 20.3‰ average has been observed throughout the Holocene period (Thode, 1991; Nehlich, 2015). Evaporitic sulphates and uplifted marine sulfides reflect the oceanic $\delta^{34}S$ value from the time period in which they formed (Peterson and Fry, 1987). Sulphur from the ocean and the geosphere enters the atmosphere and soil through weathering, evaporation, rainfall, and tectonics, figure 4.4 below demonstrates this cycle (Nehlich, 2015). Delta values of sulphur are highly divergent, ranging from -53.1‰, measured in marcasite from a petroleum deposit, to 87‰, sampled from barite concretions on the ocean floor (Thode, 1991). This range reflects the fractionation effect of the oxidation or reduction of sulphur containing molecules, which can produce a change of 25‰ (Nehlich, 2015).

In the lithosphere $\delta^{34}S$ values are largely influenced by type. Sedimentary rock produces the most variable $\delta^{34}S$ values, ranging from -40‰ to 40‰ (Fornander et al., 2008). Igneous rock is the least variable, with values falling into a narrow range near 0‰ (Thode, 1991). Metamorphic rocks have an intermediate range of -20‰ to 20‰ (Fornander et al., 2008). Sedimentary rock includes compounds that have entered the biological sulphur cycle; the wide range of $\delta^{34}S$ values result from the fractionation involved in biological reactions (Thode, 1991). The primary mechanism of the biological sulphur cycle is bacteria. Bacterial oxidation of inorganic sulphur compounds is practised by three groups: photosynthetic

autotrophs, chemosynthetic autotrophs, and heterotrophs. Of these, only chemosynthetic autotrophs produce large fractionation effects. These bacteria are aerobes, requiring free oxygen to release energy via the oxidation of sulphide. A few extant genera of bacteria are capable of reducing sulphates. The reduction of sulphate to sulphide occurs through either assimilatory or dissimilatory reactions. Assimilatory reduction is typical of plant metabolism and, in animals, the synthesis of amino acids and proteins from constituent molecules. The fractionation associated with these reactions is relatively small; organic sulphur ranges from +0.5‰ enriched to -4.4‰ depleted in ^{34}S relative to the sulphate source. Large fractionation effects are produced by dissimilatory reduction, during which bacteria in anaerobic conditions release hydrogen sulphide (H_2S) from organic matter into the lithosphere. The resultant $\delta^{34}S$ can be widely divergent, from -46‰ to 3‰; the fractionation effect reflects the metabolic rate of the bacteria, low metabolic rates producing the largest effects (Thode, 1991). Coal, oil, gas, and sulphide ores, like sedimentary rock, have been measured at a wide range of $\delta^{34}S$ values, from -40‰ to 30‰ (Nehlich, 2015).

Soil $\delta^{34}S$ values arise from the admixture of the underlying bedrock and sulphur containing minerals in the local area. The soil content is determined by weathering processes and the concentration of sulphur in the constituent minerals will determine to what extent they affect the $\delta^{34}S$ value of the soil. Despite the wide range of $\delta^{34}S$ values found in the lithosphere, soil sulphates predominantly fall within a range of 0‰ to 10‰ (Nehlich, 2015). Microbial activity in the soil may alter the $\delta^{34}S$ ratio; however, the large fractionation effects are not typically found in this aerobic environment (Richards et al., 2003).

As previously discussed, the oceans are a large, uniform reservoir of sulphur. Experiments measuring sulphur ratios in seawater taken from 16 locations in the Atlantic, Arctic, and Pacific oceans at varying depths found a range of 19.3‰ to 20.8‰ (Thode et al., 1961). However, some variation in marine $\delta^{34}S$ does occur. Bacterial reduction of sulphates present in seawater creates an isotopically light benthic profile relative to seawater sulphate (Nehlich, 2015). The influence of

bacterial reduction on the $\delta^{34}S$ of marine sediments varies. The sediments of the Black Sea are depleted in ^{34}S 55‰ relative to sea sulphate, while coastal sediments near Venezuela are depleted in ^{34}S by only 15‰ relative to sea sulphate (Thode, 1991). Estuaries may also be depleted in ^{34}S due to the introduction of fresh water (Nehlich, 2015). The Baltic Sea, for instance, is restricted from the open ocean by the Danish Strait and fed by an extensive terrestrial catchment; low $\delta^{34}S$ values from seal bones found at archaeological sites on the Baltic coast potentially demonstrate this freshwater influence (Craig et al., 2006). The oceans also have an impact on terrestrial $\delta^{34}S$ values through the 'sea spray effect'; that is, aerosolized sea salt sulphates and rain with oceanic sulphur ratios. Coastal soils, due to this effect, trend from near oceanic $\delta^{34}S$ values to the local inland terrestrial value. In Japan, this effect has been measured and has been shown to influence soil samples up to 30 km inland (Nehlich, 2015).

Freshwater sulphur content is a combination of precipitation and local geology. Rain and snow $\delta^{34}S$ values are produced through evaporation; thus, over the oceans $\delta^{34}S$ values are high, ranging from 12‰ to 18‰. However, remote continental areas are more influenced by biogenic sulphur; precipitation has been measured as low as 2.2‰ (Thode, 1991). The majority of precipitation $\delta^{34}S$ measures have fallen within a range of 0‰ to 10‰ (Nehlich, 2015). Freshwater sulphates demonstrate a wider range of -22‰ to 20‰, with most falling within -5‰ to 15‰ (Privat et al., 2007; Nehlich, 2015). However, bacterial reduction in lake and riverbeds can produce extreme $\delta^{34}S$ values, as low as -62‰, in sediments (Privat et al., 2007). This wide range, as well as the mixing that occurs in estuarine areas, complicates the identification of freshwater $\delta^{34}S$ signatures without extensive contextual sampling (Privat et al., 2007). Furthermore, freshwater signals will affect the adjacent soil $\delta^{34}S$ values; in floodplains this effect may be seen over a large geographic area (Nehlich, 2015).

Natural contributions of sulphur to the atmosphere create a spectrum of $\delta^{34}S$ values dependent on the origin of the volatilized sulphur. The two major sources of sulphur to the atmosphere are sea spray and dimethyl sulphide (Thode, 1991). Sea

spray, volatilized by the wind, is consistent with the ocean $\delta^{34}S$ value, 20.3‰ (Nehlich, 2015). Dimethyl sulphide is a compound release by marine algae via the reduction of sea sulphates (Thode, 1991). Dimethyl sulphide is volatile; however, its precursor dimethylsulphoniopropionate has a measured $\delta^{34}S$ range of 18.9‰ to 20.3‰ and fractionation between these two chemical species is less than 1‰ (Amrani et al., 2013). Hydrogen sulphide and other isotopically light gaseous sulphur compounds account for approximately 6% of atmospheric sulphur. In most cases H_2S is oxidized too quickly to contribute isotopically light sulphur to the atmosphere; however, during heavy storms deep water masses may be agitated sufficiently to release H_2S. Additionally, littoral sediments regularly produce significant emissions with an average $\delta^{34}S$ of 4‰. Volcanic emissions also provide a minor contribution of sulphur to the atmosphere that is centred on 0‰ ±7.5‰. These contributions account for 2-5% of atmospheric sulphur in modern recordings. Decaying organic matter represents a variable contribution of sulphur to the atmosphere, high where vegetation is abundant and low to negligible where vegetation is sparse. Sulphur volatilized by decomposition will reflect the local precipitation, freshwater, and soil $\delta^{34}S$ values (Thode, 1991).

Plants absorb sulphates from the soil through their roots or from the atmosphere through their leaves. Atmospheric sulphate can be transferred to vegetation through wet or dry deposition; wet deposition includes rainwater or sea spray as vectors, while dry deposition involves the respiration of gaseous SO_2 (Richards et al., 2003). The proportion of atmospheric sulphate utilized by vegetation depends on the sulphur content of the soil. In soils with little to no sulphur content, plants will obtain most of their sulphates from the atmosphere and will have $\delta^{34}S$ reflecting the local precipitation (Thode, 1991). However, with adequate soil sulphate, only 25-35% of a plant's sulphur may be drawn from the atmosphere (Richards et al., 2003). Plants form two amino acids using sulphur: cysteine ($C_3H_7NO_2S$) and methionine ($C_5H_{11}NO_2S$). Methionine is synthesized from cysteine, which in turn is synthesized from another amino acid, serine ($C_3H_7NO_3$). The fractionation effect associated with the biosynthesis of these amino acids is minor, with the average plant $\delta^{34}S$ value -1.5‰ relative to the local environment (Nehlich,

2015). However, the effect is variable and has been measured as high as +3‰ and as low as -8‰ relative to the environment (Nehlich, 2015). Variation between plants within a single location can reach ±5‰ (Nehlich, 2015). The range of terrestrial vegetation reflects the range of the underlying bedrock, falling between -22‰ and 22‰ (Richards et al., 2003). However, over large areas these extremes are smoothed out and the average values fall between 2‰ and 6‰ (Peterson and Fry, 1987). Marine vegetation shows a far narrower range, reflecting the uniform ocean water sulphate, with values between 17‰ and 21‰ (Fornander et al., 2008). Freshwater vegetation is highly variable, with ranges of -22‰ to 20‰ found within a freshwater system (Vika, 2009). Estuarine environments in particular may show high variability in $\delta^{34}S$ values over a constrained area, due to the ^{34}S enriched influence of the ocean and the ^{34}S depleted influence of the riverbed. In the Great Sippewissett Marsh in Massachusetts, for example, marsh grasses were measured at an average $\delta^{34}S$ of -2.4‰ while planktonic algae within the same biota measured 18.6‰ (Peterson et al., 1985).

Sulphur in animals is predominantly bound in three amino acids: cysteine, methionine, and taurine. Of these, only methionine is present in the type I collagen present in bone or dentine, the primary sources of material for archaeological isotope analyses (Richards et al., 2003). Isotopic studies have been done on hair preserved from archaeological sites; sulphur in hair is predominantly present as cysteine (Macko et al., 1999; Richards et al., 2003). Vertebrates cannot synthesize methionine and instead must obtain this amino acid from their diets; as such, the $\delta^{34}S$ value of methionine should reflect the dietary protein of an animal averaged over the period of tissue synthesis (Nehlich, 2015). Cysteine may originate from the diet or from the conversion of methionine; therefore $\delta^{34}S$ values from hair may not directly correlate with dietary protein (Nehlich, 2015). The spacing between diet and tissue $\delta^{34}S$ values has been studied and while a range of values have been found, the trophic shift has been established as negligible compared to the range of $\delta^{34}S$ values typical in terrestrial and marine ecosystems (Richards et al., 2001; Nehlich, 2015). A trophic shift of -1‰ is often used in dietary reconstructions (Vika, 2009; Nehlich et al., 2010; Nehlich, 2015). Faunal $\delta^{34}S$ values, therefore, reflect the local

environmental $\delta^{34}S$ values as bound into biomolecules by plants, ranging from -20‰ through 20‰ (Nehlich et al., 2010). Marine organisms cluster around 20‰, while terrestrial organisms are spread more widely from -5‰ through 10‰ (Nehlich et al., 2010). However, understanding $\delta^{34}S$ patterns within an ecosystem requires knowledge of the local geology, hydrology, and biosphere. Concentrations of sulphur are high in the oceans relative to freshwater and terrestrial environment; as such, the sea spray effect may overwhelm other sulphur sources on islands or coastal areas leading to terrestrial plants and animals presenting with marine $\delta^{34}S$ signatures near 20.3‰ (Nehlich et al., 2012). Furthermore, marine signals may be affected by freshwater effects in estuaries. Archaeological $\delta^{34}S$ data from cod showed a range of values from 9.2‰ to 18.2‰, suggesting the fish, which were relatively depleted in ^{34}S were caught near shorelines where the freshwater effect would be most pronounced (Nehlich et al., 2014). Surprisingly low $\delta^{34}S$ values may be found where reduced sulphides from aquatic environments contribute to the ecosystem. Terrestrial fauna samples from Roman era sites in Oxfordshire were found to range from -13.5‰ to 0.5‰, suggesting the regular flooding events exposed the local flora to ^{34}S depleted soil from the local riverbeds (Nehlich et al., 2011). One species of mangrove bivalve has $\delta^{34}S$ values measured at -21.5‰, likely due to a symbiotic relationship with a sulphide-oxidising bacteria that lives in its gills (Kinaston et al., 2014). These outliers demonstrate the necessity of a deep understanding of the local area before attempting to interpret $\delta^{34}S$ data in a meaningful way.

A further complication of sulphur isotopic studies is the issue of anthropogenic introductions of sulphur to the environment. These contributions include natural gas, smelting, coal, and petroleum. While these chemicals will not have made significant contributions to the environment prior to the Industrial Revolution, their subsequent consumption has altered the modern sulphur cycle (Thode, 1991). Therefore, modern environmental analogs cannot be used to accurately reflect past conditions (Nehlich, 2015). Petroleum samples have been measured over a wide range, -10‰ to 40‰, as have samples of coal, -30‰ to 30‰ (Thode, 1991). Petrochemical pollution has been found to have a measurable effect

on both sulphur concentration and sulphur isotope ratios. Soil and herbage samples from the Rothamsted Park Grass experiment have shown that sulphur concentrations can be positively correlated with UK emissions, while $\delta^{34}S$ values are negatively correlated with emissions. The measured $\delta^{34}S$ difference between an 1863 minimum and a 1972 maximum was 10.6‰ (Zhao et al., 1998). Modern agricultural fertilizers may also have an effect on local $\delta^{34}S$ values of vegetation, and the animals foddered on it, as well as local water systems due to run-off (Nehlich, 2015). The magnitude of the effect of anthropogenic sulphur cannot be accurately estimated; therefore, it is important for archaeological studies to include contextual samples of contemporary or, at least, pre-industrial origin (Craig et al., 2006). However, if sufficient contextual data can be gathered $\delta^{34}S$ isotope analysis may be able to determine the relative dietary contributions of terrestrial, marine, and freshwater organisms.

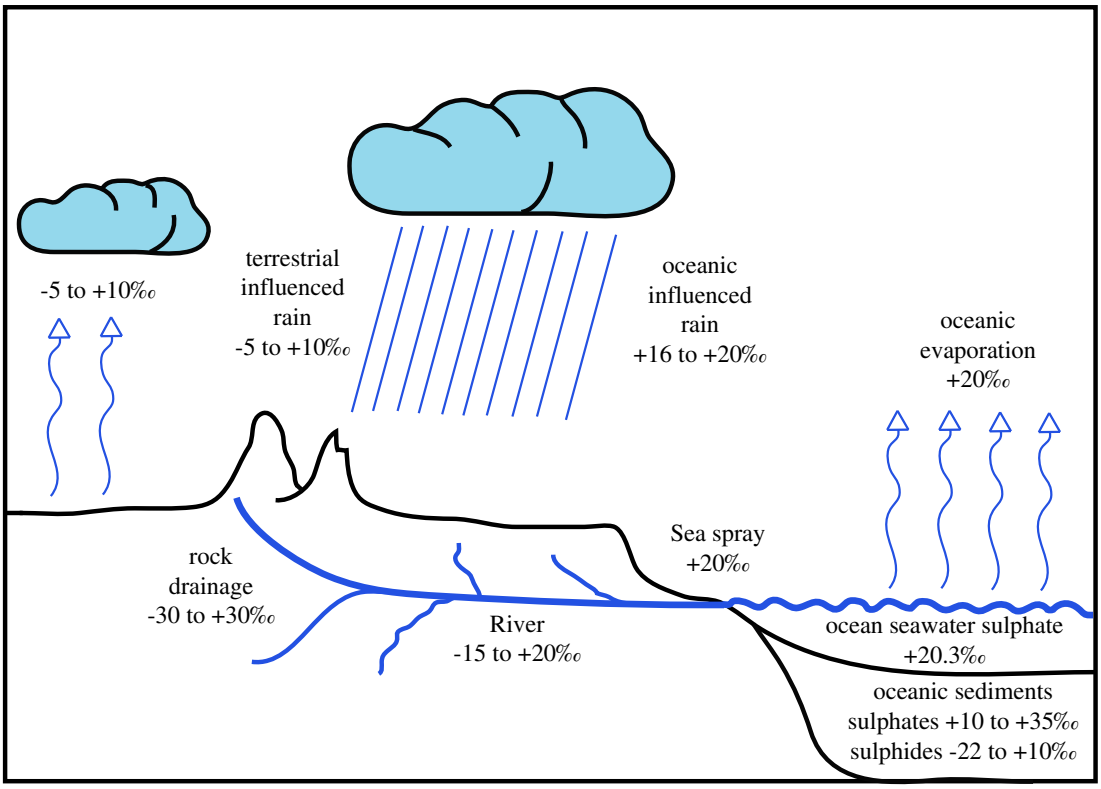


Figure 4.4: The sulphur cycle: this figure shows the natural variation in sulphur that will affect the $\delta^{34}S$ values of local flora and fauna (Nehlich, 2015, p. 3).

4.7: Interpreting Diet

The enormous potential for dietary reconstruction via stable isotope analysis can only be realized through a careful consideration of the data. Several conditions must be met to ensure the inferences made are valid. First, there must be well-preserved samples from the individuals to be analysed (Schwarcz, 1991). The samples must not have deviated from their *in vivo* isotopic composition either through degradation of the tissue or contamination by exogenous substances (van Klinken, 1999). These issues have been discussed above; see section 4.3. Secondly, the isotopic offset between the tissues used for the analytical sample and the diet must be established. This must include an understanding of metabolic routing and its potential to skew the data derived from isotopic studies; collagen specifically is known to disproportionately reflect the protein component of the diet (Mays, 2010). Furthermore, the isotope ratio of the sample represents an average of the diet during the formation of the tissue analysed; this formation period must be understood and recognized during data interpretation. In adults, femoral samples will represent an average of ten to twenty years, rib samples reflect approximately a five-year average, while dental samples reflect diet during dentine formation (Beaumont et al., 2015). Additionally, in order to effectively isolate the dietary components contributing to the average, the isotopic ranges of possible foods must be known (Schwarcz, 1991). Finally, there must be a measurable isotopic variability in potential food sources; the meat and milk of a cow, for instance, are isotopically indistinguishable (Hedges and Reynard, 2007). Isotopic dietary interpretations must account for this invisible variability; at least, by recognizing the inherent limitations of isotopic diet models.

The isotope ratio of a tissue is determined by the isotope ratios in the nutritional reservoir and the fractionation effects involved in tissue synthesis (Arneson and MacAvoy, 2005). Collagen is a protein assembled from constituent amino acids. These can be divided into essential amino acids, which must be obtained from the diet, and non-essential amino acids, which can be synthesized by an organism. Essential amino acids must be drawn from dietary protein. There are also non-essential amino acids that have essential precursors, these also must be

drawn from dietary protein. Together these two groups of amino acids account for 19.5% of the carbon in collagen. In theory, the remaining amino acids could be synthesized from lipid or carbohydrate macronutrients. However, research suggests up to 62% of carbon atoms are derived from protein, as the *de novo* synthesis of proteins is metabolically expensive compared against the routing of dietary proteins into protein synthesis (Jim et al., 2004). Herbivores can derive protein both through digestion of vegetal proteins and through the transamination of carbohydrates, varying rates of these processes will determine whether collagen in herbivores reflects their protein intake alone or their bulk dietary intake (Gannes et al., 1998). Carnivores consume proteins directly, mainly as meat, and energy as both lipids and proteins. The difference between whole diet isotope ratios and collagen isotope ratios in herbivores is therefore larger than in carnivores. Omnivores, such as humans, represent a middle ground (Lee-Thorp et al., 1989). This protein dominated signature is significant when interpreting carbon isotope ratios. Comparing collagen $\delta^{13}C$ and apatite $\delta^{13}C$ values from the same individual will yield divergent results as the collagen isotope ratio reflects dietary protein while the apatite isotope ratio is derived from an average of the whole diet (Lee-Thorp, 2008). The diet-tissue spacing for apatite $\delta^{13}C$ is consistent among individuals of a species; however, the spacing for collagen $\delta^{13}C$ will depend on what proportion of the diet is derived from protein (Harrison and Katzenberg, 2003). Nitrogen and sulphur are supplied fully by dietary protein and therefore can only represent this component of the diet (Schoeninger and Moore, 1992; Nehlich, 2015).

Generally, bone collagen is found to be 3‰ to 5‰ enriched in ^{13}C over the diet (Pate, 1994). A shift of approximately 1‰ is introduced by the metabolism of the individual, while the remaining shift is accounted for by the composition of the tissue (DeNiro and Epstein, 1978; Pate, 1994). Lipids preferentially incorporate ^{12}C; therefore, tissues that contain lipids – such as muscle, kidney, or liver – will be depleted in ^{13}C relative to tissues, such as bone collagen, that do not contain lipids (Schoeninger and Moore, 1992). Nitrogen fractionation is poorly understood; the proportion of amino acids that are routed directly into tissue synthesis versus those produced *de novo* remains unconfirmed (Fuller, 2012). However, the trophic shift

introduced by the metabolism has been measured at approximately 3‰ to 5‰ in many organisms, with the difference between human diet and human collagen estimated at 6‰ (Bocherens and Drucker, 2003; Hedges and Reynard, 2007; O'Connell et al., 2012). Further, while some difference in ^{15}N enrichment can be found between tissues, those with long turnover rates have been found to fall within 1‰ of each other (Schoeninger and Moore, 1992). Methionine is the only sulphur-containing amino acid present in mammalian collagen; it cannot be synthesized by mammals and is therefore directly derived from the diet of an individual (Richards et al., 2003). The diet-tissue spacing of $\delta^{34}S$ has been studied via controlled feeding studies resulting in a range of observed fractionation effects from -2.4‰ to 7.3‰, but the average effect was found to be 0.5 ±2.4‰ – generally considered negligible when compared to the variation in $\delta^{34}S$ values within a given environment (Nehlich, 2015).

Dietary reconstructions begin with contextual data, establishing a map or web of potential food sources and the range of isotope ratios they represent (Schwarcz, 1991). For carbon, this means establishing the ranges of C_3, C_4, and marine plants, as well as marine and terrestrial animals (Mays, 2010). For nitrogen, the major categories are trophic levels, distinguishing producers, herbivores, omnivores, and carnivores. Marine carnivores especially can be distinguished by trophic level, due to their long food chains. In some cases, it may also be possible to isolate the contribution of legumes to the diet using nitrogen isotope ratios (Mays, 2010). An example of a food source map showing carbon and nitrogen isotope ratios can be found below in figure 4.5, the ranges expected for different food sources are represented as areas on an x-y plot. Alternatively, these food chains can be understood as a food web, as shown in figure 4.6.

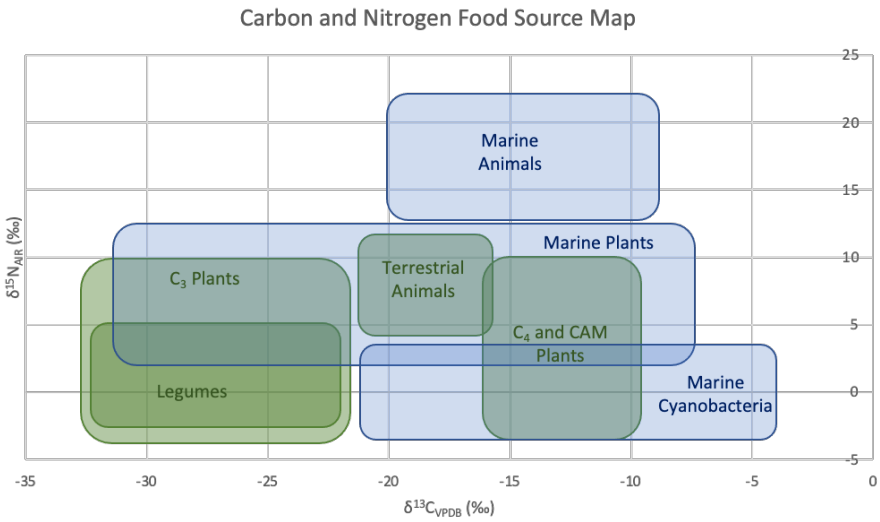


Figure 4.5: Food source map showing the carbon and nitrogen delta value ranges for isotopically distinct categories of food. Reproduced from DeNiro (1987). Figure by author.

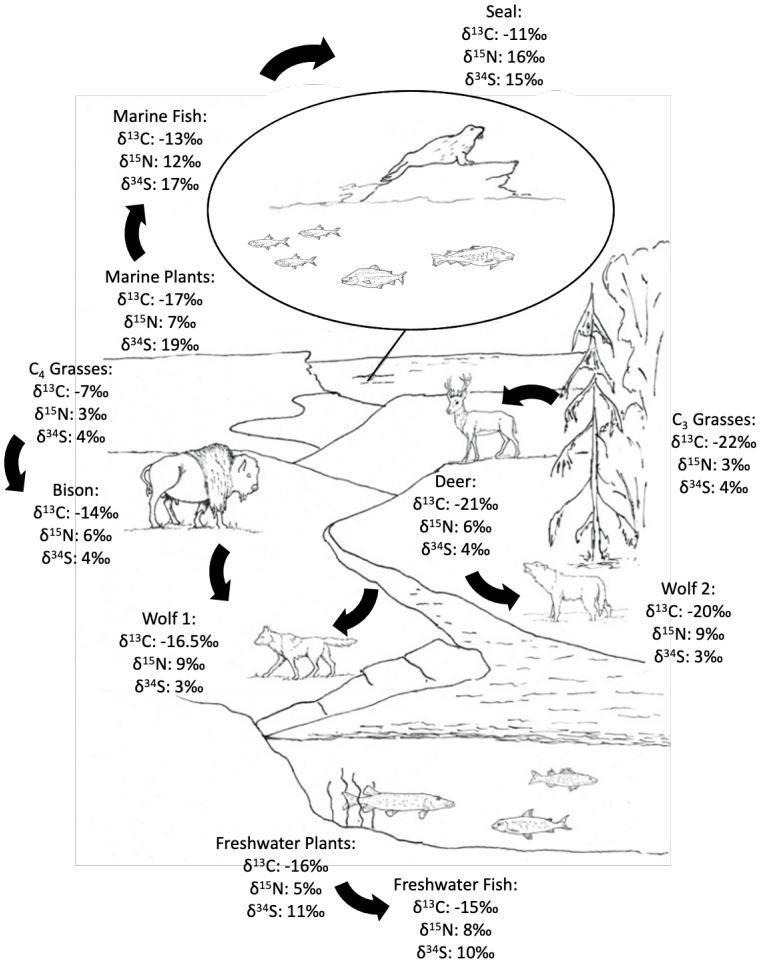


Figure 4.6: Food web diagram showing expected variation in isotope delta value due to photosynthetic pathways, trophic levels, and biomes. Carbon values based on C_3 and C_4 terrestrial averages from Shoeninger and DeNiro (1984), marine vegetation from Grupe and colleagues (2009), freshwater values from Peterson and Fry (1987), and a 1‰ trophic level change (DeNiro and Epstein, 1978). Nitrogen values based on vegetation and marine mammal averages from Pate (1994), freshwater values from Grupe and colleagues (2009), and a 3‰ trophic level change (DeNiro, 1987). Sulphur values are based on terrestrial average from Peterson and Fry (1987), freshwater and marine averages from Nehlich (2015), and a trophic level change of -1‰ (Nehlich, 2015). Illustrations by John Morrison. Figure assembled by author.

The pool of food sources can be used to establish dietary end-points; that is, theoretical diets composed of only one category of food. These end-points can then be used to estimate the proportion of a population's diet that can be represented by each category (Schwarcz, 1991). For instance, a vegan whose diet consisted only of terrestrial C_3 plants would have a $\delta^{13}C$ value between -23‰ and -20‰ and a $\delta^{15}N$ value between 8‰ and 10‰, while a vegan eating only terrestrial C_4 plants would fall between -9‰ and -6‰ for $\delta^{13}C$ and between 7‰ and 11‰ for $\delta^{15}N$ (Mays, 2010). A purely marine diet, consisting largely of carnivores and top-level predators, would have a $\delta^{13}C$ value between -14‰ and -11‰, and a $\delta^{15}N$ value between 14‰ and 19‰ (Mays, 2010). However, in most cases human populations do not fall into these extremes. Humans, estimates suggest, cannot survive on diets that depend on meat protein for more than 40% of the caloric input. Inuit populations, and other groups that subsist on high meat diets, consume the majority of their calories as fat allowing for survival on a diet of 40% meat protein (Schoeninger and Moore, 1992). Historical Inuit populations, whose diet consists overwhelmingly of large marine mammals, had an average $\delta^{13}C$ value of -14‰ and an average $\delta^{15}N$ value of 18‰ (DeNiro, 1987). Few human populations exceed meat consumption that accounts for 25% of their caloric intake (Schoeninger and Moore, 1992). The difference in the $\delta^{15}N$ values between an individual receiving 25% of their calories from meat and one who consumes only 10% of their calories as meat would be only 0.5‰. Such minor changes can be difficult to observe among small numbers of samples, instead dietary interpretations are more effective at the population level (Schoeninger and Moore, 1992). The relative contribution of three theoretical food inputs can be estimated using a linear mixing model, as seen below in figure 4.7. The input points must be isotopically distinct in both x and y coordinates, these theoretical points indicate potential food sources that would have been established for a population. Increased specificity in the available food sources will improve the accuracy of the diet estimation provided by the linear mixing model. For instance, if deer, pig, and seal bones are found at an archaeological site and analysed these will provide better

input estimates than using the general ranges for terrestrial herbivores, terrestrial omnivores, and marine carnivores (Schwarcz, 1991).

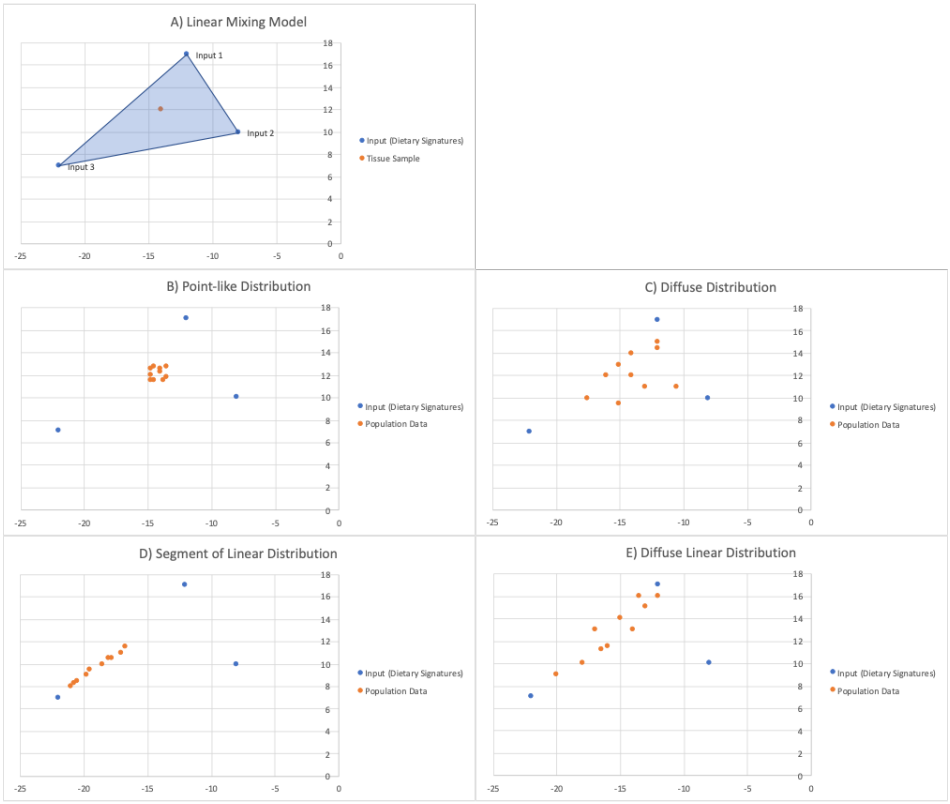


Figure 4.7: Example of a linear mixing model and some of the population distributions expected for this type of analysis. A) Shows three theoretical input signatures, the shaded area represents the possible dietary compositions covered by this model. B) If all tissue analyses form a single, clearly defined cluster the diet of the population was homogenous. C) If the analyses form a diffuse cloud the population was utilizing a range of the three food sources. There may be trends in this type of data that can be illuminated by examining sub-groups within the population. Plots D and E represent linear distributions. In both cases the populations are consuming only inputs 1 and 3 and not consuming foods from input 2. D) Shows a population with a relatively homogenous diet, consuming proportionally more of input 3 than input 1. E) Shows a more varied diet, consisting of differing proportions of input 1 and 3. As with plot C, there may be further trends in the data relating to sub-sections of the population. Reproduced from Schwarcz, 1991.

Using the mixing model displayed above, the proportional contribution (P_1, P_2, P_3) of the three dietary inputs (f_1, f_2, f_3) can be estimated for a tissue (δ_{tx}, δ_{ty}) using the following equations, figure 4.8:

$$\delta_{tx} = P_1\delta_x(f_1) + P_2\delta_x(f_2) + P_3\delta_x(f_3)$$
$$\delta_{ty} = P_1\delta_y(f_1) + P_2\delta_y(f_2) + P_3\delta_y(f_3)$$
$$1 = P_1 + P_2 + P_3$$

Figure 4.8: Equations used to determine the proportional contributions of three food sources to the diet of an individual, reproduced from Schwarcz, 1991.

More complex mixing models have been developed that employ Bayesian statistics in order to correct for uncertainty in the isotopic ranges of potential dietary inputs; however, these models still rely on the three equations above to establish the proportional dietary contributions of food sources (Hopkins and Ferguson, 2012). These models can be used to observe dietary differences between or within populations, as shown in figure 4.9.

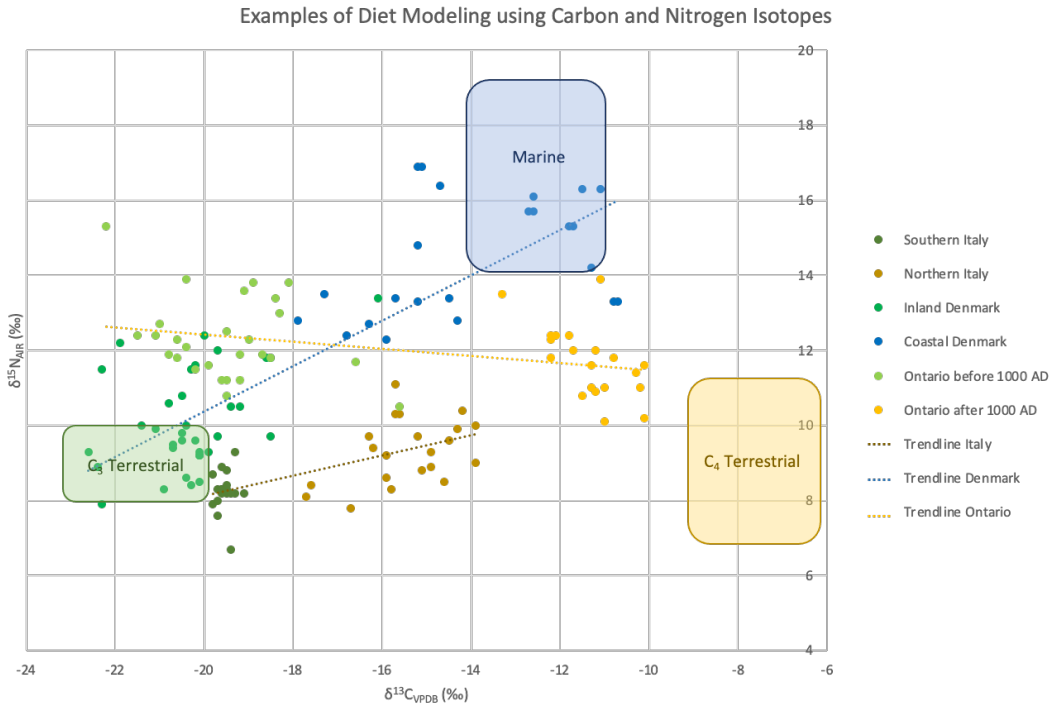


Figure 4.9: Data from three human dietary isotope studies are presented here to demonstrate how diets can be modelled against theoretical ranges for diets consisting solely of C3 terrestrial (green), C4 terrestrial (yellow), and marine (blue) food sources; the ranges for these theoretical diets were reproduced from Mays, 2010. The Italian and Canadian data show populations separated by their consumption of C4 dependent foods, while the Danish data show populations separated by their consumption of marine foods (Harrison and Katzenberg, 2003; Fischer et al., 2007; Tafuri et al., 2009).

The two Italian populations presented here show a differential dependence on C_4 plants. Both populations are from the Bronze Age; however, only the northern population has indications of C_4 plant consumption, likely millets, such as *Panicum miliaceum* (broomcorn) or *Setaria italica* (foxtail). Two theories were proposed by the authors to explain this difference: either millets were introduced to Italy from Central Europe or the short growing season, high yield, and adaptability of the millet crop were more important in the north while less tolerant species could be more easily grown in the south. In either case, significant nutritional content was still

being obtained from C_3 cultivars in northern Italy despite the adoption of millet (Tafuri et al., 2009). A similar, though stronger trend can be seen in the Canadian data. However, here the difference is temporal rather than spatial. In this study, all collagen isotope data collected from individuals dated before 1000 AD showed distinctly C_3 signatures, some with elevated $\delta^{15}N$ values suggesting the consumption of fish. After 1000 AD $\delta^{13}C$ values are significantly higher suggesting a subsistence strategy dependent on maize, a C_4 crop. However, radiocarbon dating of maize kernels and cupules suggest that maize was introduced circa 540 AD. Analysis of carbonate $\delta^{13}C$ indicates C_4 plant consumption from 500 AD. This disparity is related to dietary routing; as discussed above, collagen predominantly reflects dietary protein. Before 1000 AD, the consumption of animals feeding on C_3 plants obscured the contribution of ^{13}C enriched maize to the diet of indigenous Canadians; after 1000 AD maize became a dietary staple and its $\delta^{13}C$ signature could be seen in both collagen and carbonate (Harrison and Katzenberg, 2003). Another spatially derived dietary pattern can be seen in the Danish data. Coastal populations incorporated significant amounts of marine foods into their diets, while inland populations largely subsisted on C_3 plants and herbivores feeding on them. However, another temporal pattern was observed in this study. Following the Neolithic transition, the coastal Danish populations shifted from a marine influenced signature, enriched in ^{15}N, to a terrestrial signature, relatively depleted in ^{15}N, and became isotopically indistinct from inland populations (Fischer et al., 2007). These data have shown how dietary modeling can elucidate variation in subsistence strategies between contemporary populations over space, or in the same population over time. Dietary models can also determine whether dietary variation within a population can be correlated with sex, age, social status, or health (Schwarcz, 1991).

It is important to recognize that these data can only be analysed properly when contextualized. There are specific environments in which the typical patterns shown in figure 4.5 will not apply. For instance, research has shown that there is a negative correlation between rainfall and $\delta^{15}N$ values in plants and animals (Ambrose and DeNiro, 1986; Ambrose, 1991; Murphy and Bowman, 2006). Elevated $\delta^{15}N$ values in animals from arid regions were initially theorized to be the result of

physiological adaptations to limited water supplies (Ambrose, 1991). However, this theory was not supported by experimental data (Ambrose, 2000). Observational studies have shown that low levels of water affect the $\delta^{15}N$ of entire ecosystems (Murphy and Bowman, 2006; Hartman, 2011). Dry soils have elevated $\delta^{15}N$ values due to inhibited N_2 fixation and increased ammonia (NH_3) volatilization (Ambrose, 1991). Arid soils produce plants with high $\delta^{15}N$ values and the herbivores that feed on them incorporate these elevated values, with a relatively constant diet-tissue offset (Murphy and Bowman, 2006; Hartman, 2011). These values may significantly alter human diet reconstructions. One population living in the Atacama Desert in Chile was found to have a mean $\delta^{15}N$ value of 25‰ (Ambrose, 1991). In some cases, the $\delta^{15}N$ value pattern expected for terrestrial and marine animals may be reversed; measurements of animals from southern Africa showed springbok (*Antidorcas marsupialis*) ranging from 13.8‰ to 17.3‰ while limpet (*Patella sp.)* ranged from 7.2‰ to 8.4‰ (Sealy et al., 1987). Other environments that produce unusual isotope ratios include forest habitats and salt marshes that are depleted in ^{13}C, or coral reefs that are depleted in ^{15}N (Pate, 1994). These environmental influences on isotope ratios demonstrate the necessity of specific local contextual analyses to robust reconstruction of diet via isotope analysis.

Thus far, the dietary models presented have only compared $\delta^{13}C$ and $\delta^{15}N$ values. Isotope analyses that include evaluations of $\delta^{34}S$ can provide further information. The potential to determine the input of freshwater fish to the diet is the most lauded contribution of sulphur dietary analyses, as this is an aspect of diet that is difficult to determine through carbon and nitrogen analyses – see figure 4.10 below (Nehlich, 2015).

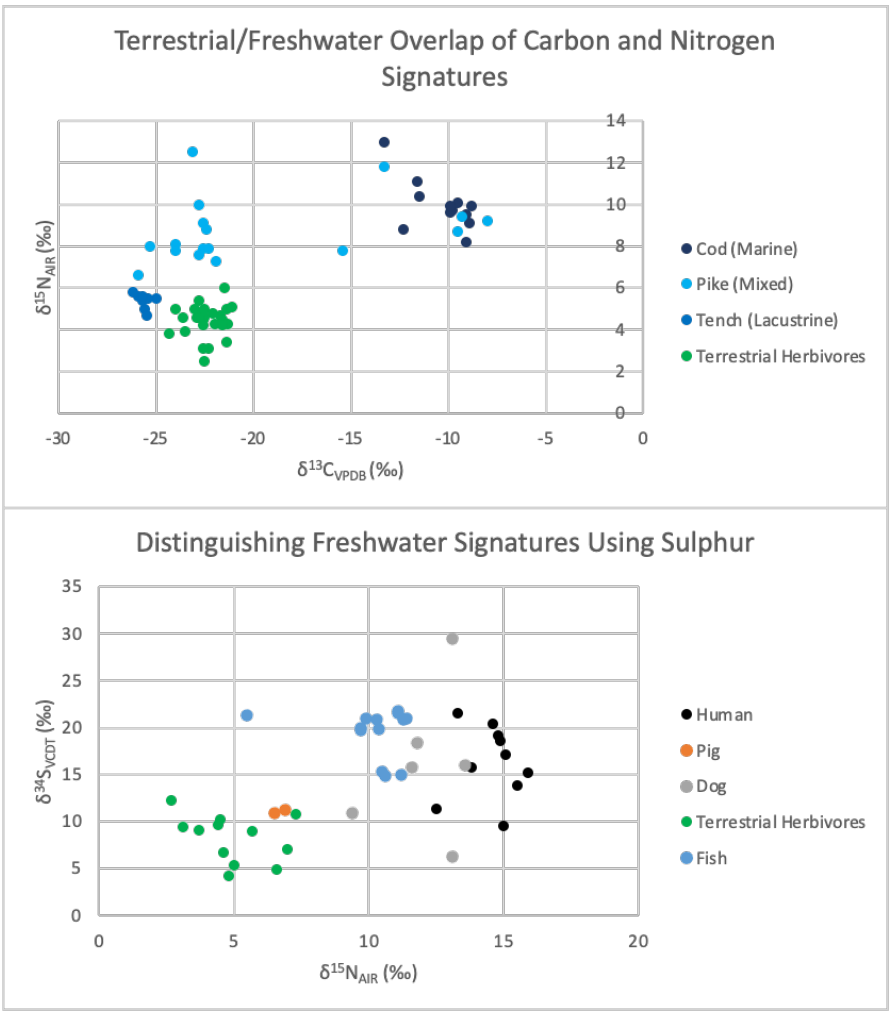


Figure 4.10: The figure above highlights the potential of sulphur isotope analysis for interpreting the contribution of freshwater dietary sources to human diets. The chart on the left demonstrates that freshwater and terrestrial animals overlap isotopically when analysing only carbon and nitrogen ratios (Reproduced from Fischer et al., 2007). The chart below shows that, where the underlying geology allows, freshwater animals can be distinguished isotopically by examining sulphur ratios (Reproduced from Privat et al., 2007). The general category 'fish' is used on the right for Northern pike (Esox lucius), perch (Perca fluviatilis) and Crucian carp (Carassius carassius).

Unlike carbon and nitrogen isotope ratios, which are affected by methods of fixation, photosynthetic pathways and trophic level shifts, sulphur isotope ratios are determined by the surrounding environment and are largely unaffected by metabolic reactions (Mays, 2010; Richards et al., 2001). As such, sulphur isotope analyses require local environmental values for effective interpretation. Terrestrial $\delta^{34}S$ signatures will reflect the local bedrock and water supply; however, when averaged over large areas terrestrial vegetation tends to fall between 2‰ and 6‰ (Peterson and Fry, 1987). Towards the coast these values will become increasingly

enriched by sea spray, trending toward 20.3‰ (Privat et al., 2007). Marine dietary sources range from 9‰ to 21‰, with clusters at 10‰ and 16‰ (Nehlich et al., 2013; Nehlich, 2015). The ^{34}S depleted cluster reflects the influence of freshwater on animals feeding along the coast or in estuarine environments, while higher values indicate animals feeding further from land. Due to this variation sulphur isotope analysis of marine zooarchaeological materials may provide information on fishing strategies, determining whether populations were accessing deep water populations or fishing along the coast (Nehlich et al., 2013). Freshwater organisms are mainly distinguished by their variability rather than a specific range of values and are therefore most easily distinguished in geologically uniform areas. In areas of geological complexity freshwater $\delta^{34}S$ profiles may be indistinct from terrestrial ones (Privat et al., 2007). Figure 4.11 below shows the expected ranges for terrestrial, marine, and freshwater dietary sources, as well as terrestrial inputs influenced by sea spray.

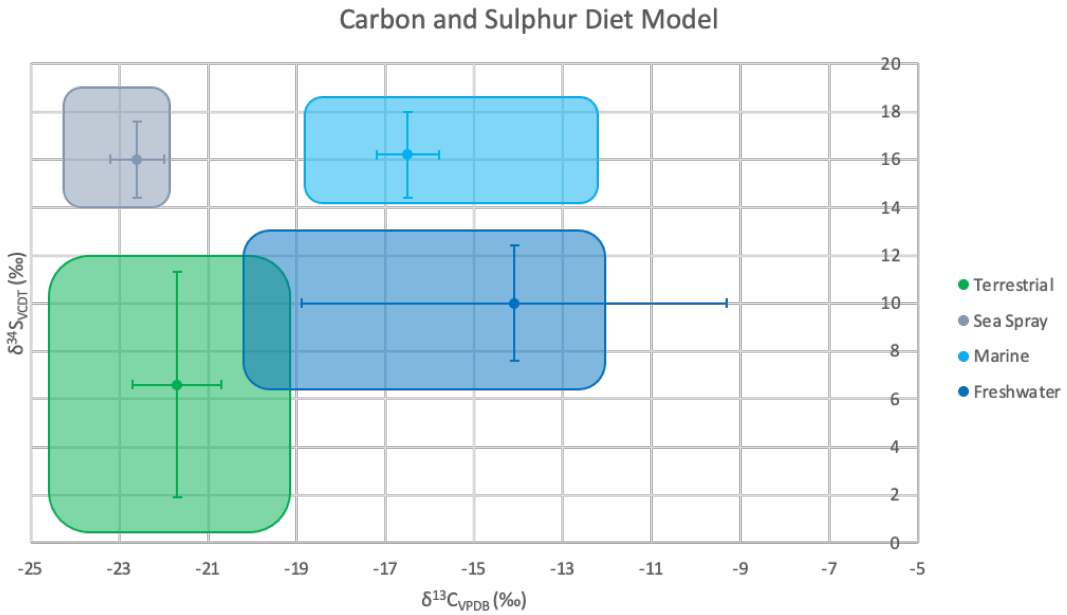


Figure 4.11: Displays the expected $\delta^{13}C$ and $\delta^{34}S$ ranges of broad dietary categories based on Scandinavian data. Shaded rectangles reflect expected ranges, data points represent average recorded values, and error bars cover one standard deviation from the average (reproduced from Nehlich, 2015).

Several important caveats regarding the interpretation of sulphur data must be emphasized at this time. Firstly, the visualization of $\delta^{34}S$ distribution depicted

above represents the averaging of data from several Scandinavian studies. This data will not be applicable in other regions; the figure is included only to demonstrate how food categories can be mapped using $\delta^{34}S$ and $\delta^{13}C$ values. Furthermore, these baseline maps must be created using pre-industrial samples; modern analogs may skew the data due to the anthropogenic alteration of the sulphur cycle (Thode, 1991; Zhao et al., 1998). Finally, when interpreting relative dietary contributions using $\delta^{34}S$ values abundance is an important consideration. Fish muscle tissues contain significantly more sulphur content than an equivalent amount of mammalian muscle tissue; for instance, carp (*Cyprinus carpio)* muscle tissue contains 0.37% sulphur by weight, while muscle tissue from cattle (*Bos taurus)* contains only 0.18% (Nehlich and Richards, 2009). Therefore, eating fish will have a disproportionate effect on the $\delta^{34}S$ value of the consumer, one that must be accounted for when interpreting diet (Nehlich, 2015).

4.7.1 Stress Studies: Weaning and Starvation

A sub-set of dietary research using isotopes is the identification of breastfeeding and weaning patterns in past populations. Infants that are breastfed have been found to have elevated $\delta^{15}N$ values, +3‰ to +5‰ relative to their mothers; effectively these infants are a trophic level above the general female adult population (Mays, 2010). This increase was discovered in 1989 and has been the subject of significant research ever since (Fogel et al., 1989; Beaumont et al., 2015). Healthy infants progress from marginally enriched in ^{15}N in utero to as high as 5‰ enriched while breastfeeding (Fuller et al., 2006a). As solid foods are introduced the $\delta^{15}N$ values will fall until the infant is fully weaned and falls in line with the adult range of $\delta^{15}N$ values, presuming the weaning diet is analogous to the adult diet (Fuller et al., 2006a). A smaller ^{13}C enrichment is seen in infants, reflecting the less substantial trophic level effect. This signature is obscured when other foods are introduced and may not be visible in archaeological populations; the initial data was derived from hair and nail samples from living infant and mother pairs (Fuller et al., 2006a). One study of Romano-British infants from Oxfordshire was did not find any indication of a breastfeeding signature via $\delta^{34}S$ analysis, despite $\delta^{15}N$ results showing

the typical enrichment curve expected for breastfed infants. However, the youngest individuals had lower $\delta^{34}S$ values that may indicate either a specialised weaning diet for the infants or a pregnancy/lactation diet among the mothers that involved higher levels of freshwater fish than the general population (Nehlich et al., 2011). Most studies of weaning patterns are cross-sectional. Bulk collagen samples are taken from non-adults of various ages and compared against the adult dietary average, assumed to represent the $\delta^{15}N$ value of the weaning diet. However, recent studies have used incremental dentine samples to conduct longitudinal observations of weaning practises within a population (King et al., 2017). Dentine is not remodeled during an individual's lifespan and adult dentitions provide a record of the diet at the time of tissue formation; therefore, researchers are able to compare the $\delta^{15}N$ values of those that survived childhood to those that did not (Beaumont et al., 2015). Longitudinal studies have indicated that the weaning model that has been previously accepted is too simple and does not account for other factors that may influence the $\delta^{15}N$ value of tissues formed during infancy (Beaumont et al., 2015).

The chemical reactions that determine stable isotope fractionation within an organism are affected by the organism's health status and stress responses (Reitsema, 2013). This effect was first observed in birds suffering from starvation; Hobson and colleagues identified a ^{15}N enrichment that could be correlated with diet restrictions or fasting behaviors (Hobson et al., 1993). When nitrogen is not ingested in sufficient quantities the body may catabolise existing proteins. As excreted urea is depleted in ^{15}N, the remaining pool of nitrogen used in tissue synthesis becomes enriched in ^{15}N. The $\delta^{15}N$ values of individuals suffering from anorexia have been measured 0.5‰ to 2.0‰ above the same individuals following treatment; $\delta^{15}N$ was measured longitudinally using hair samples (Reitsema, 2013). A similar $\delta^{15}N$ increase was observed in hair samples from pregnant women suffering from morning sickness, with no corresponding change in $\delta^{13}C$ values (Fuller et al., 2005). However, pregnant women suffering from hyperemesis gravidarum showed both an increase in $\delta^{15}N$ values and a decrease in $\delta^{13}C$ values (Reissland et al., 2020). Decreased $\delta^{13}C$ values are expected with weight loss due to the catabolism of lipids present in the body (Reissland et al., 2020). Stress responses related to pathology may also

increase $\delta^{15}N$ values. Osteomyelitic bone sampled from an individual suffering from AIDS was found to be nearly 2‰ higher than the surrounding non-pathological bone samples, indicating that the pathological tissue formed under a catabolic state (Katzenberg and Lovell, 1999). There have been some attempts to tie specific pathologies to stable isotope variation. White and Armelagos compared $\delta^{15}N$ values of mummies diagnosed with osteopenia against healthy individuals from Sudanese Nubia; they were able to correlate the disease with elevated $\delta^{15}N$ values but only in female individuals (White and Armelagos, 1997). Conversely, individuals suffering from cirrhosis were found to have $\delta^{15}N$ values 3.2‰ lower than healthy controls, likely due to pathological interference in the excretion of ^{14}N (Petzke et al., 2006). Several of the studies mentioned above used hair, nails, or muscle tissue to determine $\delta^{15}N$ values; these tissues have relatively fast turnover rates when compared to bone collagen. Stress-related changes to isotope ratios are unlikely to be detected in bone; the individual is likely either to have died or recovered before the effect of catabolism can be measured in bone (Richards and Montgomery, 2012). However, bone samples taken from pathological lesions, formed under stressed conditions, or from non-adults, who experience more rapid bone deposition during growth, may have elevated $\delta^{15}N$ values related to catabolism (Katzenberg and Lovell, 1999). Furthermore, dentine will reflect the diet and health status of the individual during tissue formation, including episodic periods of starvation or disease (Beaumont et al., 2013; Beaumont and Montgomery, 2016).

4.8: Isotope Studies on Burned Bone

The majority of isotope research conducted on burned bone has focused on bone mineral. With several studies focused on whether reliable radiocarbon dates can be obtained from samples of burned bone (Lanting et al., 2000; Olsen et al., 2008; Zazzo et al., 2009; Hüls et al., 2010; Zazzo et al., 2012). Lanting and colleagues (2001) initially reported correlation between calcined bone samples and charcoal samples recovered from the same contexts. However, burning experiments have since shown that there is carbon exchange between bone apatite and the burning environment. Hüls and colleagues (2010) demonstrate that modern bone samples

burned in artificial atmospheres including fossil CO_2 produced ^{14}C dates older than expected, with up to 86% of carbon in burned samples derived from exogenous sources. Similarly, archaeological bones burned on fires open to the environment fueled by modern wood were produced ^{14}C younger than expected, in one sample from a Neolithic context this produced an approximately 6000 year "rejuvenation" (Zazzo et al., 2012). Similar carbon exchanges were seen in burning experiments measuring $\delta^{13}C$ values from carbonate, with $\delta^{13}C$ values of burned bone samples suggesting a 39% to 95% exchange of carbon between bone samples and fuel sources (Hüls, 2010; Zazzo et al., 2012; Snoeck, 2014). However, the process of calcination does render the bone relatively inert and post-burial alterations of $\delta^{13}C$ values or ^{14}C dates are unlikely (Olsen et al., 2008; Snoeck, 2014). Several studies have also investigated the potential of bone mineral from burned bones for isotope research on mobility (Munro et al., 2007; Harbeck et al., 2014; Harvig et al., 2014; Snoeck, 2014; Snoeck et al., 2016; Toncala et al., 2017; Zieler, 2017; Grupe et al., 2018; Snoeck, 2018). Controlled heating experiments demonstrating the conservation of strontium ratios at up to temperatures of 1000°C were conducted by Harbeck and colleagues in 2011. Their findings were confirmed and expanded by later experiments (Harvig et al., 2014; Snoeck, 2014). Calcined bone is resistant to mineral exchange with the burial environment, due to changes in the crystal structure caused by high temperatures, allowing for better retention of *in vivo* ratios of $^{87}Sr/^{86}Sr$ relative to unburned bone (Snoeck, 2014). The use of $^{87}Sr/^{86}Sr$ analysis on samples of cremated bone has been widely applied to archaeological samples (Snoeck, 2014; Snoeck et al, 2016; Toncala et al., 2017; Zieler, 2017; Grupe et al., 2018; Snoeck, 2018). More recently, lead stable isotopes have been studied from samples of cremated archaeological bone, with encouraging results (Toncala et al., 2017; Grupe et al., 2018), though further research will be needed to determine whether these analyses are reliable. Research into $\delta^{18}O$ values from burned bone have shown that these values are relatively stable when measured from either phosphate or carbonate up to temperature exposures of approximately 200°C but vary significantly above this temperature threshold (Munro et al., 2007; Harbeck et al., 2011). Further experimentation has shown that oxygen exchange with the burning environment occurs altering the $\delta^{18}O$ values of burned bone samples

relative to unburned controls (Snoeck, 2014). Futhermore, $\delta^{18}O$ values are more useful in provenancing bone when correlated with strontium or lead isotope ratios; however, as discussed, these ratios are more reliably measured from calcined remains (heated to ~500°C or higher), from which samples $\delta^{18}O$ values would be unreliable (Munro et al., 2007; Harbeck et al., 2011; Snoeck, 2014; Grupe et al., 2018).

The application of stable isotope analysis to collagen from burned bones has had an uncertain past. In 1971, when Longin proposed his new method of collagen extraction he advocated the use of "partially burned bones", though no accompanying information was provided to indicate the temperature range associated with partial burning (Longin, 1971). In an investigation of Hopewell agriculture, Bender and colleagues were able to obtain isotope data from "charred" bone, though only $\delta^{13}C$ values were evaluated (Bender et al., 1981). In 1983, when discussing techniques for measuring carbon isotopes from bone collagen Chisholm and colleagues mention briefly that analyses of burned bones yield "non-reproducible" results (Chisholm et al., 1983). However, not until 1985 was there a study that specifically investigated the influence of burning on the isotope ratios of bone collagen (DeNiro et al., 1985). This study was then referenced by researchers to explain anomalous isotope results among samples that had been burned (DeNiro, 1985; Ambrose, 1991). Most researchers investigating diet through stable isotope analysis simply omitted any samples of burned bone or avoided cultures where cremation was the main funerary practice (Schurr et al., 2008). However, more recent research has investigated the potential for isotope analysis from bones exposed to lower temperatures to determine if collagen preservation is sufficient for dietary reconstruction (Schurr and Hayes, 2008; Schurr et al., 2008). Further research investigated whether isotope ratios and collagen quality indicators could be used as a proxy measurement for DNA preservation in burned bones (Harbeck et al., 2011). These three more recent studies, as well as the initial study of isotope ratios in burned bones by DeNiro and colleagues are discussed in detail below.

DeNiro and colleagues conducted the first study to evaluate whether heat exposure would affect $\delta^{13}C$ and $\delta^{15}N$ values in 1985. This study consisted of three stages. The first involved a variety of animal bone samples divided into three samples – one was boiled for one hour, one roasted for two hours and the third was a control. Boiled samples averaged a difference of -0.1±0.5‰ for $\delta^{13}C$ and -0.5±0.7‰ for $\delta^{15}N$ compared against untreated controls, while roasted samples averaged a difference of -0.4±0.3‰ for $\delta^{13}C$ and -0.4±0.6‰ for $\delta^{15}N$. The second stage involved heating goat (*Capra* sp.) tali at different temperatures for three hours. During this second stage, $\delta^{13}C$ and $\delta^{15}N$ values were within 1.5‰ at 170°C but showed larger deviations when heated to 295°C or higher. The goat tali were sourced from different individuals, which may explain some of the differences observed. The third stage of the experiment was designed to mitigate the variation caused by using multiple individuals in the second stage; pig (*Sus scrofa*) femora were powdered and homogenized, then heated to 200°C for varying time periods. As time of exposure increased collagen concentrations decreased. However, the atomic ratio of C:N was unchanged for up to four hours of heating; $\delta^{13}C$ and $\delta^{15}N$ values for these samples were within 1.2‰. After six or more hours of heating C:N ratios were no longer conserved and isotope ratios varied by as much as 5‰. The researchers proposed using the C:N ratio as a guide to determine whether isotope ratios represented unaltered *in vivo* values. DeNiro and colleagues suggest that low temperature exposures associated with cooking may not alter isotope ratios significantly but did not recommend the use of bones exposed to higher temperatures, such as those of cremated individuals, for dietary reconstructions (Deniro et al., 1985).

Schurr and Hayes (2008) used samples of cow (*Bos taurus*) bone for a controlled heating experiment. Samples were heated to temperatures between 150°C and 600°C for between 0.5 hours and 5 hours. The majority (17/23) of samples heated to 350°C or less showed C:N ratios that fell within the 2.9-3.6 range indicating acceptable collagen. There was gradual diminishing of organic content up to 350°C, with rapid loss from 400°C, after which extraction yields were too low for isotopic analysis. Isotope ratios of bone samples heated below 200°C for up to five

hours were unaltered, as were those of bone samples heated to 200°C for less than one hour. In bones heated above 200°C $\delta^{15}N$ values increased with increased temperatures (maximum increase of 5‰), while $\delta^{13}C$ values were relatively consistent (ranging from -14.3‰ to -13.0‰). Time was a less significant but important factor in the alteration of $\delta^{15}N$ values. This study also investigated the potential of *g*-values, a measure of free radicals by electron spin resonance (ESR), to determine temperature of heat exposure in bone samples. Unheated modern bone samples did not produce measurable ESR spectra, but bone samples heated to 150°C and above could be analysed. From 150°C to 350°C the *g*-values of burned bone decreased, but at higher temperatures the *g*-value increased. Below 275°C the *g*-values of burned bone varied with exposure times as well as temperature. The *g*-values of demineralized collagen extracts followed a more predictable pattern: constant up to 275°C, then declining with increased temperature exposure. The correlation between *g*-values and $\delta^{15}N$ values was used to create a regression equation for the reconstruction of original $\delta^{15}N$ values of burned bones. Schurr and Hayes (2008) also tested archaeological specimens from three sites: Angel site, Indiana; Yokem Site, Illinois and the Pete Klunk mound group, Illinois. The three sites ranged in age from the Late Archaic period (c. 1500 BP) to the Middle Mississipian (c. AD 1400). The samples taken ranged from seemingly unaffected through calcined. The $\delta^{15}N$ values followed the experimental pattern, with burned samples yielded higher values relative to unburned samples. However, *g*-value reconstructions of $\delta^{15}N$ values from archaeological burned bones were unsuccessful. Unexpectedly, $\delta^{13}C$ values of charred bones were lower than uncharred samples; these values were accompanied by C:N ratios indicative of humate contamination in the samples. Schurr and Hayes proposed that samples from burned bones might be able to show large dietary differences but that the smaller dietary variations expected within a population would be obscured by temperature-related changes to $\delta^{13}C$ and $\delta^{15}N$ values (Schurr and Hayes, 2008).

Schurr and colleagues (2008) published another controlled heating experiment using cow (*Bos taurus*) bones. The bones were heated at intervals between 150°C and 600°C for a period of 0.5 hours and 3 hours. The researchers

observed weight loss, carbon and nitrogen content and $\delta^{13}C$ and $\delta^{15}N$ values. They found weight loss, %C, %N, and extraction yields were highly dependent on temperature, but less influenced by time. Isotope ratios of carbon and nitrogen were unaltered below 200°C with slight changes observed up to 350°C. At temperatures above 200°C, $\delta^{15}N$ values increased with increased temperature relatively independent of exposure time. In comparison $\delta^{13}C$ values showed no systematic change with increased temperature or time but values became increasingly scattered around the control value. Archaeological specimens discussed in this paper were the same samples reported in the previous publication discussed above (Schurr et al., 2008).

Harbeck and colleagues (2011) conducted a controlled heating experiment investigating the change in isotope ratios and the preservation of DNA in the tibiae of cattle heated from 100°C to 1000°C for up to four hours. Colour analysis, histological observations, UV-fluorescence, X-ray diffraction, thermogravimetric, and differential thermal analysis were conducted on these samples to determine if these methods could provide sufficiently specific temperature estimations to provide a model for samples exposed to unknown temperatures. Bone heated up to 200°C retained a viable C:N molar ratio, but this ratio fell below 2.9 above 200°C and continued to fall with increased temperature exposure. Both the $\delta^{13}C$ and $\delta^{15}N$ values were consistent up to 200°C, then decreased with increasing temperatures above this threshold, with the most significant change occurring between 300°C and 400°C. As mentioned above, this study also involved the analysis of $\delta^{13}C$ and $\delta^{18}O$ from carbonate, which followed a similar pattern to the $\delta^{13}C$ and $\delta^{15}N$ values from collagen, and analysis of $^{87}Sr/^{86}Sr$ from apatite; this value was unaffected throughout the experiment. Amplifiable DNA was obtained from samples heated up to 600°C. The additional observations conducted were able to separate burned bones into three broad temperature ranges: I – up to 300°C, II – below 600°C, and III – above 600°C. However, at 300°C the stable isotope ratios observed in this study would already be altered from their biogenic values; therefore, Harbeck and colleagues recommend that these analyses only be conducted on bone that shows an unaltered or brown colouration of the exterior surface or an unaltered light blue UV-

fluorescence. This experiment also involved the assessment of histological appearance, UV-fluorescence, and stable isotope analysis from ten modern cremated individuals with known DNA preservation. Though retention of unburned samples from these individuals was precluded by ethical considerations, one individual had an unburned femoral sample taken during autopsy and this sample was observed as a control. The DNA amplified from the cremation of this individual did not match the femoral sample, suggesting there may be a high risk of contamination when obtaining remains from a modern crematorium (Harbeck et al., 2011).

These four studies do not agree regarding patterns of change in stable isotope ratios that occur in bone collagen extracted from bones that have been exposed to heat. However, one finding was consistent among the four studies: there is a threshold temperature below which isotope ratios retain their original values. This temperature threshold is approximately 200°C. The implication is that isotopic dietary reconstructions may be possible from archaeologically cremated remains, if temperature estimations can effectively determine that the bone samples used for analysis have only been exposed to low temperatures. As discussed in Chapter 3, archaeological cremations have been measured in excess of 1000°C, but temperatures are inconsistent throughout the body. Therefore, it may be possible to select samples from bones that have been largely shielded from the heat of the pyre - by overlying flesh, clothing, or pyre goods – or bones that have fallen through the pyre into the underlying ash before becoming calcined – such as the small bones of the hands and feet (McKinley, 1989). This does however raise the issue of determining whether bone has been heated to above 200°C. Most of the initial changes associated with cremation take place at around 300°C. However, there has been some research into the efficacy of FTIR analysis in recording the effect of heating on the organic portion of bone, including lower temperature effects (Ellingham et al., 2015b).

4.9: Isotopic Diet Reconstructions on Anglo-Saxon Populations

This project involves the $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ analysis of bone collagen from Anglo-Saxon individuals. As such, it is necessary to understand the previous research that has been done in this area to contextualise the isotope data presented in chapter 7. Several dietary reconstructions have been conducted on individuals excavated from early Anglo-Saxon sites. Thus far all of these reconstructions have been based on carbon and nitrogen isotope ratios; no attempts at sulphur isotope analysis have yet been published on an Anglo-Saxon population. The picture of the early Anglo-Saxon diet that can be inferred using $\delta^{13}C$ and $\delta^{15}N$ values is an homogenous one, see figure 4.12. Generally, early Anglo-Saxon individuals show $\delta^{13}C$ values that indicate the consumption of C_3 terrestrial plants and herbivores. The $\delta^{15}N$ values are typically slightly elevated above what would be explained by terrestrial plants and herbivores alone, suggesting the consumption of freshwater fish, water birds, or omnivores, such as pigs (Privat et al., 2002; Lucy et al., 2009; Mays and Beavan, 2012; Hannah et al., 2018). The consumption of significant amounts of marine protein is precluded by the $\delta^{13}C$ values. At the cemetery site of Wally Corner, Berinsfield dated to the mid-5th to early 7th centuries several faunal samples were analysed to provide a baseline for human isotope analysis. Only one pig *(Sus scrofa*) sample was available for analysis, but this sample produced a distinctly herbivorous $\delta^{15}N$ value (6.0‰) (Privat et al., 2002). Faunal data from St. Giles, a rural hospital site c. 12th-15th centuries, and from Wharram Percy, a rural parish c. 10th-16th centuries, show pig $\delta^{15}N$ values ranging from 6.2‰ to 9.7‰ (Müldner and Richards, 2005). Though the data available indicates that pigs were largely being raised on herbivorous diets, the sample size is small and from a significantly later time period than the focus of this study. Further data would help to determine whether this is a true pattern or the result of a selection bias. Thus, the range of $\delta^{15}N$ values found among early Anglo-Saxon communities may be the result of the incorporation of either omnivore protein or freshwater fish and/or water birds into a subsistence strategy based largely on domestic animals and plants; $\delta^{34}S$ analysis may help to clarify this picture in future.

Attempts to correlate isotope data with sex, age, or status indicators have largely failed (Privat et al., 2002; Mays and Beavan, 2012; Hannah et al., 2018). There are no dietary differences between males and females that can be distinguished through the analysis of carbon and nitrogen isotopes (Privat et al., 2002; Lucy et al., 2009; Mays and Beavan, 2012; Hannah et al., 2018). There have been some weak trends relating $\delta^{15}N$ values to age, with younger individuals tending to be enriched in ^{15}N relative to adults (Privat et al., 2002; Hannah et al., 2018). The highest $\delta^{15}N$ values tend to be found among the youngest individuals; this may be a residual weaning signature, with slow turn-over rates in bone collagen preserving the elevated breastmilk signature (Privat et al., 2002). In a weaning study at Queenford Farm, 4th to 6th century AD cemetery site in the Upper Thames Valley, $\delta^{15}N$ values indicated that most non-adults were fully weaned around 3-4 years of age, though some may have been breastfed up until 5.5 years (Fuller et al., 2006b). Alternatively, ^{15}N enrichment has also been correlated with nutritional stress or pathology, which may explain the elevated $\delta^{15}N$ values in younger individuals (Hannah et al., 2018). Ideally, this could be determined using incremental dentine to determine whether the ^{15}N enrichment was found throughout the population during their youth suggesting a weaning signature, or if this enrichment could be correlated with non-survivors suggesting stress (Beaumont et al., 2015). The correlation of diet with geographic differences has been slightly more successful. In a survey of multiple early Anglo-Saxon sites, Mays and Beavan found that coastal sites showed the highest $\delta^{13}C$ values (mean -19.8‰, versus inland -20.3‰, and riverine -20.7‰) while sites located near major rivers showed the highest $\delta^{15}N$ values (mean 10.3‰, versus coastal 9.6‰, inland 9.5‰) (Mays and Beavan, 2012).

This data evokes an egalitarian picture of early Anglo-Saxon subsistence. However, the indications from literary sources and mortuary archaeology are of a highly stratified society (Lucy, 2000). Likely there was differential access to foods that were considered high status, but this may not have produced any isotopically observable differences among those who ate them. Status may have been conferred on specific cuts of meat, with the remaining protein available to lower-status

individuals, or, status may have been associated with meat but not secondary products such as milk, eggs, or cheese (Privat et al., 2002; Hannah et al., 2018).

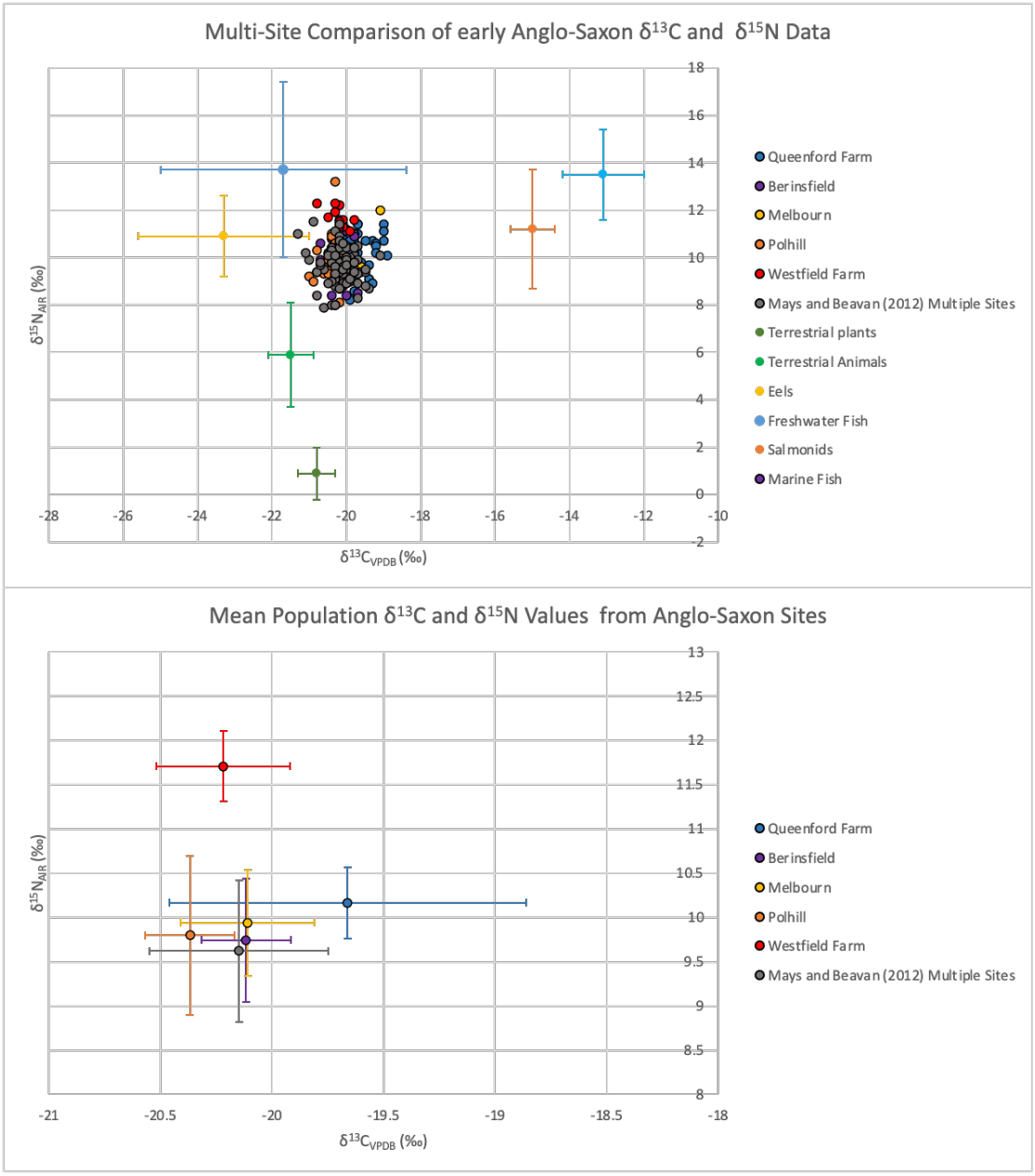


Figure 4.12: Above: Figure shows individual data points from Anglo-Saxon sites plotted against floral and faunal ranges for UK food sources from Mays and Beavan (2012). Food source data points represent a mean value, error bars cover one standard deviation. Queenford Farm (4th-6th centuries, Oxfordshire) data reproduced from Fuller et al., 2006b. Berinsfield (5th-7th centuries, Oxfordshire) data reproduced from Privat et al., 2002. Melbourn (6th-7th centuries, Cambridgeshire) and Polhill (7th-8th centuries, Kent) data reproduced from Hannah et al., 2018. Westfield Farm (7th century, Cambridgeshire) data reproduced from Lucy et al., 2009. Mays and Beavan (2012) investigated 18 different sites (5th-7th centuries), presented here as one population for clarity. All included individuals were adults. Below: Human data presented alone. Data points represent the mean population value, error bars cover one standard deviation.

4.10: Summary

This chapter provided background information on isotope analysis as used for dietary reconstruction. The basic ideas behind isotope analysis were presented in the introduction, followed by a discussion of the materials used in analysis including the quality indicators that are used to ensure that isotope analyses are valid. Specific discussion of the discovery, reservoirs, and cycling of carbon, nitrogen, and sulphur was provided to explain the origin of the ratios observed in isotope analyses. There was then a discussion of how these ratios can be compared and contrasted to model the diets of past populations. The issue of collagen preservation in the event of burning events was then discussed, with the conclusion that isotope analysis from collagen may be possible provided the samples have only experienced low temperatures. Finally, a summary of the isotope research currently available for Anglo-Saxon populations was provided as context for this research.

Chapter 5: Materials and Methods:

5.1 Introduction:

The primary aim of this experiment is to investigate the potential of light stable isotope analysis applied to burned bone. In order to achieve this, two phases of experimentation were designed: a controlled heating experiment and an archaeological application. Section 5.2 will explain the materials used for the controlled heating experiment and discuss the reasoning behind the selection of these materials. Section 5.3 will outline the methods used in the controlled heating experiment. Section 5.4 will provide the background context of the samples used in the archaeological application and section 5.5 will outline the methods used for this application.

The first stage of the experiment explores the temperature threshold for the conservation of biogenic carbon ($\delta^{13}C$), nitrogen ($\delta^{15}N$), and sulphur ($\delta^{34}S$) values obtained from bone collagen. DeNiro and colleagues explored the detrimental effect of heat exposure on the collagen content of bone (1985). As collagen melts at approximately 60°C the effect of heat on collagen preservation is unsurprising; however, the mineralized collagen of the bone matrix is more resistant to heat (Holden et al., 1995). More recent research suggests that collagen extraction sufficient for isotope analysis is possible from bones heated up to 300°C, but that the values of $\delta^{13}C$ and $\delta^{15}N$ are altered above 200°C (Schurr and Hayes, 2008; Schurr et al., 2008; Harbeck et al., 2011). The purpose of the controlled heating experiment presented here is to confirm the temperature threshold for conservation of $\delta^{13}C$ and $\delta^{15}N$ values, assumed to be approximately 200°C, and to determine if a similar threshold exists for $\delta^{34}S$ values.

Additionally, this experiment seeks to determine whether these analyses would be applicable to archaeological cremated bone that has been exposed to unknown burning events. Thus, indicators of burning intensity were recorded and compared against indicators of collagen quality during the controlled heating

experiment. Two measurements of burning intensity were taken: bone colour was used as a broad temperature indicator and FTIR spectroscopy was used to produce absorption spectra that more precisely indicate thermal exposure. These measurements were then correlated with collagen quality indicators: collagen yield, %C, %N, %S, C:N ratio, C:S ratio, and N:S ratio. These observations provide a model for changes due to heat exposure that can be used in the archaeological application phase to estimate the thermal history of archaeologically cremated bone.

The archaeological application stage of the experiment will apply the techniques developed in the experimental stage to bone samples taken from individuals interred at Cleatham and Elsham Anglo-Saxon cemeteries. Samples were taken from both cremated and inhumed individuals to determine whether these two groups represent isotopically distinct populations. Among the cremated individuals, samples that appeared to have been exposed to lower temperatures were selected. These samples were then analysed by colour and absorption spectra to estimate the specific temperatures they had been exposed to in the past. Collagen was then extracted from bone samples taken from both cremated and inhumed individuals for $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ analyses. Collagen quality indicators and FTIR results were used to determine whether these isotope ratios reflect biogenic values or whether they have been compromised by thermal or diagenetic processes.

5.2 Controlled Heating Experiment - Materials:

Cow (*Bos taurus*) bone was used as a proxy for human bone for this experiment. Research into animal bone proxies has suggested that dogs (*Canis familiaris*), pigs (*Sus scrofa*), sheep (*Ovis aries*), and cattle have bone composition similar to humans, with dogs having bone composition that is most similar to human. Dog bone was deemed impractical for this experiment, as these animals would only be available after natural deaths. Animal tissues derived from natural deaths pose greater health and safety risks than those killed and butchered under controlled agricultural conditions. Further, the possibility of pathology-related variation among

samples would be increased in these animals. Of the commercially available proxies pig closely resembles human bone in bone particle density, but samples produced significantly higher levels of extractable proteins (Aerssens et al., 1998). Higher levels of extractable proteins may bias the results toward collagen preservation; thus, pigs were considered inappropriate for this study. Cattle bones had the lowest level of extractable proteins among the animal proxies, though still higher than human levels (Aerssens et al., 1998). Therefore, cattle were selected as the most appropriate substitute for human bone.

This experiment focused on changes in cortical bone only. To obtain relatively uniform samples of cortical bone, humeri were selected as the source material. The humeri were obtained from a local butcher and all material complied with food safety standards, reducing the risk of contamination and easing disposal of wastes. The humeri provided were cleaned of overlying flesh by the butcher. Two humeri were prepped to provide samples, but only one was used as this humerus provided sufficient tissue for the intended analysis. The second humerus was frozen and retained in the event that further samples were required.

5.3 Controlled Heating Experiment - Methods:

5.3.1 Sample Preparation:

The humeri were frozen to minimise heat exposure from the saw during sectioning. For safety and to prevent movement, bones were clamped in place while sectioned. All cutting was done within a disposable containment unit in order to ensure all animal waste tissue was removed from the laboratory. The epiphyses were removed with a hacksaw and discarded. The diaphysis was split lengthwise with a hacksaw to produce two halves. These halves were allowed to thaw and marrow was scraped from the endosteal surface of the bone. Remnants of overlying flesh were removed with a scalpel, aided by soaking the bone in warm water. No chemical treatments were used to remove blood or fats from the bone. The bone sections were frozen again. The halves prepared above were cut lengthwise with a hacksaw into quarter sections. Then, an electric rotary multi-tool with a rotary saw

attachment was used to cut the bone into sections. Any remnants of trabecular bone were removed, producing sections of diaphyseal cortical bone. Bone sections were cut to a minimum of 3 grams to allow sufficient collagen for $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ analyses. Figure 5.1 shows the steps involved in producing these bone sections. Collagen comprises approximately 21% of fresh bone by weight; however, as methods for collagen isolation are a balance between eliminating all extraneous material and destroying the collagen itself, collagen yields are often closer to 11% from fresh bone samples (van Klinken, 1999; Harbeck et al., 2011; Jacob et al., 2018). Thermal degradation of the samples will further reduce the collagen yields in these samples. While 0.5 grams is considered sufficient for typical $\delta^{13}C$ and $\delta^{15}N$ analyses, sulphur comprises less than 1% of bone collagen, thus requiring larger samples (Mays, 2010; Nehlich, 2015). Furthermore, larger samples were used to allow for the unknown reduction in collagen yields resulting from heat exposure. Bone samples were photographed, weighed, and analysed with a spectrophotometer before heating.

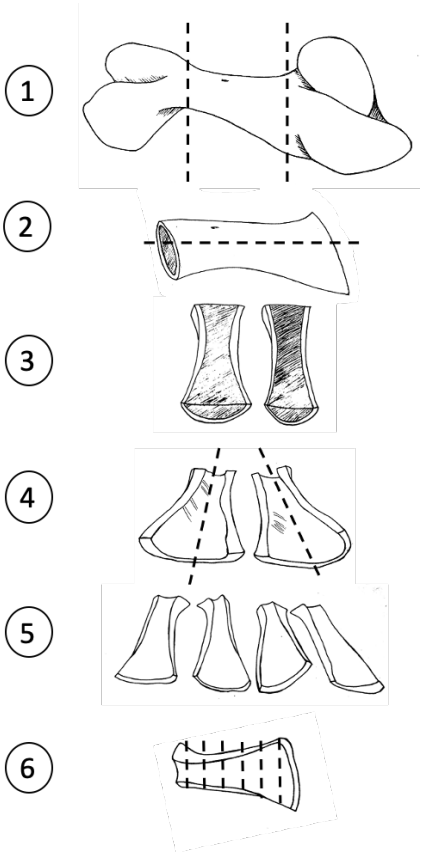


Figure 5.1: Sample preparation. 1) Epiphyses were removed from the bovine humerus. 2) Diaphysis halved lengthwise. 3) Marrow removed from diaphysis halves; figure shows marrow present. 4) Remaining trabecular bone removed. Each half was cut lengthwise to produce four quarter sections as shown in image 5. 6) Each quarter section cut into a sample weighing at least 3 grams. Figure by author.

5.3.2 Heating Experiment:

Samples were placed in heat-resistant ceramic crucibles in a Carbolite AAF 1100 muffle furnace under a fume hood. Both crucibles and furnace were heated above target temperatures prior to the experiment to ensure no contaminants were volatilized during testing. Samples were heated to temperatures of 100°C to 400°C at 50°C increments. This temperature range reflects previous research; lower temperatures should yield unaffected collagen and higher temperatures likely will fail to produce collagen at the extraction stage (DeNiro et al., 1985; Shurr and Hayes, 2008; Schurr et al., 2008; Harbeck et al., 2011). The increments should allow for a narrow definition of the threshold at which isotope ratios are conserved. Natural temperature fluctuation within the furnace precluded increments smaller than 50°C; narrower target temperatures would fail to reflect real differences in sample temperature. The furnace was preheated and run for at least 1 hour to allow temperatures to stabilize before samples were introduced. The samples were removed from the freezer and allowed to reach room temperature before being placed in the furnace. Thawed samples were heated for 0.5 hours, 1 hour, and 2 hours at each target temperature. Three samples were exposed to each target temperature for each length of time, with three samples held as unheated controls yielding a total of 66 samples, as shown in table 5.1. All nine samples for each target temperature were introduced to the furnace together, with three samples removed after 0.5 hours, three more removed after one hour and the final three samples removed after two hours. Trial heating experiments without samples showed that the temperature fluctuations caused by opening the muffle furnace to remove samples were minimal, specific fluctuations recorded during the experiment can be seen in section 6.2. Furthermore, oxygen was introduced to the muffle furnace after each interval due to the opening of the furnace door. Once samples were removed, they were allowed to return to room temperature before being handled. When

cooled, the samples were again weighed, photographed, and analysed with a spectrophotometer.

Table 5.1: Number of samples allocated to each burning condition for a total of 66 experimental samples.

Exposure Time	Temperature (°C)							Total
	100	150	200	250	300	350	400	
0.5 Hours	3 Samples	3 Samples	3 Samples	3 Samples	3 Samples	3 Samples	3 Samples	21 Samples
1 Hour	3 Samples	3 Samples	3 Samples	3 Samples	3 Samples	3 Samples	3 Samples	21 Samples
2 Hours	3 Samples	3 Samples	3 Samples	3 Samples	3 Samples	3 Samples	3 Samples	21 Samples
Total	9 samples	9 samples	9 samples	9 samples	9 samples	9 samples	9 samples	63 Samples
+3 unheated control samples = 66 samples								

5.3.3 Colour Analysis:

A Minolta CM-2600d spectrophotometer was used to analyse the colour of bone samples before and after heating. The spectrophotometer is equipped with a silicon photodiode array detector, a ø52 mm integrating sphere and three pulsed xenon lamp light sources. The repeatability of spectral reflectance is dependent on wavelength, falling within a standard deviation of 0.1% for 380 nm to 740 nm and 0.2% for 360 nm to 380 nm. Colorimetric measurements are repeatable within a standard deviation of ΔE*ab 0.04. Measurements were made under a standard D65 light setting. The D-series illuminants were statistically defined based on measurements of daylight, D65 is an average daylight illuminant with a correlated colour temperature of 6504K that is commonly used in colourimetric analyses (Fairchild, 2013). The ultraviolet illumination was set to 100%. Measurements were taken through a ø3 mm aperture, as established by the CM-A147 target mask, a dust cover (CM-A149) was also used to prevent the friable burned bone samples from contaminating the integrating sphere of the spectrophotometer – for consistency the dust cover was also used for the unburned samples. Illumination was recorded both with specular component included (SCI) and specular component excluded (SCE). The spectrophotometer was calibrated to both a zero standard, open air extending at least one metre, and a white standard, issued by the manufacturer and protected from light exposure by an opaque cover. Measurements were taken using the 2° observer angle, established as a standard observer by the CIE in 1931, in CIE

L*a*b* colour space (Fairchild, 2013). In CIE L*a*b* colour space colour data is represented as a coordinate in three-dimensional space, where L* represents lightness as a value between black (0) and white (100), a* represents the spectrum between red and green, and b* represents the spectrum between yellow and blue. Both a* and b* axes cross through an achromatic grey at the origin. The spectrophotometer also records a measure of reflectance or gloss represented by the letter G. The spectrophotometer was set-up with a delay of 0.3 seconds, to prevent the motion of the trigger button from affecting the measurements taken, and each measurement recorded was the result of five measurements averaged automatically by the spectrophotometer. This average was recorded as a single data point.

The bone samples measured were not uniform in colour. To accurately reflect this variation a number of readings were taken across the bone surface with the viewed surface changed between measurements. To determine the minimum number of measurements needed to characterise a sample thirty measurements were taken on four bone samples. The mean standard deviation of the first five results was calculated, then after each consecutive measurement the mean standard deviation was calculated and plotted. The resulting graph was used to determine how many measurements were required until the mean standard deviation stopped changing. The plateau in data presented in figure 5.2 represents the minimum number of measurements required to reflect the average colour of the sample. For each colour variable the mean standard deviation leveled between fifteen and twenty measurements as can be seen in figure 5.2, thus twenty measurements were considered sufficient to represent the colour of bone samples accurately. This test was initially done with fresh bone and repeated with heated samples. Fresh samples were found to be more variable; therefore, twenty measurements were considered representative of heated samples as well.

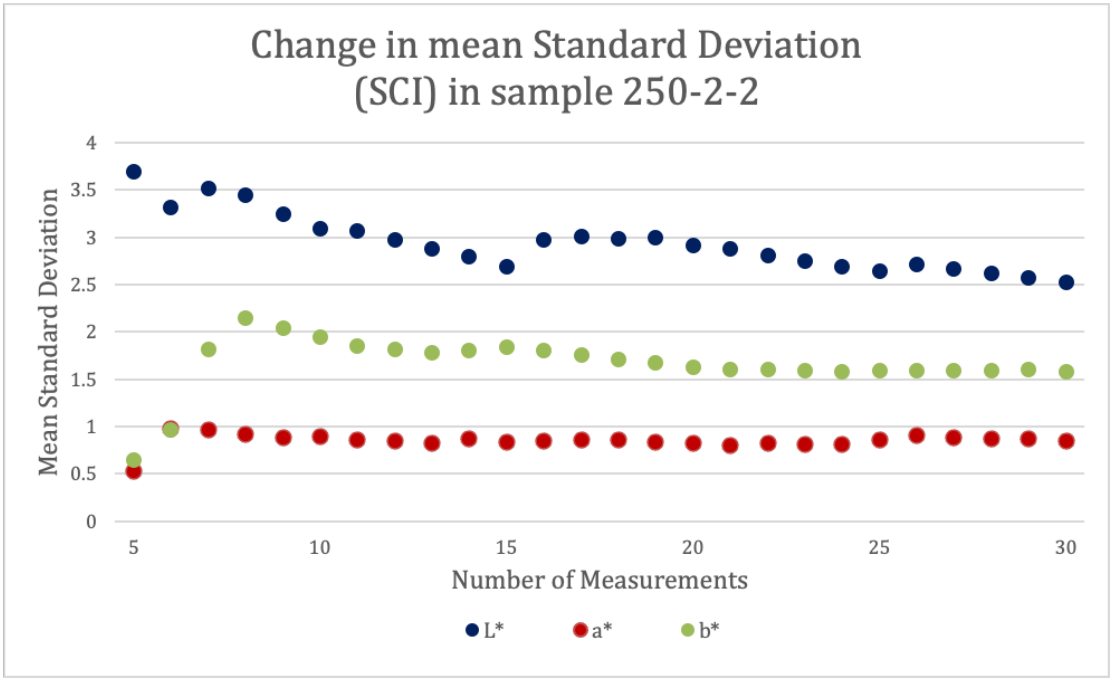


Figure 5.2: Change in mean standard deviations for a sample of fresh bone, sample number 250-2-2. While both SCI and SCE measurements were taken, only the SCI data is presented here.

Spectrophotometers are designed to measure colour on flat surfaces. As such, only the cut surfaces of the bone samples were measured. This also insured that the measurement reflected bone and not remnants of periosteal or endosteal tissue. To provide good contact between the aperture mask and the bone sample the spectrophotometer was supported on an adjustable stand and the irregularly shaped sample was held parallel using an inert glass gravel as a support medium, as seen in figure 5.3.

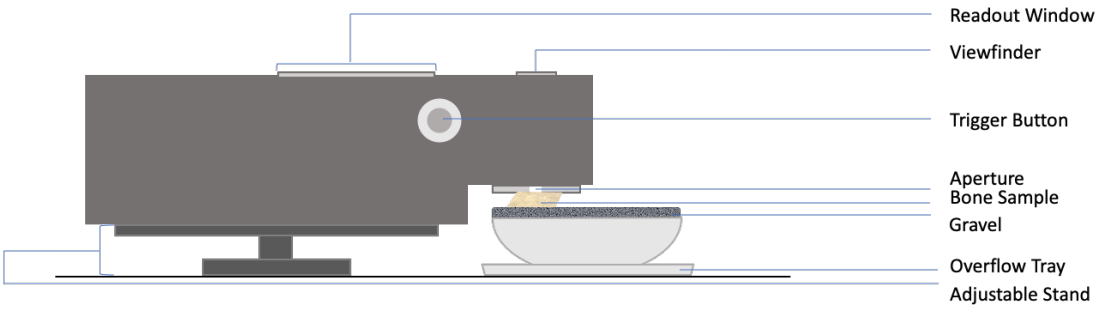


Figure 5.3: Showing the set-up used to measure bone colour by spectrophotometer. An adjustable stand supporting the spectrophotometer and gravel supporting the irregularly shaped bone samples allowed good contact between the aperture mask and the bone sample. Figure by author.

5.3.4 FTIR Spectroscopic Analysis:

Sub-sections were cut from each sample of bone for analysis by FTIR spectroscopy. These were cut using an abrasive disc on an electric rotary multi-tool, then ground to a powder in an agate mortar and pestle. On average the ground samples used in this stage of analysis comprised 0.05 g of bone, though samples of 0.01 g of bone were found to be sufficient to produce reliable FTIR data. FTIR results are influenced by particle size and some researchers suggest sieving samples of ground bone to control for this effect; however, this effect was less significant in bone samples that had been heated (Kontopoulos et al., 2018). Additionally, this effect is less significant when analysing FTIR using an ATR device than when using KBr preparations (Beasley et al., 2014). As such, sieving of the ground bone samples prior to analysis was not conducted in this experiment. A Bruker Alpha FTIR unit was used to produce infrared spectra as controlled and interpreted using OPUS 7.5 software. This software includes an automated atmospheric compensation based on background readings; this feature was used to reduce noise due to water vapour in measured spectra. Readings were taken with an Alpha-P Platinum ATR module accessory equipped with a diamond crystal with an operational range from 50,000 cm^{-1} to 50 cm^{-1}. Measurements were taken in the 2000-400 cm^{-1} range with a resolution of 4 cm^{-1}. Thirty-two scans were averaged to produce each spectrum and each sample was analysed in triplicate.

5.3.4 a) Baseline Correction

Before FTIR spectra can be used for analysis a baseline correction must be conducted to account for artifacts of spectral slope. To determine the baseline spectrum regions of the spectra without features related to the samples were identified: 2000 cm^{-1} to 1725 cm^{-1}, 1375 cm^{-1} to 1275 cm^{-1}, 1225 cm^{-1} to 1150 cm^{-1}, 850 cm^{-1} to 650 cm^{-1}, and 525 cm^{-1} to 400 cm^{-1}. The minima in each of these ranges were identified and plotted. Using Excel, a line of best fit for these minima was generated, this curve was identified as the baseline spectrum. The baseline spectrum for each data set was subtracted from the absorbance spectrum (Essential FTIR, 2021). The corrected spectra were then used for analysis.

5.3.4 b) Modelling Burning Intensity at Low Temperatures

While temperature is an important variable in the alteration of bone during burning events, there are other influential factors such as duration – 'burning intensity' is used to refer collectively to these variables. The crystallinity index (CI) has been used as a measure of burning intensity in past FTIR research on bone (Thompson et al., 2013). However, CI is most effective at modelling burning intensities involving temperatures between 400°C and 700°C. Previous FTIR research on experimentally burned bone has identified seven absorption peak ratios that effectively characterise the change due to temperature exposure. These ratios are CI, CO/P, CO/CO_3, CO_3/P, C/P, PHT and FWHM at 1035 cm^{-1}, defined in section 3.5.5a (Thompson et al., 2013). A linear regression analysis was performed by Ellingham and colleagues to derive a temperature prediction formula from these ratios, seen in figure 5.4 (2015). PHT was found to weaken the prediction model and was excluded; however, one further ratio was included: the carbonyl/carbonate (C/C) ratio at wavenumbers 1455 cm^{-1} and 1415 cm^{-1} respectively (Ellingham et al., 2015b). In order to represent burning intensities involving temperatures below 400°C, models were created by plotting these absorption peak ratios against each other to produce an x-y scatter of the FTIR data from the controlled heating experiment. Comparisons of absorption peak ratios that effectively separated lower and higher burning intensities were identified for use in analysing archaeological bone samples exposed to unknown burning intensities.

5.3.5 Lipid Removal:

Fresh bone samples contain 1-2% lipids. Lipids contain carbon that is isotopically lighter than the carbon in bone collagen and will therefore affect $\delta^{13}C$ measurements. The collagen extraction process does not remove lipids; instead this organic portion accumulates and may account for up to 18% of the extracted collagen unless the lipids are specifically removed (Liden et al., 1995).

Prior to the lipid removal procedure, the bone samples were cut into sections in order to increase surface area to volume ratio; this improves the interaction between the reagents and the sample during both the lipid removal and collagen extraction procedures. The samples were cut, using an abrasion disc on an electric rotary multi-tool. Approximately one gram was tested initially. The remaining sample was retained against insufficient collagen extraction. The sub-sample was then weighed to the nearest milligram to provide an initial weight.

To remove lipids from the samples for this experiment a solution of dichloromethane and methanol in a 3:1 ratio (by volume) was used. The samples in solution were sonicated for 15 minutes, then centrifuged at 3,000 rpm for 10 minutes. The supernatants were reserved for $\delta^{13}C$ analysis of the lipid content of the bone. The bone was washed with the reagent three times; eight milliliters of reagent was used in each instance. Distilled water was then added to the remaining sample and sonicated for 15 minutes. The samples were centrifuged again at 3,000 rpm for 10 minutes and the supernatant discarded. The remaining sample was placed on a heating block at 50°C for 24-48 hours until dry. Samples were weighed again to provide a starting weight for the collagen extraction procedure.

5.3.6 Collagen Extraction:

The collagen extraction procedure followed a modified version of the Longin (1971) method. Samples were demineralized in 0.5 M HCl at 4°C. Bone samples were kept in the solution until soft, with acid changed every 48 hours to maintain a constant pH. The softened bone pseudomorphs were rinsed in ultrapure water until reaching a neutral pH. Demineralization times varied between bone samples. Those that softened first were kept in ultrapure water at 4°C until all samples were completely demineralized. Next, the pseudomorphs were placed in ultrapure water to which HCl was added to obtain a pH 3 solution. This solution was heated to 70°C for 48 hours to denature the collagen. The collagen, in solution, was separated from the substrate using EZEE filters. The solution was then frozen solid before being lyophilized. During lyophilization the water is sublimed from the solid, leaving dry

collagen. The dry collagen was then weighed and compared against the dry bone weight to determine collagen yield. Between 0.3 mg and 0.5 mg of collagen were transferred into tin capsules using tweezers and weighed. The tin capsules were crimped closed and formed into a ball. The balls containing collagen were then analysed by mass spectrometer.

5.3.7 Isotope analysis:

Stable isotope ratios were analysed in the Stable Isotope Biogeochemistry Laboratory (SIBL) at Durham University. A Costech Elemental Analyser (ECS 4010) connected to a Thermo Scientific Delta V Advantage isotope ratio mass spectrometer was used to measure total organic carbon, total nitrogen and stable isotope ratios of the samples of collagen prepared in the previous section; see figure 5.4. Total organic carbon and total nitrogen data were obtained using the internal standard Glutamic Acid, 40.82% C and 9.52% N. Isotopic accuracy of these measurements was monitored through routine analysis of in-house standards, which are calibrated rigorously against international standards (e.g. USGS 40, USGS 24, IAEA 600, IAEA N1, IAEA N2) providing a linear range in $\delta^{13}C$ between -46‰ and 3‰ and in $\delta^{15}N$ between -4.5‰ and 20.4‰. When measured for replicate analyses of international standards, the analytical uncertainty in carbon and nitrogen isotope analysis was routinely ±0.1‰. Analytical uncertainty on replicate sample analysis of the international standards was ±0.1‰ and was <0.2‰ on replicate sample analysis.

For sulphur isotope analysis an equal weight of vanadium pentoxide (V_2O_5) and collagen, between 4 mg and 6 mg each, were added to the tin capsules; this facilitates the combustion process that releases the sulphur from collagen. These capsules were introduced to a Costech Elemental Analyser (ECS 4010) connected to a Thermo Scientific Delta V Plus isotope ratio mass spectrometer for sulphur isotope analysis. Total sulphur was also measured during this process. The accuracy of these measurements was monitored against international standards: IAEA-S-2, IAEA-S-3, IAEA-S-4, IAEA-SO-5, and NBS 127. Replicate analyses of international standards typically yielded an analytical uncertainty for sulphur isotope analysis of <0.2‰.

Carbon isotope ratios, corrected for ^{17}O contributions, were reported in the standard delta (δ) notation in per mille (‰) relative to the Vienna Pee Dee Belemnite (VPDB) standard. Nitrogen and sulphur isotope ratios were reported using the same notation, against the atmospheric nitrogen (AIR) and Vienna Canyon Diablo Troilite (V-CDT) standards respectively.

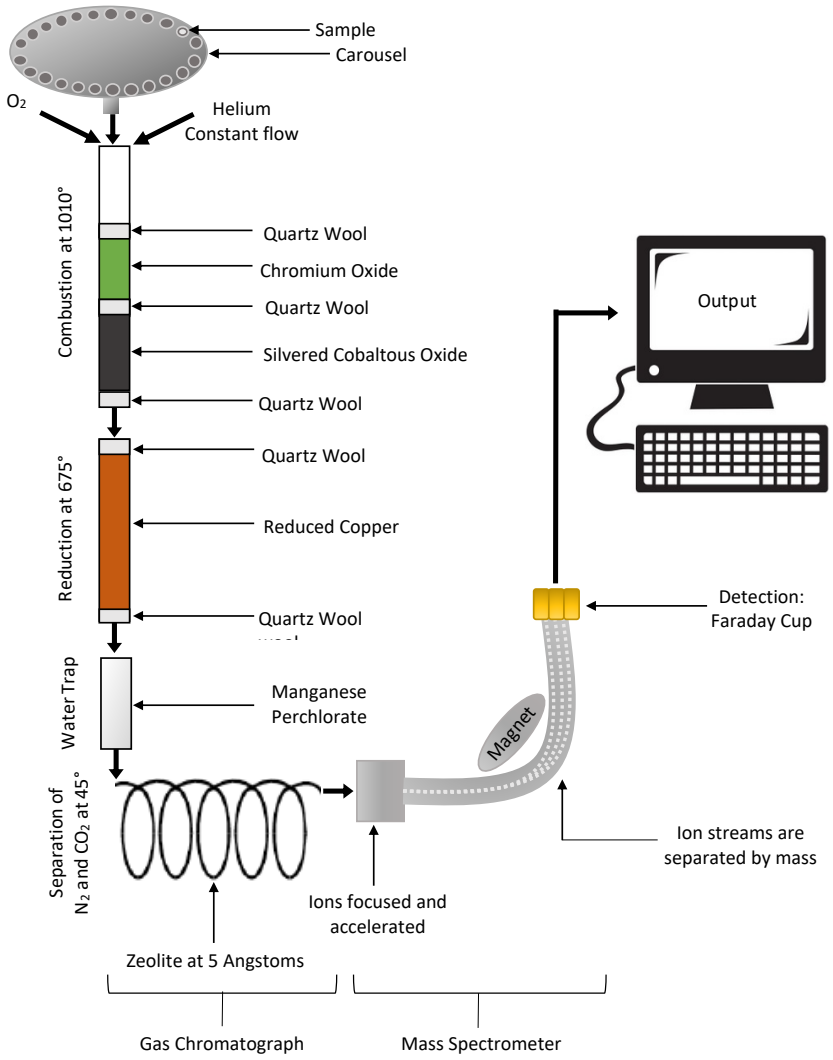


Figure 5.4: Schematic of an elemental analyser and isotope ratio mass spectrometer set-up used to measure total organic carbon, total nitrogen, and stable isotope ratios of solid samples. Samples, bone collagen or reference standards, are wrapped in tin capsules and placed in the carousel. The system is flushed with helium, then the sample and oxygen are injected together, and flash combusted. Reagents scrub extraneous substances during the combustion and reduction phases, leaving only N_2, CO_2 and H_2O gases. The manganese perchlorate acts as a water trap as the gases cool, leaving only N_2 and CO_2. The two remaining gases are separated as they travel through the zeolite, lighter gas molecules moving more quickly through the pores. Finally, a magnet separates the ion streams. The stream of molecules incorporating heavier isotopes is less affected by the electromagnetic pull, while that with lighter isotopes bends further towards the magnet. A faraday cup detects the abundance of each ion. Figure by author.

5.3.8 Statistical Methods:

Statistical comparisons were made using the Kolmogorov-Smirnov test, a non-parametric statistical test that evaluates the greatest difference in the cumulative proportion of two samples. This test is appropriate for assessing differences in continuous or discrete data from two populations and especially suited to small sample sizes. Additionally, the Kolmogorov-Smirnov test does not require the evaluated populations to consist of equal numbers of individuals (Massesy Jr., 1951; Lilliefors, 1967). The Kolmogorov-Smirnov test compares the distribution of two data sets and is considered a powerful nonparametric test for sample sizes smaller than 25 (Field, 2013). The test compares a critical value, calculated using the formula in figure 5.5, against the maximum difference between the cumulative proportions of the two samples. If the maximum difference exceeds the critical value, the null hypothesis is rejected and there is a less than 5% chance that the difference between the two populations could be caused by random chance (Massesy Jr., 1951; Lilliefors, 1967).

$$critical\ value = c(\alpha) * \sqrt{\frac{(N_1 + N_2)}{(N_1 * N_2)}}$$

Figure 5.5: Equation to determine the critical value test statistic for the Kolmogorov-Smirnov test. Where c(α) = the inverse of the Kolmogorov distribution at a significance level α, N_1 = sample one population size, and N_2 = sample two population size. A significance level of 0.05 was used. After Massesy Jr., 1951.

While the Kolmogorov-Smirnov test is powerful, it is susceptible to suggesting significance driven by small sub-sets in the data or by outlying data points (Nachar, 2008; Field, 2013). Thus, a second statistical comparison was made using the Mann-Whitney U test. This is another non-parametric statistical test that compares the medians of two data sets. The Mann-Whitney U test is appropriate for small sample sizes and has a low risk of giving a falsely significant result (Nachar, 2008). The test compares the minimum of two values (U_1, U_2) calculated from the data against tables of critical values (U_{crit}) to determine whether two populations can be considered stochastically equal at a selected statistical threshold (Nachar, 2008). The calculations for U_1 and U_2 are given in figure 5.6. If the smaller of U_1 and U_2 is less than the critical value, then the null hypothesis is rejected and there is a less

than 5% chance that the difference between the two populations is the result of chance (Nachar, 2008). When the population of either data set exceeds 30, the tables of critical values cannot be used. Instead, a *z* value is calculated and compared against a critical value z_{crit} which for a 95% confidence interval is 1.96. The calculation for the *z* value is also given in figure 5.6. If the calculated *z* value exceeds 1.96 the null hypothesis is rejected.

$$U_1 = N_1N_2 + \left(\frac{N_1(N_1+1)}{2}\right) - R_1$$

$$U_2 = N_1N_2 + \left(\frac{N_2(N_2+1)}{2}\right) - R_2$$

$$z_U = \left| \frac{U_{min} - \left(\frac{N_1 * N_2}{2}\right)}{\sqrt{\frac{(N_1 * N_2) * (N_1 + N_2 + 1)}{12}}} \right|$$

Figure 5.6: Equation to determine U_1 and U_2. Where N_1 is equal to the number of observations in the first group and R_1 is equal to the sum of the ranks assigned to the first group. The minimum of U_1 and U_2 is then compared against a test statistic for a significance level α. In the equation for z_U the U_{min} value represents the minimum of U_1 and U_2. After Nachar 2008.

Where the Kolmogorov-Smirnov test indicates a significant difference between data sets and the Mann-Whitney U test disagrees, the data is reviewed. If the difference found by the Kolmogorov-Smirnov test appears to be driven by a specific sub-set, these results are considered a false positive. In no case was significance found by the Mann-Whitney U test and not by the Kolmogorov-Smirnov test.

5.4 Archaeological Application – Materials:

Early Anglo-Saxon mixed rite cemeteries present the ideal test population for the archaeological application of light isotope analysis on cremated remains. By definition, these cemeteries contain contemporaneous cremated and inhumed individuals, a mixture of funerary rites that continues to puzzle archaeologists. Dietary reconstruction of these individuals has the potential to determine whether there were cultural differences among these two groups during their lives that can be correlated with the mortuary ritual that was observed for them in death. Furthermore, previous research into Anglo-Saxon diets, conducted solely on

inhumed individuals, has shown a distinctly homogenous picture; thus, any dietary differences among cremated individuals should be readily apparent. To facilitate sample selection, cemeteries with full osteological analyses available were preferred, though this severely limited the number of suitable sites[3]. However, osteological analyses were available for two large mixed rite cemeteries in North Lincolnshire: Cleatham and Elsham (Squires, 2011). Individuals from these sites were sampled for this experiment. Both of these cemetery sites were located within the early Anglo-Saxon kingdom of Lindsey, a brief context for this kingdom is provided below, section 5.4.1. More specific context is then provided for each cemetery, Cleatham in section 5.4.2 and Elsham in section 5.4.3. Finally, the selected sample is presented in section 5.4.4.

5.4.1 The Kingdom of Lindsey:

The kingdom referred to by historians as Lindsey emerged in the fifth century from the post-Roman re-organisation of Britain. 'Lindsey' is a 12th century term applied retroactively to an area that was referred to as 'Lindissi', 'Lindesse', 'Lindesfari', 'Lindesfaran', 'Lindesig' or 'Lindeseg' in various earlier sources (Green, 2008; Yorke, 1993). All of these terms are derived from the root 'Lindēs' a British Latin word referring to the 'people of Lincoln'. Lincoln is further derived from the British 'Lindon', meaning 'pool', and the Latin 'colonia', referring to a high-status city (Bassett, 1989). Brayford pool laying in the centre of Lincoln, though much reduced in modern times, is the pool for which the city and the kingdom were named (Sawyer, 1998). 'Lindissi' and 'Lindesse' are the terms used by Bede and the Anglo-Saxon Chronicle, both can be translated as 'the people of Lincoln' (Green, 2008). The interesting evidence of all these terms is the persistence of a Romano-British root in the name of an Anglian Kingdom, historians interpret this continuity as evidence of a relatively peaceful transition to Germanic rule in the Kingdom (Leahy, 2007). For

[3] Squires (2012) identified twelve early Anglo-Saxon cemetery sites with associated osteological analyses of the cremated bone assemblages. Of these only five were complete analyses conducted on large assemblages (consisting of more than 200 cremations).

clarity, the term Lindsey will be used to refer to the kingdom in the following discussion.

Lincoln was a provincial capital following the Diocletian division of Roman Britain (Green, 2008). Bishop Adelphius, who presided over the diocese of Lincoln, was documented as attending the Council of Arles in 314 (Green, 2008). Further characterisation of Roman Lincoln and the surrounding area is archaeological in nature. Roads connecting Lincoln to Leicester and to London demonstrate the importance of the city during the Roman period (Eagles, 1989). The fourth century province was prosperous, as evidenced mosaics built in villas throughout the province dated to the fourth century (Leahy, 1993). Extensive fortification at Lincoln, Caistor, and Horncastle indicate that the Romano-British population expected violence. However, evidence of this expectation coming to fruition is uncertain. Coin hoards have been considered indicative of unrest; twenty-one hoards have been discovered in the area and twelve of those were dated to the fourth century. Further, villas at Scampton and Norton Disney were abandoned and show fire damage (Leahy, 1993). Fires, however, may be accidental and coin hoards may lay unrecovered due to instability unrelated to invasion – as evidenced by the nine hoards of Roman coins discovered in the region dating to periods when Britain was firmly under Roman rule. Conversely, evidence of a peaceful introduction of Germanic settlers to the area may be present in the continuity of Romano-British worship, Romano-British pottery evidence, and 5th century British elite items. In Lincoln itself, the fourth century church of St. Paul-in-the-Bail and its sixth century reconstruction, attest to the persistence of Romano-British Christianity in the city. In rural areas, dedications to St. Helen at springs and waterways speak to a similar continuity (Green, 2008). While there may be a dearth of evidence for violent incursions into the area around Lincoln, Britain was certainly under threat during the late fourth and early fifth centuries. Late Roman Britain was subject to raids and embroiled in internal conflicts. There may be some evidence of this unrest in the city of Lincoln itself, where some demolition in the city can be dated to 370 by coins found in the rubble (Sawyer, 1998).

The Anglo-Saxon period kingdom of Lindsey was formed via the amalgamation of tribal groupings around the Humber estuary (Leahy, 2007). Lindsey is defined by the Humber estuary in the North and the North Sea in the East. The Western boundary is formed by the River Trent in the South and the Hatfield Chase marshes in the North. The River Witham and the surrounding fens enclose Lindsay in the South (Leahy 2007).

Archaeological evidence provides only vague information on the early years of the migration period. The paucity of artefacts that can be attributed specifically to a surviving native population exacerbates the issue (Sawyer, 1998). The adaptation of Roman artefacts or workshops cannot definitively be tied to either surviving native populations or early Germanic settlers. Four wheel-thrown pots were found at the Anglo-Saxon cemetery at Cleatham, these Roman productions were repurposed as cinerary urns. Other examples involve the late use of kilns, as seen at Gainsborough with kilns showing evidence of use into the fifth century (Green, 2008). The concentration of British elite items around Lincoln indicates a survival of a native elite in the area. These items include twelve post-Roman Class 1 penannular brooches, as well as fourteen 'celtic' hanging bowls (Green, 2008). The early Germanic archaeological evidence is similarly unclear, with more specific evidence appearing from the sixth century forward. This is largely a problem of interpretation. Archaeological interpretations are more effective with large quantities of artefacts, typological dating of artefacts is more precise and thus the context and sequencing of evidence is more informative (Sawyer, 1998). The most compelling evidence for the immigration of Germanic peoples into the area around Lincoln in the mid-fifth century are the large cremation cemeteries established during this period (Leahy, 1993). There were four large cremation cemeteries in the kingdom of Lindsey: Cleatham, Elsham, South Elkington, and West Keal (Leahy, 1993). Inhumation was the predominant funerary rite practised by Romano-British populations from the later third century; thus, the re-introduction of cremation has traditionally been interpreted as not only evidence Germanic influence but evidence of an ethnically German community (McKinley, 2015; Lucy, 2000). Leahy records

forty-three pagan cemeteries within the Kingdom of Lindsey, where either cremation or furnished inhumation are common practice (1993).

The historical record offers no further information on the kingdom of Lindsey until the seventh century, but efforts have been made to interpolate the intervening history from later sources. Bede provides details on the re-introduction of Christianity to northern England and includes a few specific mentions of Lindsey, based on the accounts of the local bishop, Cynebehrt (Seller, 1907; Foot, 1993). Bede first mentions Lindsey when Bishop Paulinus, under the auspices of King Edwin of Northumbria, converts Blæcca the praefectus of Lincoln circa 627 (Seller, 1907; Eagles, 1989). Paulinus had been sent to England by Augustine in 601 but remained in Kent until 625 (Seller, 1907; Stenton, 1971). Paulinus was then ordained as a bishop and sent to Northumbria to provide spiritual support to Æthelberg; Æthelberg, a Kentish royal, was married to King Edwin of Northumbria. Edwin himself was baptised at York in 627 (Seller, 1907; Stenton, 1971). From this period forward, while Christianity had a toehold in the region, religion in Lindsey followed that of the reigning monarch through successive conquests of Pagan and Christian kings (Foot, 1993). The Tribal Hidage, a list of Anglo-Saxon kingdoms and territories, that survives in an eleventh century document likely compiled from earlier Mercian sources, provides a record of Lindsey (Green, 2011; Blair, 2013). The Kingdom of Lindsey was evaluated with Hatfield Chase at 7,000 hides; equivalent to the kingdoms of Essex or Sussex (Foot, 1993). Hides were an inexact division of territory based on value rather than area, defined as the amount of land required to support a peasant family (Stenton, 1971). The territories listed in the Hidage ranged from 300 through 30,000 hides, though these measures were certainly inexact and likely exaggerated (Stenton, 1971).

None of this documentation is contemporary with the use of either the Cleatham or Elsham cemeteries; however, from the available historical documentation, the Kingdom of Lindsey appears to be a polity of average to large size for the Anglo-Saxon period (Squires, 2011; Stenton, 1971). One that was repeatedly conquered by her neighbours and may never, in fact, have been fully

independent (Bassett, 1989). The subjugation of Lindsey by neighbouring kingdoms has left the impression that Lindsey was relatively under-developed or impoverished. However, excavations at Fiskerton and Flixborough suggest that Lindsey was wealthy in the eighth and ninth centuries while subject to Mercian and Danish rule (Yorke, 1993). Yorke argues that rather than interpreting Lindsey's history of subjugation as evidence of weakness, instead this pattern should be understood as evidence of the desirability of the territory (1993). Under Bede's regional division of Anglo-Saxon period England, Lindsey would fall into the Anglian sphere of control. However, the archaeological evidence is more complicated. The majority of the fifth century metalwork found is Anglian in design, however, Saxon brooches and Frankish elements have also been found (Leahy, 1993). Additionally, there is no evidence of a catastrophic end to the Romano-British population. Instead, there is some evidence that the native population continued to hold power around Lincoln through the fifth century (Leahy, 1993). Taken together, the picture of early Lindsey that emerges is of an average-sized, relatively wealthy kingdom where the ruling class may have been predominantly Anglian, but the population was not homogenous in either ethnicity or cultural identity.

5.4.2: Cleatham

The early Anglo-Saxon cemetery of Cleatham is located in North Lincolnshire at the National Grid Reference SE932008 (Leahy 2007). Though the site falls within Manton parish, the cemetery is actually located on the boundary between Manton and Kirton parishes; 17.9% of Anglo-Saxon cemeteries have been discovered within 100 metres of a parish boundary, including South Elkington and West Keal, both cremation cemeteries that served the Kingdom of Lindsey. The site sits on the crest of a Jurassic limestone escarpment referred to as the 'Lincoln Edge'. The soil profile is comprised of intractable calcareous brown earth over limestone, though in areas the limestone is instead covered in late glacial sand (Leahy, 2007). The soil is described as freely draining, slightly acidic, and sandy by the National Soil Resources Institute (Soilscapes, 2020). The site lies seven kilometres from the River Ancholme, which until the 17th century construction of a sluice, was a tidal creek surrounded by

marshland. The area remains very wet, with small standing pools and areas of bog present during the excavation (Leahy, 2007). The area supports woodlands of pine, oak, and birch, though towards the northern edge there are extensive heathlands (Leahy, 2007). As a township of Manton parish, the land on which Cleatham cemetery sits was valued at 90 shillings in the Domesday Book, recorded as three manors and some sokeland (Leahy, 2007).

The discovery of the Anglo-Saxon cemetery site in 1856 was recorded Edward Trollope, Archdeacon of Stow; he reported the discover of fifty to sixty "Saxon sepulchral urns" on the property of T. B. Richardson, Esquire of Hibaldstow (Leahy, 2007). Bronze artifacts discovered at this time and mistaken for gold resulted in treasure hunting which may have disturbed archaeological features prior to excavation. Edward Peacock presented finds from the site to the Society of Antiquaries in 1893. No further finds were reported until 1978 when Mrs. K.P. Brumby reported the discovery of a large area of broken pottery and burnt bone at Cleatham House Farm. The debris was evaluated in September of 1979 and two small areas were excavated yielding ten urns, but only bases remained for seven of these and the excavators believed that ploughing had already destroyed the site (Leahy, 2007). Kevin Leahy's interest in the Anglo-Saxon period, spurred on by the finds of metal detectorists and forced into action by impending plans for deep ploughing in the area, led to the full excavation of Cleatham cemetery from 1984 to 1989, see site plan in figure 5.7 (Leahy, 2007).

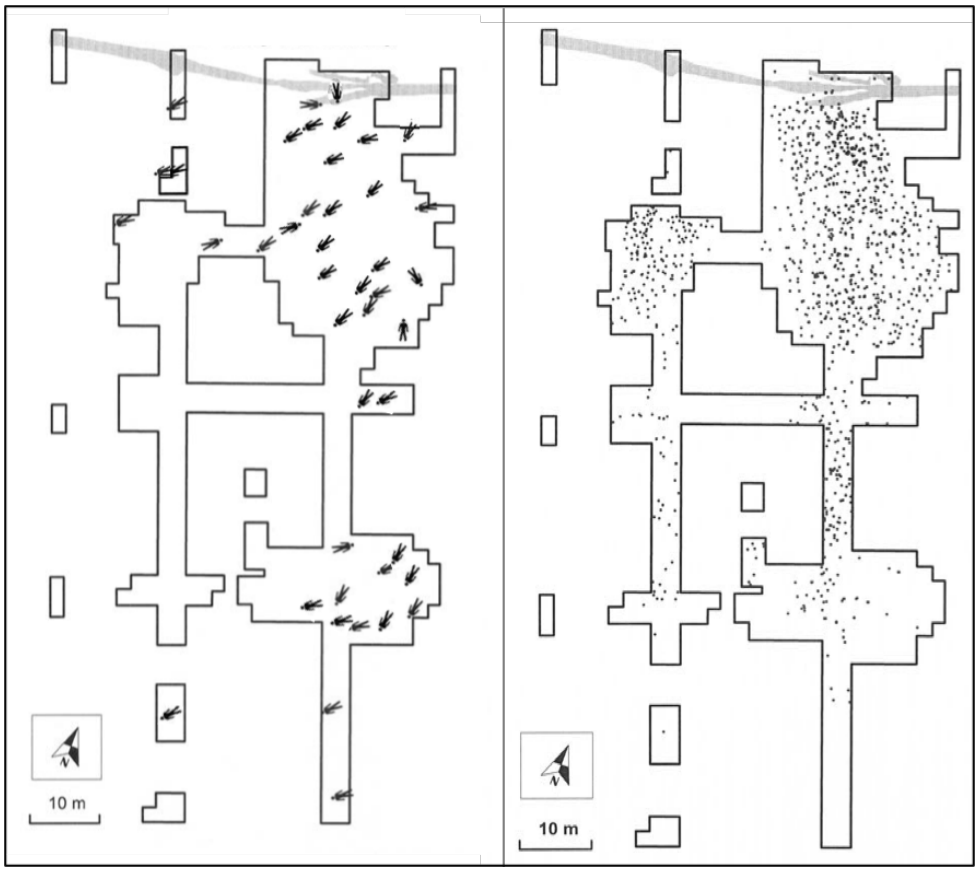


Figure 5.7: Site plan of Cleatham cemetery. Left: Inhumation burials. Right: Cremation burials. Reproduced from Leahy, 2007.

The excavations at Cleatham yielded 1204 urns and 62 inhumations; as the ratio of cremations to inhumations is 19:1, Cleatham is often referred to as a cremation cemetery rather than a mixed rite cemetery (Leahy, 2007). Leahy estimated that 86% of the urns were recovered; the number of cremation burials at Cleatham, including the 50-60 urns from the 1856 excavations and approximately 140 urns from the unexplored area of the cemetery, was estimated at 1400 (2007). In contrast, Leahy estimated that only 51% of the inhumations were recovered, thus a further 66 inhumations may lay undisturbed for a total of 128 inhumations (2007). Stratigraphically the cremations appear to predate the inhumations at the site, but associated finds suggest the two mortuary rites were used concurrently. Cleatham was used as a cemetery from the fifth through seventh centuries, though only eleven graves could be dated to the seventh century or 'final phase' (Leahy, 2007).

5.4.2 a) Cleatham Inhumations

Grave cuts at Cleatham ranged from 20 mm to 950 mm; there was a correlation between grave goods and depth, all graves deeper than 500 mm contained grave goods. No correlations were found between grave depth and sex, age, or date of burial. Stones or masonry were found in the fill of twenty-five graves, but no traces of coffins or post-holes were discovered. The majority of graves were aligned west to east (86°-156°), though alignment was highly variable. No correlations were found between grave alignment and age, sex, or date of burial. Body position could be determined for 55 (89%) burials, see table 5.2 for details (Leahy, 2007).

Table 5.2: Body position of the inhumations at Cleatham cemetery. Data from Leahy, 2007.

Body Position	Number of Individuals	Percentage
Crouched	4	6.5
Extended	28	45.2
Flexed	20	32.3
Prone	3	4.8

Prone burials are often given disproportionate attention by archaeologists due to the assumption that these burials are deviant. However, two of the prone burials at Cleatham do not show any other evidence of deviant burial rites: grave 31 held an adult male equipped with an iron buckle, knife, animal bone, and a spearhead and grave 55 held a young adult female without grave goods (Leahy, 2007). Grave 11, also buried prone, was decapitated and the skull was found two metres away with urn 115; this burial has been tentatively interpreted as a sacrifice killed to accompany the individual interred within urn 115 (Leahy, 2007).

A skeletal report on the inhumations found at Cleatham was produced by Betina Jakob for her MSc at Sheffield University in 1999; a summary of the findings was included in the 2007 published report on the excavation of Cleatham cemetery (Leahy, 2007). Acidic soil conditions, pH ≈ 5.5, at Cleatham resulted in generally poor preservation of the skeletal remains. Two burials, G2 and G39, had no surviving

bone remaining. Thus, the skeletal report is based on a population of 60 individuals for whom some bone was preserved. Of these, sex estimation was possible for 37 (62%) individuals: fifteen females and twenty-two males. The correlation between gendered grave goods and biological sex was generally good. Two individuals had biological sex estimations that contradicted their associated grave goods. Grave 9 was identified as a probable male, aged 45+, due to the poor preservation of the skeletal material the burial was counted as female based on the presence of five rings, a pin, two brooches, a knife and 32 beads in the grave. Grave 17 was identified as a male, aged 18-25, but was accompanied by a plain domestic pot, an annular brooch, a knife and a single bead. The age at death was determined for 47 (78%) individuals, see demographic breakdown in table 5.3 (Leahy, 2007).

Table 5.3: Age and sex data from the inhumation burials at Cleatham cemetery. Data from Leahy, 2007.

Age	Female	Male
Non-adult	10 (16.7%)	
Young Adult (18-25 years)	8 (13.3%) [57.1% of females]	13 (21.7%) [56.5% of males]
Adult (18+ years)	2 (3.3%) [14.3% of females]	2 (3.3%) [8.7% of males]
Mature Adult (25-45 years)	4 (6.7%) [28.4% of females]	4 (6.7%) [17.4% of males]
Old Adult (45+ years)	-	4 (6.7%) [17.4% of males]
Indeterminate	13 (21.7%)	

The sex ratio is slightly unbalanced towards males, but both sexes were primarily dying as 'young adults' (Leahy, 2007). Of perhaps more significance is the under-representation of non-adults among the Cleatham inhumations. Only five (8%) individuals were estimated at less than thirteen years of age and only a single (2%) infant was recovered (Squires, 2012). Leahy proposed that the smaller remains of non-adults may not have survived the acidic burial environment at Cleatham, or that there may have been a preference towards cremation for the youngest

individuals (2007). However, later research by Kirsty Squires did not provide evidence of an abundance of non-adults among the Cleatham cremations (2011).

Stature estimation was possible for ten individuals. The male height ranged from 1.74 m to 1.87 m, and averaged 1.81 m. Only one female individual was sufficiently preserved to allow for stature estimation, her height was estimated at 1.63 m. The figures for both sexes are taller than expected for Anglo-Saxon populations, but these findings are based on a very small sample (Leahy, 2007).

The most common pathology recorded among the Cleatham inhumations was degenerative joint disease, with 21 individuals (5 females, 16 males) showing some indication of degenerative joint changes. The most commonly affected joint was the hip, followed by the spine. The level of degeneration was interpreted as the result of heavy manual labour, such as might be expected for those cultivating land. There were six individuals (1 female, 5 males) with observable fractures. All fractures were well-healed, and none were definitively indicative of inter-personal violence. One individual, an adolescent female buried in grave 20, showed signs of cribra orbitalia; a possible second case was recorded in a young adult female, grave 50. However, only thirteen skulls were recovered with orbits preserved; thus, the numbers are too small for a meaningful interpretation of the data relative to other sites (Leahy, 2007). Generally, this population appears to have been relatively healthy: rates of trauma were not unusually high, few indications of nutritional stress were found, and these individuals appeared to reach their full stature. However, it is important to recognize that the observation of pathology was hindered due to the level of preservation at the site and interpretations of the health status of this population should not be made without due consideration of this limitation (Leahy, 2007).

The association between demographic information and grave goods was considered in two ways. First, sex and age were compared against the total number of finds in a grave. Second, sex and age were compared against the number of types of find within a grave; this second method was adopted to prevent graves with large

numbers of beads from skewing the data. However, the results of the two methods were the same. Females were found with more grave goods and more types of grave goods than males. Mature and old adults were found with more types of grave goods than younger adults, young adults and adolescents (12-18 years) had comparable results and children (1-12 years) were accompanied by the fewest grave goods (Leahy, 2007).

5.4.2 b) Cleatham Cremations

Of the 1204 cremation burials found at Cleatham cemetery only nine were recovered without a containment vessel. Some of the deposits were globular in shape when excavated, suggesting that in place of an urn these cremations may have been buried within an organic bag that did not survive (Leahy, 2007). One further cremation, 'urn' 687, was discovered within an unfired clay envelope. These un-urned cremations do not appear otherwise distinguished from the general population cremated at Cleatham. Four of the nine burials without any preserved container were associated with grave goods and 'urn' 687 held fragments of iron tweezers. The weight of cremated bone in un-urned cremations was lower, median weight of 385 g, than observed in urned cremations, 404 g; however, considering the range of cremation weights this difference is not significant (Squires, 2011). Cremation burials without cinerary urns were also found at Spong Hill (42/2000), at Portway (22/86), and at Loveden Hill – though these last are questionable due to disturbed context (Leahy, 2007). Another unusual discovery at Cleatham was urn 317, an undisturbed urn found without any contents; empty urns were also found at Loveden Hill (Leahy, 2007).

Both cremation and inhumation burials were found throughout the site. Attempts were made to establish an 'horizontal stratigraphy'; identifying nuclei of older burials from which the later burials can be dated by proximity, a strategy that proved successful at Spong Hill but was not possible at Cleatham. However, due to an unusual level of intercutting between cremation burials, Kevin Leahy was able to construct a Harris Matrix of inter-related contexts (2007). Five phases were

established using this method. Urns from discrete contexts were related to these phases by decoration classification, ultimately allowing 605 of 1204 urns to be phased to some extent, see table 5.4 below (Leahy, 2007).

Table 5.4: Total number of urns that were attributed to each of the five Cleatham urn phases. Some urn groups covered more than one phase; these were not included in the 'single phase' totals but were spread across the phrases in the 'across phases' column. Reproduced from Leahy, 2007.

Phase	Urns - Single Phase	Urns – Across Phases
5	45	58.3
4	59	113.7
3	44	102.5
2	95	137.7
1	160	192.5
Total	**403**	**605**

The urns at Cleatham do not appear to be the result of any professional, centralised pottery workshops or craftsmen. Instead, the vessels were likely produced by non-specialists. This assumption is based on the overwhelming proportion of urns of 'average' quality (1701/1204, 90%) and the wide range of fillers or tempers found in the fabric of the urns. Four urns found at Cleatham were wheel-thrown, reminiscent of Roman pottery. However, examinations of these urns suggest that while the production method was Romano-British the forms appear to be Anglo-Saxon (Leahy, 2007).

Most of the urns at Cleatham were decorated, with 61% (732) recorded as having some form of decoration; however, compared against other Anglo-Saxon cemeteries this rate is low (Leahy, 2007). The inter-site average is 77%, based on the eighteen cemeteries studied by Richards for his 1987 study of cremation urns. Despite the prevalence of plain urns, Cleatham does not appear to have been a poor cemetery as a high proportion of grave goods were found associated with the cremations at the site. In fact, burials in plain urns had comparable incidence of grave goods to those in decorated urns; 57% of plain urns held grave goods, while 56% all of the cremations at Cleatham were found with grave goods (Leahy, 2007). Despite the unprecedented phasing of the urns that was possible at Cleatham, no

clear trajectory of urn styles could be established. Some trends in decoration were found, the use of stamps for instance increased over time – with 85% of phase five urns decorated with stamps versus only 21% in phase one. However, no decorations could be linked entirely to a single phase. The most significant trend was the reduction of variation in urn decoration that was seen over time, which may indicate that production of urns was becoming specialised (Leahy, 2007).

Minority burial practises among the cremations at Cleatham included the re-use of domestic vessels, stones in the burial context, deliberate perforation of the cinerary urn, and window urns. Soot was considered evidence that an urn was used as a domestic vessel before burial, thirty-five (2.9%) urns at Cleatham showed this evidence (Leahy, 2007). Stones were found associated with urns in 53 (4%) of the cremation burials at Cleatham, both field stone and dressed Roman masonry were used. Pottery lids have been found at other Anglo-Saxon cremation cemeteries, though none were found at Cleatham, one possibility is that these stones were placed in the burials as lids for the associated urns. Alternatively, the stones may have once been cairns or burial markers (Leahy, 2007). Eighty-one of the urns had been deliberately perforated prior to burial. This represents 10% of the 827 urns that could be classified by shape, size and decoration; a rate that is comparable to Elsham, where 7% were perforated, and to Spong Hill, 10%. In fifteen cases the perforations were then filled with molten lead. A single urn discovered at Cleatham, Urn 433, was fitted with a small glass window, examples of windowed vessels have also been found at Elsham, Loveden Hill, and Spong Hill (Leahy, 2007).

Though Leahy recorded 1204 cremation burials, only 979 deposits of cremated bone were recorded from Cleatham (Squires, 2011). An osteological analysis of these cremations was conducted by Kirsty Squires in 2011 as part of her doctoral thesis. Of the 979 deposits of cremated bone analysed, 969 were found to contain human remains. Forty double burials were identified, of these 27 (67.5%) were comprised of one adult and one non-adult. Thus, the population of cremated individuals buried at Cleatham was established as 1009 (Squires, 2011).

Age was estimated for 856 individuals, though this number falls to 602 individuals when categories more specific than 'adult' and 'non-adult' were used, see table 5.5 below. A high proportion of individuals who were cremated at Cleatham died between the ages of 19-30 years. Among non-adult deaths there was a peak between the ages of zero and four years. Despite this, infants and children were under-represented. Infant mortality in pre-industrial societies has been estimated at 40-50%, at Cleatham only 12% of those assigned to an age category were infants (0-4 years) and only 8% were children (5-12 years) (Squires, 2011).

Table 5.5: Number of cremated individuals assigned to each age category at Cleatham. For 254 individuals age could only broadly be determined as either 'non-adult' or 'adult'. Age could not be assigned at all to 153 individuals. Reproduced from Squires, 2011.

Age Category	Age Range	Number of Ind.	Broad Category	Number of Ind.
Fetus/neonate	Up to 39 wks in utero	3	Non-adult (0-18 years)	359
Infant	0-4 years	99		
Child	5-12 years	71		
Adolescent	13-18 years	54		
Young Adult	19-25 years	164	Adult (19+ years)	497
Younger Mature Adult	26-30 years	185		
Older Mature Adult	31-40 years	23		
Older Adult	41+ years	3		
Total		**602**	**Total**	**856**

Only 30% of the adults at Cleatham retained sexually dimorphic bone markers that allowed for sex estimation. Ninety individuals (18%) were confidently assigned as either male or female, with an additional fifty-seven recorded as either 'probable males' or 'probable females'. Fifty-eight individuals were confidently assigned as female, nearly double the number confidently assigned as male, which was 32. The inclusion of those whose sex could only be estimated as 'probable' re-enforces this sexual disparity with 98 individuals either assigned as 'female' or 'probable female' and only 49 individuals assigned as 'male' or 'probable male'. Though there was a clear sexual disparity at Cleatham, twice as many females were identified as males. As sex could only be estimated for a third of the individuals at Cleatham these data should be interpreted with care (Squires, 2011).

Squires recorded evidence of pathology or non-metric traits in 155 (15%) individuals, as shown in table 5.6 below (2011). The non-metric traits, not strictly pathological, observed included Wormian bones, metopic sutures, enamel extensions, and an acetabular crease. Squires noted that due to time constraints a full assessment of health and disease was not possible for the Cleatham cremations (2011). Periostitis was the most frequently recorded paleopathological condition, evidence was found on 37 individuals, typically on the tibiae and fibulae. Exostoses were found on the bones of 28 individuals, primarily on the calcanei or patellae. Osteophytic growths, found on 17 individuals, were predominantly on vertebrae. A number of individuals suffered from multiple conditions, as seen in the individual from burial MT88AKW who showed osteophytic growth, Schmorl's nodes and degenerative joint disease (Squires, 2011). Two specific conditions were tentatively identified. The individual from burial MT89BBX had destructive and infective lesions on a vertebral body that may indicate tuberculosis, and the individual from burial MT88AHY had several cranial fragments that were abnormally thick that may indicate Paget's disease. However, in both cases there was insufficient evidence for a definitive diagnosis (Squires, 2011).

Table 5.6: Number, crude prevalence rate (CPR) and true prevalence rate (TPR) of paleopathological markers identified on cremated individuals at Cleatham. Reproduced from Squires, 2011.

Pathology	Number of Individuals	Percentage (CPR)	Percentage (TPR)
Periostitis	37	3.67	7.96
Exostosis	28	2.78	23.53
Pronounced Musculoskeletal Markers	28	2.78	2.73
Non-metric trait	18	1.78	1.06
Osteoarthritis	17	1.68	1.23
Osteophytic Growth	17	1.68	1.54
Dental Caries	15	1.49	2.06
Non-specific Infection	11	1.09	1.01
Schmorl's Nodes	8	0.79	1.82
Cribra Orbitalia	5	0.50	0.58
Depressions to the Skull	5	0.50	0.58
Porotic Hyperostosis	5	0.50	0.58
Antemortem Tooth Loss	4	0.40	4.76
Degenerative Disc Disease	4	0.40	0.91
Degenerative Joint Disease	4	0.40	0.76
Cyst	3	0.30	0.35
Dental Abscess	3	0.30	0.32
Periodontal Disease	2	0.20	2.38
Fracture	1	0.10	0.27
Severe Tooth Wear	1	0.10	0.14
Tuberculosis?	1	0.10	0.23
Pagets?	1	0.10	0.12

Animal bone appears to be an important facet of the cremation ritual at Cleatham, as 370 (38%) of the cremation burials included faunal remains. In comparison, only 4 (7%) of the inhumations at Cleatham were accompanied by animal remains. Few of the faunal remains could be identified to species, but bones were found from bears, dogs, hare, pigs, sheep/goats, cattle, horses, and birds. In sixteen burials faunal remains consisted of more than one species (Squires, 2011). One burial, MT89BEC, was accompanied by three species: horse, dogs, and bear. However, if a zooarchaeological assessment is conducted these figures can be expected to increase (Squires, 2011). Nine deposits appear to be accessory vessels, containing animal bone but little or no human bone, although found in context with cremation burials. Four of the accessory deposits contained remains that could be identified by species: three horse and one pig (Squires, 2011). Adults were more commonly accompanied by faunal remains, while only 98 (26%) non-adult individuals were accompanied by faunal remains. More females than males were accompanied by animal bone, but this may be a factor of the disproportionate sex ratio identified at Cleatham (Squires, 2011).

Material representing grave furnishings was found in 625 (65%) burials at Cleatham, while identifiable artefacts were found in 580 (60%) burials (Squires, 2011). The most common artefact identified were combs made of worked bone or antler, found in 288 burials. Beads were also very common, found in 277 burials, examples were found made of glass, crystal, coral, and bone. Artefact types found among the pyre and grave goods at Cleatham are shown in figure 5.8 below along with the number of artefacts found. No clear differences were found in the types of artefacts afforded to non-adult burials versus adult burials, neither were any artefact types clearly associated with biological sex (Squires, 2011).

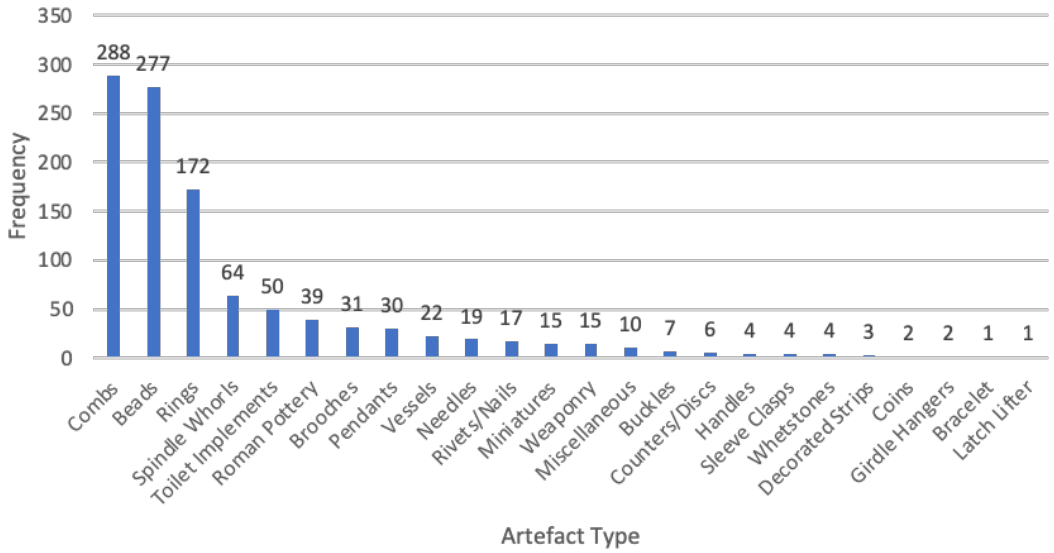


Figure 5.8: Histogram showing the frequency of pyre and grave goods identified at Cleatham from the cremation burials. Reproduced from Squires, 2011.

Cremation weights recorded at Cleatham ranged from 4470 g, in burial MT84GB(b), to 0.5 g, in burial MT84MA. However, burial MT84GB(b) was largely horse bone, the largest human bone deposit was burial MT89BEC, which weighed 3973 g. Of the 977 cremation deposits weighed, only 418 exceeded 500 g, figure 5.9 below shows the distribution of cremation weights at Cleatham (Squires, 2011). There was no association between the recovered weight of burned bone found in a deposit and the biological sex of the individual. There was some association between cremation weight and age, but this would be expected due to body size difference before cremation. The cremated bone deposits were also sieved through compartments with 2 mm, 5 mm, and 10 mm mesh and the resulting accumulation of bone was weighed. Bone fragments collected on the 10 mm sieve accounted for 48% of the burned bone at Cleatham, while 81% was collected by the 10 mm and 5 mm sieves (Squires, 2011). The largest fragment of cremated bone was a proximal fibula diaphysis from burial MT89BJX, which measure 106 mm. The average length of the largest fragment found in the cremation burials at Cleatham was 48 mm (Squires, 2011). Compared against measurements taken from modern crematoria, where the largest fragments were measured at 250 mm, the cremated bones at Cleatham seem to have been subject to disturbance whether during collection, deposition, or excavation that resulted in further fragmentation than can be

explained by heat exposure alone (McKinley, 1994a). However, the maximum fragment size found at Cleatham is comparable to those found at Sancton and Spong Hill, 100 mm and 102 mm respectively (Squires, 2011). The measurements at these cemeteries were not considered indicative of deliberate fragmentation of human remains before burial, instead this fragmentation relates to the brittle nature of cremated bone recovered from dry conditions (McKinley, 1994a).

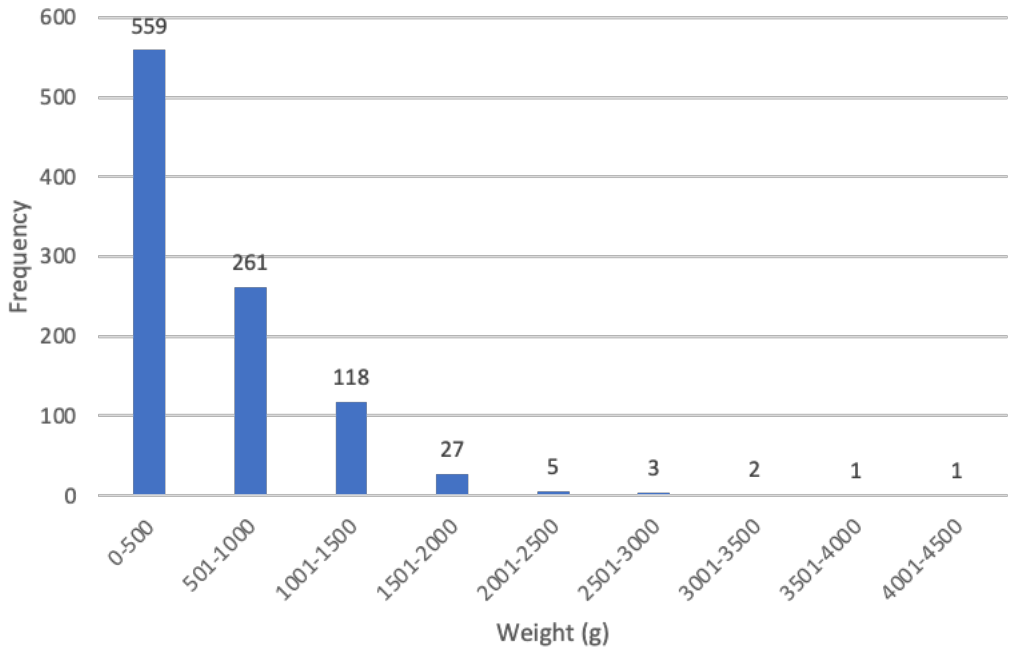


Figure 5.9: Distribution of weights of cremated bone recovered from burials at Cleatham, reproduced from Squires, 2011.

5.4.3: Elsham

The early Anglo-Saxon cemetery Elsham is also located in North Lincolnshire, at the National Grid Reference TA046125 (Squires, 2011). The site falls within the West Lincolnshire Wolds an area of diverse geology dominated by a late Jurassic and Cretaceous period chalk escarpment (Leahy, 2007; Natural England, 2015). The soil at Elsham is freely draining, slightly acidic with a loamy texture (Soilscapes, 2020). Several large cremation cemeteries have been associated with places central to the group identity of Anglo-Saxon communities. Elsham has been associated with Banetby le Wold, a manorial site and soke centre, and with Yarborough Camp, the moot for Yarborough wapentake (Leahy, 2007).

The site was threatened by the construction of the Humber Bridge approach road; thus, a salvage excavation was conducted in 1975 and 1976 by Chris Knowles and Freda Berisford (Squires, 2011). The extent of the cemetery was established, except to the west where a portion of the site extended under Middlegate Lane and could not be recovered. However, several of the urns had been damaged by ploughing prior to excavation (Webster and Cherry, 1977). An excavation report was not published for Elsham but a series of unpublished records exist including a site plan, draft publication of the site report, and a list of finds. A reproduction of the site plan can be seen in figure 5.10 below. An osteological report was also produced by Mary Harman, though in the intervening period the methods and recording techniques used have become out-dated (Squires, 2011).

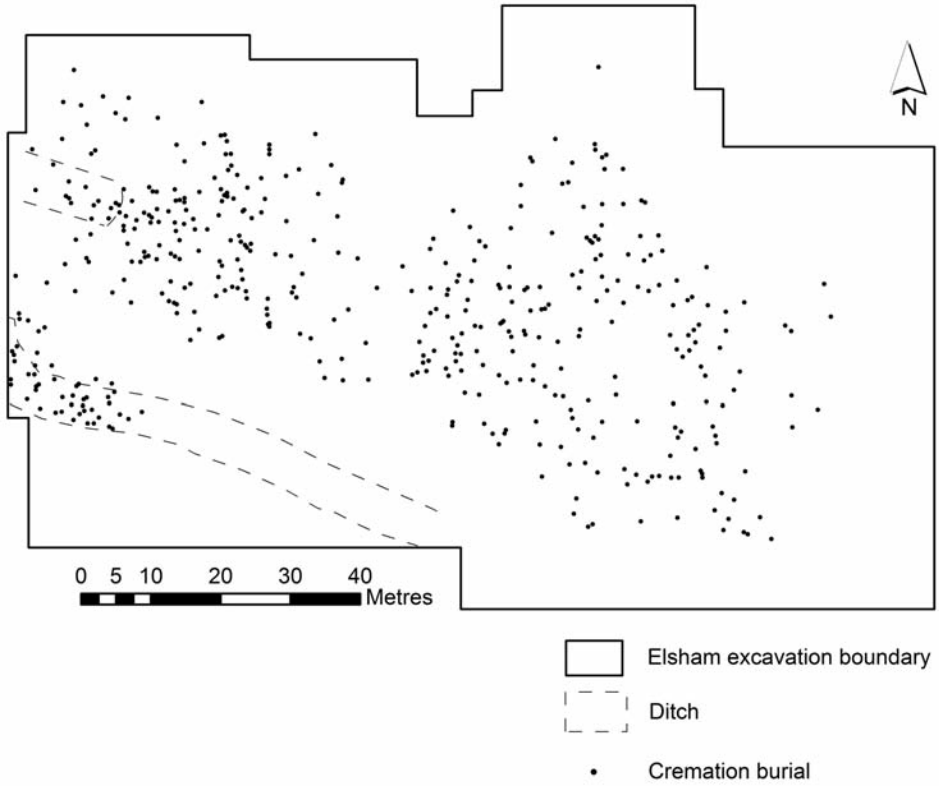


Figure 5.10: Site plan for Elsham cemetery, unfortunately the inhumation burials were not recorded on the original site plan (Squires, 2013, p. 156).

The excavation yielded at least 569 cremation burials, though earlier reports listed 600 cremations (Webster and Cherry, 1977; Squires, 2011). Eight inhumation burials were also discovered at the site, though two of the inhumations were Bronze Age burials (Squires, 2012). The Anglo-Saxon material from Elsham cemetery was dated to the fifth and sixth centuries (Squires, 2013). Similar to Cleatham, the high ratio of cremations to inhumations, 125:1 at Elsham, has resulted in the site being referred to as a cremation cemetery rather than a mixed rite cemetery (Leahy, 2007).

5.4.3 a) Elsham Inhumations

Two of the eight burials at Elsham cemetery, EL75RX and EL75RY, were assigned Bronze Age dates on the basis of an associated beaker vessel and the relationship between these burials and a prehistoric ditch that ran through the south-western corner of the site (Squires, 2011). Seven individuals were recovered from the six Anglo-Saxon period inhumation burials, with EL76JO identified as a double burial, (Squires, 2011). Two of the Anglo-Saxon burials were considered 25-75% complete, while six retained only 25% or less of the original skeletal material. The preservation of the skeletal remains was also very poor, likely due to the wet and acidic soil conditions at Elsham (Squires, 2011).

The Anglo-Saxon remains consisted of five adults and two non-adults. However, due to poor preservation and completeness the sex of only three adults could be estimated: two females and one male, full demographic information is provided in table 5.7 below. Stature estimation was only possible for one individual, an adult of unknown sex, estimated at 1.75-1.76 m tall (Squires, 2011). This height falls within the range of those estimated at Cleatham, who were taller than the average Anglo-Saxon population; however, a single data point cannot be considered representative (Leahy, 2007). Among the inhumations at Elsham, only adult individuals were found to show pathological indicators. Burial EL75EN exhibited the highest number of pathologies including: Schmorl's nodes, osteophytic growth on the vertebral borders, periostitis of the lower limb and two carious lesions (Squires,

2011). Burial EL76JO(a) also displayed extensive pathologies with spinal osteophytosis, increased porosity of the thoracic vertebrae, osteophytic growth on both patellae and several hand phalanges (Squires, 2011). As only three of the inhumation burials were associated with grave goods, statistical analysis is impossible. However, the presence of grave goods with both non-adult burials is interesting (Squires, 2011).

Table 5.7: The demographic attributes, grave goods and pathologies of the Anglo-Saxon inhumations excavated at Elsham cemetery. Reproduced from Squires, 2011.

Inhumation Number	Age Category	Sex	Pathology	Grave Goods
EL75EN	Young Adult (19-25 years)	Female	Schmorl's nodes, osteophytes, periostitis, caries	2 Fe knives, Fe buckle, Cu-alloy needle
EL75RR	Young Adult?/Younger Mature Adult? (19-30 years)	?		None
EL76AK	Adult (19+ years)	?	osteochondritis dissecans	None
EL76AL	Older Mature Adult (31-40 years)	Male	calculus	None
EL76GU	Non-adult (0-18 years)	?		2 Cu-alloy sheet lozenges, glass bead, Fe knife, bone comb fragments
EL76JO(a)	Older Mature Adult (31-40 years)	Female	Osteophytes, porosity of T. vertebrae	Iron buckle
EL76JO(b)	Infant (0-4 years)	?		None

5.4.3 b) Elsham Cremations

Though there are 569 cremation burials catalogued from Elsham, three were missing when Kirsty Squires conducted her osteological analysis in 2009 (Squires, 2012). Of the 566 cremation burials analysed, 552 held human remains. The remaining fourteen cremation burials appear to have been accessory vessels, containing cremated animal bone. Seven double burials, a single triple burial and three probable double burials were identified resulting in an estimation of 564 as the minimum number of individuals (Squires, 2011). As at Cleatham, the most common

combination of individuals in a multiple burial was at least one adult with a non-adult, nine of the multiple burials at Elsham followed this pattern. The single triple burial consisted of one adult male, one adult female and an infant accompanied by grave goods and an animal bone (Squires, 2011).

Age estimation was possible for 491 (87%) of the individuals cremated at Elsham, see table 5.7 below. As at Cleatham the most populated age bracket was between 19-30 years, the 'young adult' and 'younger mature adult' categories. Unlike Cleatham, where the highest proportion of non-adults were dying as infants, there is an even distribution of individuals among the non-adult age categories at Elsham (Squires, 2011). However, there is an under-representation of infants (8%) and children (9%). This trend appears consistent between Anglo-Saxon cremation cemeteries; the average proportion of the population represented by infants has been found to be 10%, children were only found to be slightly higher at 16% (Squires, 2011). Several theories have been proposed to explain the under-representation of infants and children among cemetery populations. The inherent fragility of non-adult remains and the potential that these individuals were buried in shallower graves may have precluded their survival *in situ*. There has also been bias against identification and recovery of infant remains at both excavation and post-excavation analysis. These explanations would apply to both cremated and inhumed individuals in the archaeological record. However, one further theory is proposed that applies specifically to cremations. Non-adult remains may not have been recovered from the pyre site, particularly if cremated with a second individual or an animal (Squires, 2012).

Table 5.8: umber of cremated individuals assigned to each age category at Elsham. For 168 individuals age could only broadly be determined as either 'non-adult' or 'adult'. Age could not be assigned at all to 73 individuals. Reproduced from Squires, 2011.

Age Category	Age Range	Number of Ind.	Broad Category	Number of Ind.
Infant	0-4 years	40	Non-adult (0-18 years)	170
Child	5-12 years	44		
Adolescent	13-18 years	35		
Young Adult	19-25 years	64	Adult (19+ years)	321
Younger Mature Adult	26-30 years	109		
Older Mature Adult	31-40 years	28		
Older Adult	41+ years	3		
	Total	**323**	**Total**	**491**

Biological sex was estimated for 58 individuals at Elsham, representing 18% of the adults at the site. Five of the older adolescents were also assigned a biological sex raising the total to 63 (19%) individuals. Including these older adolescents there were 40 (63%) females and 23 (37%) males. Probable sex was estimated for a further 26 individuals, 15 probable females and 11 probable males, which does not affect the ratio between females and males. The disproportionately high number of females identified among cremated remains has also been found at Cleatham, Sancton, and Spong Hill (Squires, 2011). Whilst these data must be interpreted with caution due to the small proportion of individuals for whom sex could be estimated, the inter-site consistency of the trend is interesting. One proposed theory is that robust sex markers that would indicate biological male sex may be rendered female-appearing due to the shrinkage of bone when exposed to heat; however, the degree of shrinkage observed among the cremated remains at both Cleatham and Elsham was deemed insufficient to support this explanation (Squires, 2011).

Evidence of pathology or non-metric traits were found on the remains of 90 (16%) individuals, as shown in table 5.9. Non-metrics traits were observed on nine individuals and included Wormian bones, metopic sutures, and various cranial foramina. Dental caries was the most common pathology recorded at Elsham, with 28 individuals recorded as suffering from one or more carious lesions – most commonly observed on premolars and molars (Squires, 2011). As at Cleatham, periostitis was a commonly observed condition among the cremated individuals at Elsham, largely affecting the fibulae and tibiae. Osteophytic growth, found on the remains of six individuals, was largely observed on the margins of vertebral bodies (Squires, 2011). The use of these data to infer population health is unwise, as an unknown number of skeletal markers will have been lost before analysis.

Additionally, Squires noted that due to time constraints a full assessment of health and disease was not possible for the Elsham and Cleatham cremations (2011).

Table 5.9: Actual number, crude prevalence rate (CPR) and true prevalence rate (TPR) of paleopathological markers identified on cremated individuals at Elsham. Reproduced from Squires, 2011.

Pathology	Number of Individuals	Percentage (CPR)	Percentage (TPR)
Dental Caries	28	4.96	7.33
Schmorl's Nodes	12	2.13	6.38
Periostitis	12	2.13	3.21
Pronounced Musculoskeletal Markers	9	1.60	2.78
Non-metric trait	9	1.60	1.16
Osteoarthritis	7	1.24	0.74
Osteophytic Growth	6	1.06	4.79
Cribra Orbitalia	5	0.89	0.97
Antemortem Tooth Loss	5	0.89	0.97
Osteoporosis	2	0.35	2.22
Cyst	1	0.18	0.40
Os Acromiale	1	0.18	0.39
Dental Abscess	1	0.18	0.19
Fracture	1	0.18	0.19
Spondylosis	1	0.18	0.53

Forty percent, 227 individuals, of the burials at Elsham cemetery were accompanied by faunal remains. This rate is similar to the early Anglo-Saxon cremation cemeteries at Cleatham (38%), Sancton (40%), and Spong Hill (46%). Though a full zooarchaeological analysis was not undertaken at Elsham, 173 of the recovered remains could be identified to species, with 73 faunal remains unidentified. The species observed included sheep, horse, cattle, pig, bear, bird, dog, crustacean, and fish. Sheep represented the most frequent animal remains found with the cremation burials at Elsham, accounting for 51 of 246 instances. Horse bones were the next most common inclusion, 19% (n=47) of the faunal remains (Squires, 2011). Of the 227 individuals buried with animal remains, sixteen were accompanied by two species of animal. All but three of these burials included horse remains and more than half included sheep remains, further emphasising the importance of these two species. One burial, EL75QQ, was accompanied by three species: horse, cattle, and sheep (Squires, 2011). As mentioned above, fourteen accessory deposits were recovered at Elsham. Eight of these deposits contained horse remains, two of these also included identifiable sheep remains. Two further

accessory deposits contained the remains of large ungulates that may have been either horse or cattle. Age could be estimated for 186 of the 227 individuals buried with faunal remains, of these 138 (74%) were adults while only 48 (26%) were non-adults. Most of the identified species were found with both adults and non-adults, however, bear phalanges were only found with adults and dog remains were only found with non-adults. Though these trends may not be significant as only 6 instances of bear phalanges and only 4 instances of dog bone were identified. As both bear and dog remains were found across age categories at Cleatham cemetery, this trend cannot be verified by inter-site comparison. More females (23) than males (9) were accompanied by animal remains though this may be a factor of the larger number of females identified at Elsham (Squires, 2011).

Pyre and grave goods were considered together at Elsham. Material representing pyre or grave goods was identified from 341 (60%) cremation burials. Identifiable artefacts were discovered with 236 (42%) cremation burials (Squires, 2011). By far the most common artefact found were combs made of worked antler or bone, recovered from 107 burials. Other relatively common artefacts included beads, spindle whorls, and toilet implements. A full breakdown of the artefacts recovered from cremation burials at Elsham can be found below in figure 5.11. Of those buried with recognizable artefacts, age could be estimated for 211 individuals – 148 (70%) adults and 63 (30%) non-adults. While adults were more likely to be accompanied with grave good the types of artefacts afforded to adults versus non-adults could not be clearly distinguished. Biological sex was estimated for 46 of the individuals accompanied by identifiable artefacts: 24 females, 10 probable females, 8 males and 4 probable males. None of the female-specific or male-specific artefacts occurred in sufficient numbers for the pattern of association to be significant (Squires, 2011).

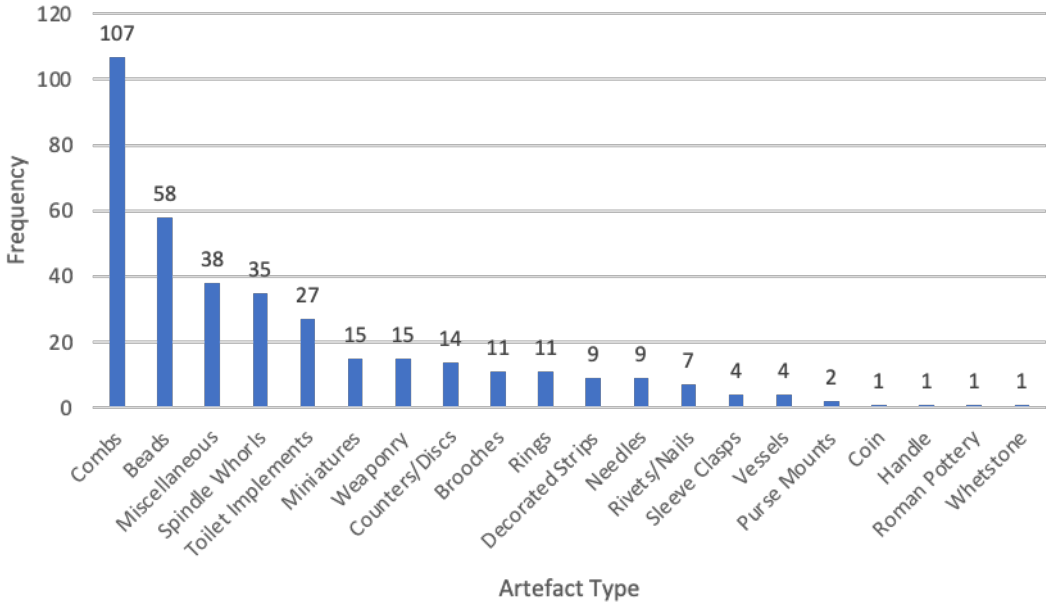


Figure 5.11: Histogram showing the frequency of pyre and grave goods identified at Elsham from the cremation burials. Reproduced from Squires, 2011.

Burial EL75PH weighed 5406 g and was the heaviest cremation recorded at Elsham, though this burial contained three individuals who were accompanied by sheep remains. The smallest quantity of cremated remains was recovered from EL76BJ, which weighed only 0.3 g. The average weight at Elsham was 523 g, while the median weight was 382 g – indicating the skewed distribution of the weight of cremated remains, which can be seen in figure 5.12 below (Squires, 2011). The cremated remains from each deposit were also sieved in the same manner as discussed for the Cleatham cremations. The 10 mm sieve collected 47% of the bone from the cremations at Elsham, while 81% was collected by 5 mm and 10 mm sieves; these percentages are nearly identical to those recorded at Cleatham (Squires, 2011). The maximum fragment size recovered from the cremation burials at Elsham was a femoral fragment that measured 89 mm, while the average maximum fragment size was 43 mm (Squires, 2011). As discussed above, the fragmentation of

these remains indicates some pre- or post-depositional disturbance of the remains but is insufficient to indicate intentional breakage of the remains (McKinley, 1994a).

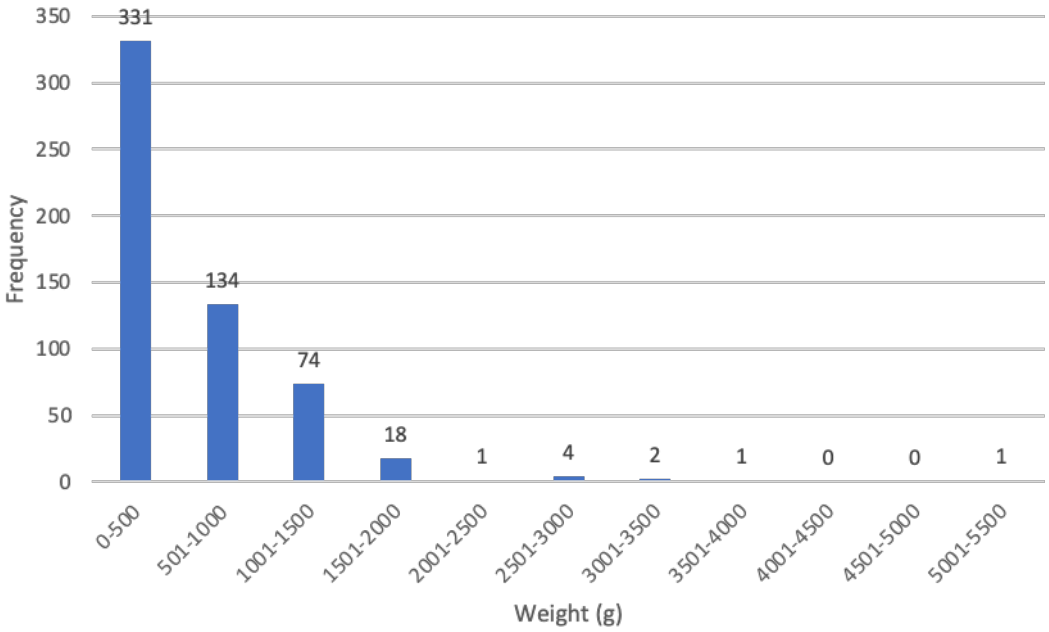
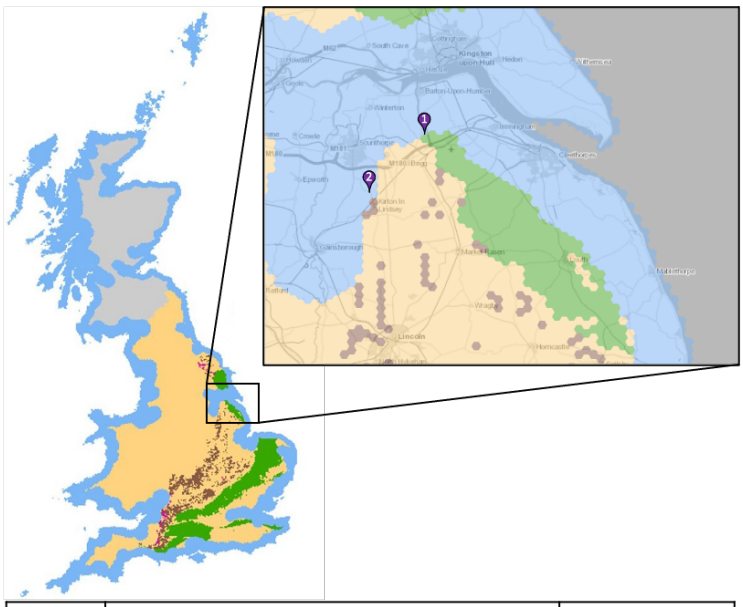


Figure 5.12: Distribution of weights of cremated bone recovered from burials at Elsham cemetery, reproduced from Squires, 2011.

5.4.4: Geochemical Context of Northern Lincolnshire:

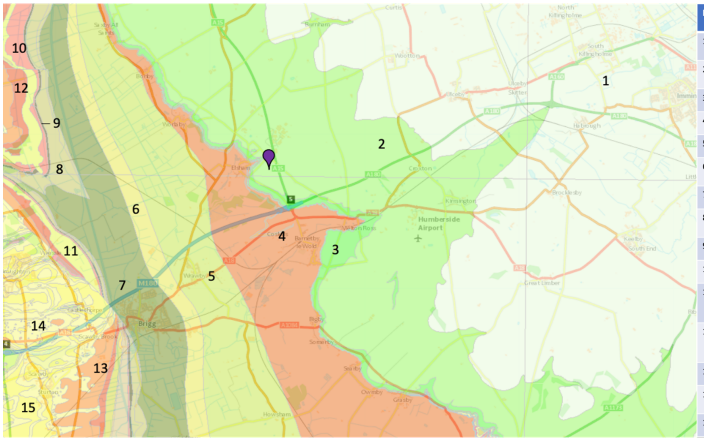
Sulphur isotope ratios of plants and animals, as discussed in section 4.6, reflect the geochemistry of soil and the water table on which they are grown or raised. In order to interpret sulphur isotope data from the biosphere, an understanding of the expected local ranges of geochemical and hydrological $\delta^{34}S$ values is necessary. These contextual data should be bolstered with contemporary local animal $\delta^{34}S$ data, if available. Broadly, $\delta^{34}S$ values in the Britain are expected to fall between -9.3‰ and 21‰ (Evans et al., 2018a). This range is based on modern sampling of vegetation and can be divided into several areas defined by dominant geological substrate or by coastal influence; see figure 5.13.



Colour	Region or Soil Type	$\delta^{34}S$ range (‰)
	Coastal Effects	8 to 21
	Chalk	5.2 to 6.3
	Jurassic Clays	-9.3 to 1.9
	Oolitic Limestone	4.2 to 4.7
	Other Geologic Substrates, England and Wales	2.7 to 5.6
	No Data	-

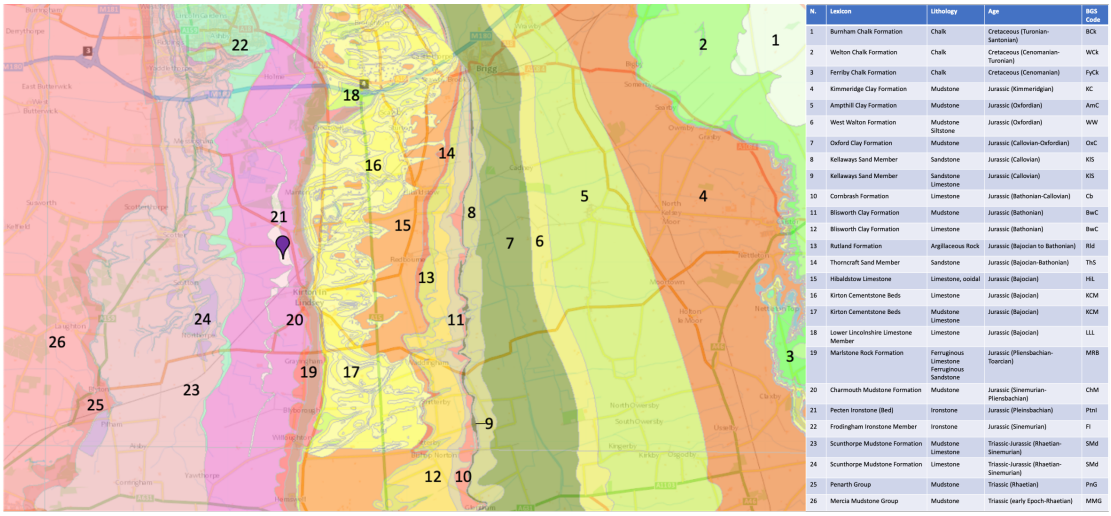
Figure 5.13: Map of English and Welsh sulphur isotope data taken from samples of modern vegetation. Numbered purple flags in the expanded portion of the map indicate sites used in this thesis: 1=Elsham, 2=Cleatham. Data from Evans and colleagues 2018b.

Figure 5.13 provides broad patterns of the geological substrates for large areas. From these broad data ranges Elsham cemetery would be expected to be influenced by the chalk and coastal effect ranges, while Cleatham would be expected to be influenced by coastal effects and the range for 'other' geological substrates. However, these broad patterns fail to capture detailed geological information, which are provided for the area around Elsham in figure 5.14 and around Cleatham in figure 5.15.



N.	Lexicon	Lithology	Age	BGS Code
1	Burnham Chalk Formation	Chalk	Cretaceous (Turonian-Santonian)	BCk
2	Welton Chalk Formation	Chalk	Cretaceous (Cenomanian-Turonian)	WCk
3	Ferriby Chalk Formation	Chalk	Cretaceous (Cenomanian)	FyCk
4	Kimmeridge Clay Formation	Mudstone	Jurassic (Kimmeridgian)	KC
5	Ampthill Clay Formation	Mudstone	Jurassic (Oxfordian)	AmC
6	West Walton Formation	Mudstone Siltstone	Jurassic (Oxfordian)	WW
7	Oxford Clay Formation	Mudstone	Jurassic (Callovian-Oxfordian)	OxC
8	Kellaways Sand Member	Sandstone Siltstone	Jurassic (Callovian)	KlS
9	Kellaways Clay Member	Mudstone	Jurassic (Callovian)	KlS
10	Cornbrash Formation	Limestone	Jurassic (Bathonian-Callovian)	Cb
11	Rutland Formation, Blisworth Limestone Formation and Blisworth Clay Formation	Argillaceous Rock Limestone	Jurassic (Bathonian)	Rld BwL BwC
12	Thorncroft Sand Member	Sandstone Siltstone Mudstone	Jurassic (Bajocian-Bathonian)	ThS
13	Hibaldstow Limestone	Limestone, ooidal	Jurassic (Bajocian)	HiL
14	Kirton Cementstone Beds	Mudstone Limestone	Jurassic (Bajocian)	KCM
15	Kirton Cementstone Beds	Limestone	Jurassic (Bajocian)	KCM

Figure 5.14: Map of geological substrates in the area around Elsham Anglo-Saxon cemetery (purple flag). Substrates are numbered to correspond with the legend to the right. Data from British Geological Survey (BGS 2021).



N.	Lexicon	Lithology	Age	BGS Code
1	Burnham Chalk Formation	Chalk	Cretaceous (Turonian-Santonian)	BCk
2	Welton Chalk Formation	Chalk	Cretaceous (Cenomanian-Turonian)	WCk
3	Ferriby Chalk Formation	Chalk	Cretaceous (Cenomanian)	FyCk
4	Kimmeridge Clay Formation	Mudstone	Jurassic (Kimmeridgian)	KC
5	Ampthill Clay Formation	Mudstone	Jurassic (Oxfordian)	AmC
6	West Walton Formation	Mudstone Siltstone	Jurassic (Oxfordian)	WW
7	Oxford Clay Formation	Mudstone	Jurassic (Callovian-Oxfordian)	OxC
8	Kellaways Sand Member	Sandstone	Jurassic (Callovian)	KlS
9	Kellaways Sand Member	Sandstone Limestone	Jurassic (Callovian)	KlS
10	Cornbrash Formation	Limestone	Jurassic (Bathonian-Callovian)	Cb
11	Blisworth Clay Formation	Mudstone	Jurassic (Bathonian)	BwC
12	Blisworth Clay Formation	Limestone	Jurassic (Bathonian)	BwC
13	Rutland Formation	Argillaceous Rock	Jurassic (Bajocian to Bathonian)	Rld
14	Thorncroft Sand Member	Sandstone	Jurassic (Bajocian-Bathonian)	ThS
15	Hibaldstow Limestone	Limestone, ooidal	Jurassic (Bajocian)	HiL
16	Kirton Cementstone Beds	Limestone	Jurassic (Bajocian)	KCM
17	Kirton Cementstone Beds	Mudstone Limestone	Jurassic (Bajocian)	KCM
18	Lower Lincolnshire Limestone Member	Limestone	Jurassic (Bajocian)	LLL
19	Marlstone Rock Formation	Ferruginous Limestone Ferruginous Sandstone	Jurassic (Pliensbachian-Toarcian)	MRB
20	Charmouth Mudstone Formation	Mudstone	Jurassic (Sinemurian-Pliensbachian)	ChM
21	Pecten Ironstone (Bed)	Ironstone	Jurassic (Pleinsbachian)	PtnI
22	Frodingham Ironstone Member	Ironstone	Jurassic (Sinemurian)	FI
23	Scunthorpe Mudstone Formation	Mudstone Limestone	Triassic-Jurassic (Rhaetian-Sinemurian)	SMd
24	Scunthorpe Mudstone Formation	Limestone	Triassic-Jurassic (Rhaetian-Sinemurian)	SMd
25	Penarth Group	Mudstone	Triassic (Rhaetian)	PnG
26	Mercia Mudstone Group	Mudstone	Triassic (early Epoch-Rhaetian)	MMG

Figure 5.15: Map of geological substrates in the area around Cleatham Anglo-Saxon cemetery (purple flag). Substrates are numbered to correspond with the legend to the right. Data from British Geological Survey (BGS 2021).

The area surrounding Elsham cemetery, as seen in figure 5.14, is predominantly surrounded by chalk formations with a large Jurassic clay formation bordering the area to the west. From the modern $\delta^{34}S$ data presented in figure 5.13, flora growing in the area of Elsham cemetery would be expected to fall between -9.3‰ and 6.3‰. The area around Cleatham cemetery is geologically complex, as seen in figure 5.15, with mudstone formations dating to the Jurassic period as well as several limestone and ironstone formations dating to either the late Triassic or Jurassic periods. The majority of these formations fall into the 'other' category presented in figure 5.13, suggesting that flora in the area of Cleatham would likely produce $\delta^{34}S$ values between -9.3‰ and 5.6‰. While the geochemical composition

of the area is important in determining the expected $\delta^{34}S$ values in an area, hydrological influences are important as well. A map of the major watercourses in the area around Elsham and Cleatham cemeteries is provided in figure 5.16. Watercourses may carry sediments from other geological formations causing anomalous $\delta^{34}S$ values in distant areas. Furthermore, bacterial reductions in riverbeds may produce very low $\delta^{34}S$ values (Privat et al., 2007). Riverine values will influence the surrounding banks and may affect large areas in floodplains (Nehlich, 2015). Tidal effects along estuaries and watercourses may also result in a marine influence reaching further inland than would be expected from sea-spray effects alone (Nehlich 2015).

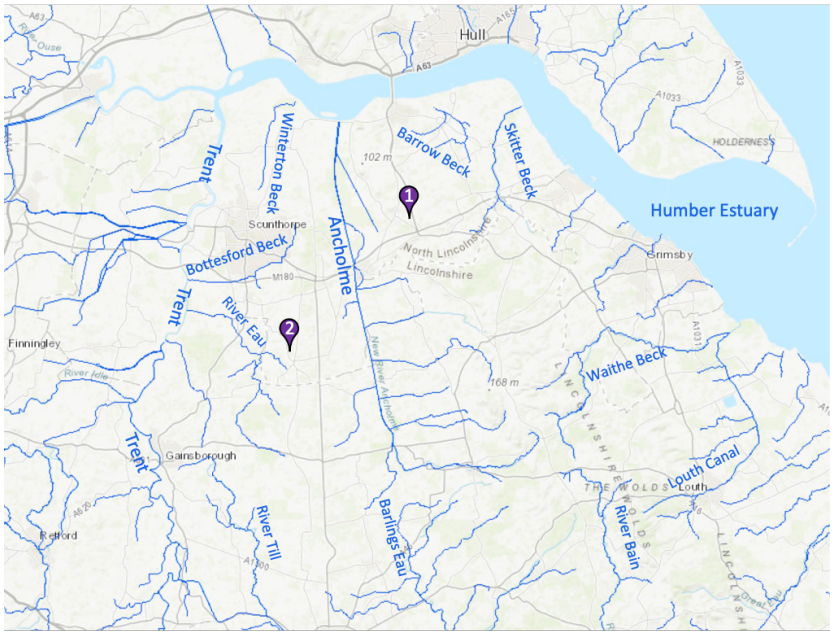


Figure 5.16: Map showing the major watercourses in the area around the sites used in this thesis, indicated by numbered purple flags: 1=Elsham, 2=Cleatham. Map from World Wildlife Fund (2021).

Elsham cemetery is situated between the Barrow Beck and tributaries of the River Ancholme. Cleatham cemetery is situated between the River Eau, Bottesford Beck, and tributaries of the River Ancholme. Both cemeteries are within the Louth Grimsby and Ancholme catchment, which is described as dominated by a "hill and vale" morphology considered to be at low risk for overland water flow (BGS 2021). Thus, flooding is unlikely to occur frequently enough in this area to cause riverine $\delta^{34}S$ values to influence terrestrial floral or faunal $\delta^{34}S$ values. According to figure 5.13, both Elsham and Cleatham may be within the range of coastal effects that

would skew $\delta^{34}S$ values of flora and fauna toward a marine $\delta^{34}S$ signature. However, these data are based on a broad estimate of distance affected by coastal influences, mainly sea spray; the estimate used for the east coast of England was 10 km (Evans et al., 2018a). This estimate does not take into consideration local prevailing winds or topography that will modulate the inland distance affected by sea spray (Nehlich, 2015).

Finally, the $\delta^{34}S$ data ranges provided in figure 5.13 were derived from modern vegetal samples. Efforts were made in the collection of these samples to avoid areas near major roads or other heavy sources of anthropogenic sulphur contamination (Evans et al., 2018a). However, due to the exploitation of fossil fuels, anthropogenic contamination of the sulphur cycle must be considered as a global phenomenon when analysing modern data (Nehlich, 2015). To fully contextualise $\delta^{34}S$ data from the individuals interred at Elsham and Cleatham cemeteries comparative samples of animal bone should be analysed as well. Preferably a range of animal bone samples contemporary with the early Anglo-Saxon period and local to the area of Northern Lincolnshire should be analysed. These samples should include the main terrestrial domesticates found at Anglo-Saxon sites: cattle, sheep, and pigs (Crabtree, 1990; O'Connor, 2011; Crabtree and Campana, 2014). Further sampling of wild species often found at Anglo-Saxon settlement sites should include terrestrial, marine, and freshwater species to establish the potential dietary range of Anglo-Saxon individuals. However, this data is not currently available. There have been sulphur studies of Roman period individuals and medieval period individuals conducted in Britain, though unfortunately these studies are clustered in the south-west of England. There have also been sulphur studies conducted on individuals from Iron Age Yorkshire. The locations of the sites used for these sulphur studies are

shown in figure 5.17. Thus, these data will not be directly comparable to $\delta^{34}S$ values measured from individuals living in northern Lincolnshire.

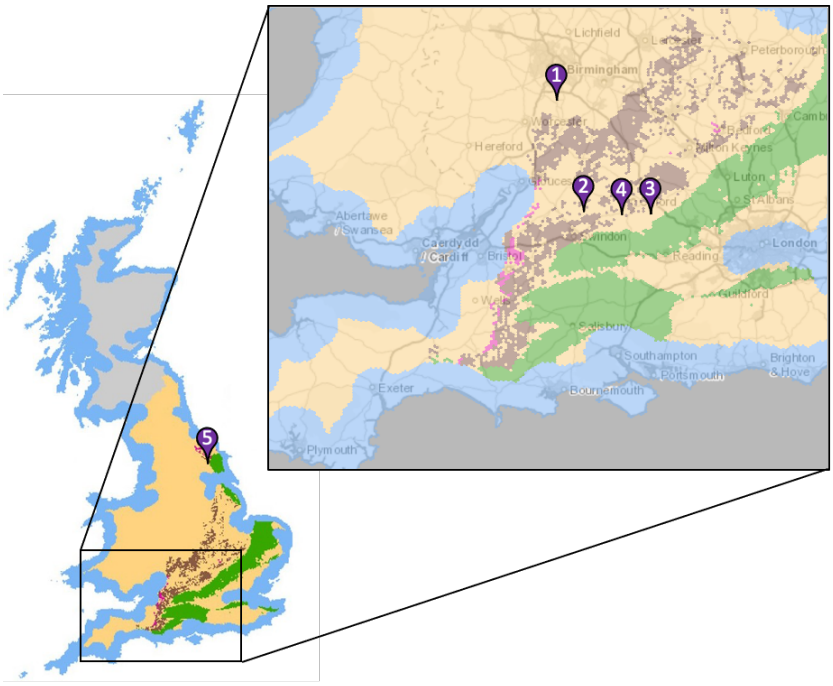


Figure 5.17: Map showing English and Welsh sulphur data as measured in modern vegetation (Evans et al., 2018b). For the $\delta^{34}S$ ranges indicated by colour coding on the map see figure 5.13. Numbered purple flags in the expanded portion of the map indicate sites with previously published sulphur data: 1) Bordesley Abbey, Worchestershire; 2) Lechlade, Gloucestershire; 3) Queenford Farm, Oxfordshire; and 4) Tubney Wood Quarry, Oxfordshire; 5) Wetwang, Yorkshire.

Isotope data were collected from individuals from Bordesley Abbey and Lechlade, both medieval sites dated to circa 1300 AD, as part of a study comparing coastal and inland $\delta^{34}S$ values across Europe (Richards et al., 2001). Data from Queenford Farm and Tubney Wood Quarry were collected as part of a study attempting to investigate, through $\delta^{34}S$ values, freshwater fish consumption in Roman Oxfordshire (Nehlich et al., 2011). Radiocarbon dates from Queenford Farm suggest the site was in use from 430 AD to 630 AD. Tubney Wood Quarry consisted of two areas of Roman period inhumations: the first area dates to the 2nd century AD and the second area dates from the 4th through to the 6th centuries AD. The data from the area surrounding Wetwang were gathered to investigate Iron Age chariot burials, comparing chariot burials to other funerary traditions from the 3rd and 2nd century BC (Jay et al., 2012; 2013). The $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ data from these five sites are presented in figure 5.18.

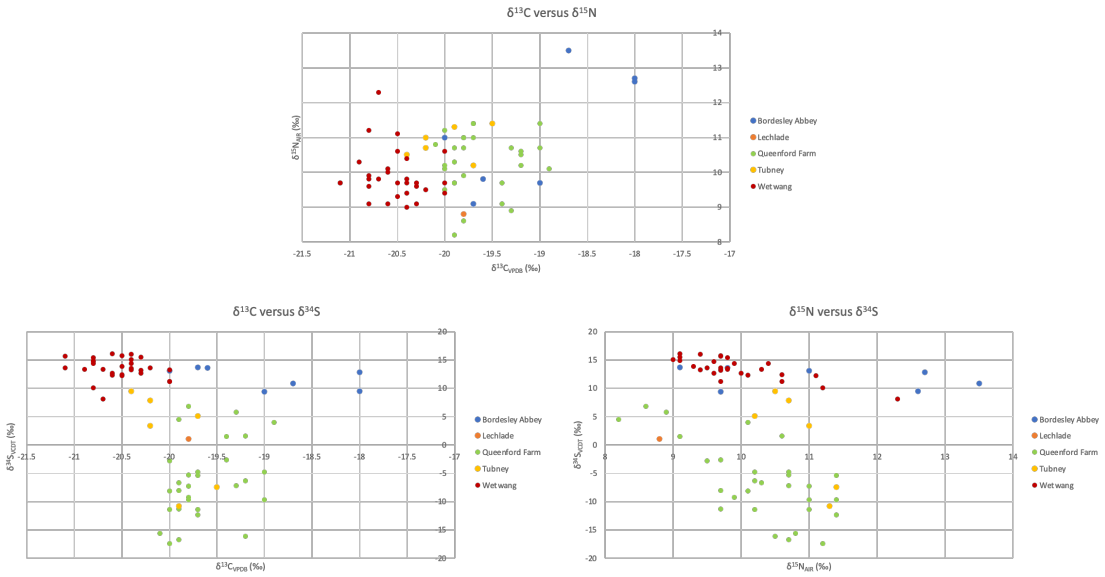


Figure 5.18: Stable isotope data from five English sites: Bordesley Abbey (n=7), Lechlade (n=1), Queenford Farm (n=28), Tubney (n=6) and Wetwang (n=29). Bordesley Abbey and Lechlade data from Richards and colleagues (2001). Queenford Farm and Tubney data from Nehlich and colleagues (2011). Wetwang data from Jay and colleagues (2013). Data included in these plots were obtained from adult individuals.

At Bordesley Abbey $\delta^{34}S$ values ranged from 9.4‰ to 13.7‰, mean 11.9‰. Richards and colleagues (2001) interpreted these values as indicative of a terrestrial diet with possible protein contributions from either freshwater or marine environments. The individual from Lechlade had a $\delta^{34}S$ value of 1.1‰, closer to the data obtained from the two Oxfordshire sites (Richards et al., 2001; Nehlich et al., 2011). At Queenford Farm $\delta^{34}S$ values ranged from -17.4‰ to 6.8‰, with a mean of -6.4‰ (Nehlich et al., 2011). Samples were also taken from terrestrial fauna at Tubney and at Barrow Hills, a nearby site dated from 130 AD to 330 AD; these ranged from -10.4‰ in a sheep to 0.5‰ from either a sheep or a goat (Nehlich et al., 2011). The negative values seen in these terrestrial fauna were interpreted as relating to regular flooding in the Thames River Valley. Flooding events would transfer sulphates with lower $\delta^{34}S$ values from the river to the terrestrial environment, typically expected to show higher $\delta^{34}S$ values. Animals raised in these floodplains would show decreased $\delta^{34}S$ values relative to animals raised in areas not subject to regular flooding (Nehlich et al., 2011). Archaeological fish bones were obtained from Queen's College, Oxford University, from layers dated to between 1475 and 1550 AD. The bones were identified as cyprinids, likely carp, and pike and

had $\delta^{34}S$ ranges of -20.9‰ to -17.4‰ (Nehlich et al., 2011). The majority of the individuals analysed from Queenford Farm had $\delta^{34}S$ values that could be explained by the consumption of terrestrial proteins. However, four individuals from Queenford Farm had $\delta^{34}S$ value lower than -15‰, interpreted by Nehlich and colleagues (2011) as indicative of a diet involving large contributions from freshwater fish. Four individuals from Tubney had $\delta^{34}S$ values higher than expected from the local terrestrial $\delta^{34}S$ data; Nehlich and colleagues (2011) felt these individuals showed a non-local $\delta^{34}S$ signature and were likely migrants to Oxfordshire. The individuals sampled from around Wetwang had $\delta^{34}S$ values ranging from 8.1‰ to 16.1‰. If the modern sulphur ranges are used to interpret this data, we would expect this range of $\delta^{34}S$ values to arise from coastal effects. However, Wetwang is not within the region expected to be affected by sea-spray and the $\delta^{13}C$ and $\delta^{15}N$ data from this site do not indicate a dependence on marine resources. Terrestrial animals sampled from this site showed a $\delta^{34}S$ value range of 13.6‰ to 15.7‰, indicating the local $\delta^{34}S$ signature for this region, largely dominated by chalk. These data are interesting, as they provide evidence of the discrepancy between modern modelling of $\delta^{34}S$ values and pre-industrial $\delta^{34}S$ values and provide valuable data for the modelling of archaeological diets using $\delta^{34}S$ values. However, these data can not necessarily be directly extrapolated to other chalk dominated landscapes. Differences in geology and hydrology must be carefully considered before making any inferences regarding diet.

5.4.5: Sample Selected for Isotope Analysis

Twenty inhumed and twenty cremated individuals were selected for analysis. Only adults were included and those with osteobiographical information were preferred, where available. At Elsham, only five adults from the Anglo-Saxon period were inhumed. One of these individuals, EL75RR, was represented by only a right parietal and was not included in this analysis. The remaining four individuals were included, see table 5.10 below.

Table 5.10: Inventory of samples taken from individuals at Elsham, inhumations. Data regarding age, sex, pathologies and accompanying grave goods from Squires, 2011.

Inhumation Number	Age (years)	Sex	Sample	Pathology	Grave Goods
EL75EN	19-25	Female	Rib frag.	Schmorl's nodes, osteophytes, periostitis, caries	Standard
EL76AK	19+	?	Unidentified frag.	Osteochondritis dissecans	None
EL76AL	31-40	Male	Fibula frag.	calculus	None
EL76JO(a)	31-40	Female	Rib frag.	Osteophytes, porosity of T. vertebrae	Few

At Cleatham, from an initial total of 62 individuals there were 37 adults for whom sex had previously been estimated. Seven of those individuals were only assigned 'probable' sex and were not selected. From the remaining thirty 'confidently' sex adults sixteen individuals were selected for isotope analysis, see table 5.11. The resulting sample included seven female and nine males. The sample is biased towards young adults, aged 19-25 years; this is a factor of the demographics of the population at Cleatham, 57% of the population for whom sex could be estimated were assigned to the young adult age category, see table 5.3. For both the Cleatham and Elsham populations ribs were the preferred sampling site, though for a minority of individuals rib samples were not available. Typically, long-bone shafts are the preferred source of bone collagen for stable isotope analysis, due to the longer turn-over time experienced by these bones (Mays et al., 2013). However, the sample selection from cremated individuals will primarily be determined by burning intensity, rather than skeletal element. Squires indicated that in several cases the less intensely cremated elements of the individuals at Cleatham and Elsham were areas of trabecular bone, which has a higher turn-over rate (2011). Thus, samples were preferentially selected from the ribs of the inhumed individuals to provide isotope data comparable to trabecular samples, due to a similarly high turn-over rate (Mays et al., 2013).

Table 5.11: Inventory of samples taken from individuals at Cleatham, inhumations. Data regarding age, sex, pathology and accompanying grave goods from Squires, 2011.

Inhumation Number	Age (years)	Sex	Sample	Pathology/Notes	Grave Goods
Grave 10	26-40	Male	Rib frag.		Few
Grave 11	19-25	Female	Rib frag.	prone, decapitated	Few, bird bones
Grave 18	19-25	Male	Unidentified frag.		Standard
Grave 19	19+	Female	Shaft frag. lower limb		Standard
Grave 25	19+	Male	Rib frag.		Rich, weapons
Grave 29	41+	Male	Rib frag.		Standard, accessory urn
Grave 31	19+	Male	Rib frag.	prone	Standard, sheep mandible
Grave 37	19-25	Male	Rib frag.		Few
Grave 38	19-25	Female	Rib frag.		Standard
Grave 40	19+	Male	Humerus shaft frag.	ulna and radius healed fractures	Standard
Grave 45	19-25	Male	Rib frag.	urn sherds in fill	Standard
Grave 48	19-25	Female	Rib frag.		Rich
Grave 49	19-25	Male	Rib frag.		None
Grave 50	19-25	Female	Rib frag.		Standard
Grave 54	19-25	Female	Rib frag.		Standard
Grave 57	19-25	Female	Rib frag.		Standard

In order to select 20 individuals from the collective 1548 cremation burials at Cleatham and Elsham (979 and 569 respectively) several criteria were employed to narrow the population before examining the remains. The first filtering stage was to remove the accessory vessels, which mainly contain animal remains, as well as any vessels that were not analysed by Kirsty Squires in 2009, as these would not have associated contextual information. This first step reduced the Cleatham population to 969 and the Elsham population to 552. The next step was to remove all non-adults and individuals for who age could not be estimated. This was meant to improve the isotopic comparison: by limiting the analyses to adults the effects of weaning and growth on stable isotope ratios, particularly nitrogen, can be mitigated (Beaumont et al., 2015). The remaining population after this step at Cleatham was 391 and at Elsham was 284. Kirsty Squires evaluated several morphological changes associated with heat exposure, these were fragmentation, shrinkage, fissuring, and

warping. Each change was graded as either no evidence of changes, minimal changes, moderate changes or severe changes observed (Squires, 2011). All individuals that were rated as severely modified in any of these categories were eliminated from consideration, as these individuals likely experienced higher temperatures that may have compromised bone collagen. This reduced the populations to 267 individuals at Cleatham and 134 at Elsham. The final filtering stage removed any burials that had been disturbed or mixed before analysis or that had cremation weights of less than 100 g. At this time any multiple burials, other than adult and infant pairs that could readily be distinguished, were also filtered out. The final selection of individuals was made from the 254 individuals at Cleatham and 124 individuals at Elsham that fit all of these criteria. In her notes on the cremations at Cleatham and Elsham, Kirtsy Squires indicated several individuals whose burning was variable or poor and these were examined first (Squires, 2011).

Samples were then selected based on gross indications of burning intensity. Colour was the most definitive selection criteria but fissuring and warping were also considered. Photographs taken during the controlled heating experiment were used to develop a scale showing the change in bone colour with increased temperature; bones from the cremated individuals at Cleatham and Elsham were compared against this scale to estimate temperature exposure, see figure 5.19 below.

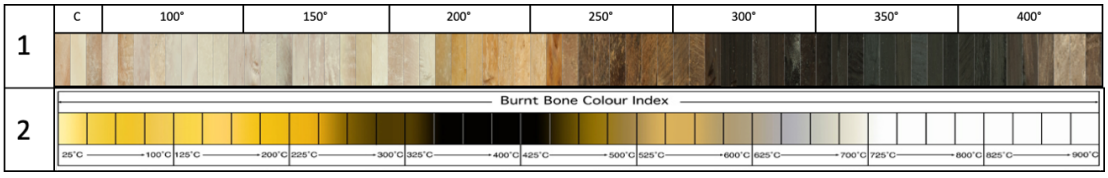


Figure 5.19: Colour scales used in the selection of bone samples. 1) Produced from photographs taken during the controlled heating experiment, photographs by Jeff Vetch. 2) Burnt bone colour index from Munro et al. (2007 p. 94).

Samples were selected if bone colour appeared yellow, brown, grey-brown, or black. Distinguishing between calcined bones, typically grey or white in appearance, stained by soil and bones exposed to low temperatures that typically appear cream, pale yellow, or light brown proved difficult. One means of distinguishing these bones was the presence of fissuring or warping, which indicated

higher temperature exposure. The cross-sectional appearance of the bone could also aid in this distinction, if the bone appeared lighter superficially but darker internally this indicated the surface of the bone had become calcined. Once bone fragments were identified as potentially having been exposed to only lower temperatures three samples were selected, each weighing approximately 1 g. The selection of multiple samples was designed to prevent the need for repeated visits to the storage facility in the case of marginal collagen yields. The samples were photographed from multiple angles to provide a record for bone fragments that were destroyed during analysis. Photographs were also taken to show the range of burning intensity, as indicated by colour, experienced by each individual from which a sample was taken, see figure 5.20 below.



Figure 5.20: Example of samples taken and photographic record. Burial MT84FT from Cleatham cemetery, numbers 1, 2 and 3 indicate samples taken for analysis, while the range shows three bones selected to demonstrate the variation in the burning intensity experience by this individual. Photograph by Simon Hughes.

The twenty individuals selected from each cemetery are presented in tables 5.12 and 5.13 below. The tables include biographical information where available. The accompanying grave goods and animal bone inclusions are listed as indications of status; no samples were taken for analysis from the animal bone inclusions.

Table 5.13: Individuals sampled from Cleatham, cremations. Information on age, sex, and accompanying animal bone/grave goods has been reproduced from Squires, 2011. Accompanying animal bone was identified by species where listed, but if species could not be determined was simply marked as 'present'. No pathologies were identified in these individuals.

Cremation Number	Age (years)	Sex	MNI	Animal Bone	Grave Goods
MT84FT	19-30		1	sheep/goat	comb, 12 glass beads
MT84IT	19+	Female?	1	present	comb
MT84KJ	19-30	Female?	1	2 species present	belt plate
MT85AQ	26-30	Female	1	present	comb, glass bead
MT85AR	26-30	Female?	1		cruciform brooch, ivory ring, comb
MT85BH	19-25		1	present	spindle whorl, ivory ring, 2 glass beads
MT86TR	19+		1	present	flint flake
MT88AAA	19-30	Male?	1	present	shears, comb, dummy tweezers
MT88ALD	19-25		2: infant		
MT89BBT	19+	Female?	1	present	tweezers, comb

Table 5.12: Individuals sampled from Elsham, cremations. Information on age, sex, pathology and accompanying animal bone/grave goods has been reproduced from Squires, 2011. Accompanying animal bone was identified by species where listed, but if species could not be determined was simply marked as 'present'.

Cremation Number	Age (years)	Sex	Pathology	Animal Bone	Grave Goods
EL75AP	19-30		os acromiale	sheep	
EL75DW	19+	Female		present	iron nail
EL75DX	31-40		osteoarthritis		
EL75ES	19-30		possible cribra orbitalia	horse	ivory
EL75LW	26-30	Male		small mammal/bird	comb
EL76IL	31-40	Female	skull fractures	horse/cattle	tweezers, burnt clay frag.
EL76MN	26-30	Female	Schmorl's nodes, osteoporosis	sheep	comb, metal sheet
EL76NN	26-30	Male			bone point/awl
EL76PY	26-30	Female	osteophytic growth	horse/cattle	glass, whorl, ivory, cowrie
EL76PZ	19-30	Female?		cattle	

The individuals selected for analysis from Cleatham cemetery presented with no pathologies, as such this column was omitted from the table. However, burial MT99ALD consisted of two individuals: an adult, who was sampled for analysis, and an infant, who was not (Squires, 2011).

5.5 Archaeological Application – Methods:

Colour analysis, collagen extraction, and stable isotope analysis were performed on the archaeologically cremated human samples following the same methods used for the bovine samples from the controlled heating experiment, see section 5.3 above. Lipid removal was not deemed necessary for the archaeological samples as lipids typically do not survive the burial environment in sufficient amounts to affect stable isotope analysis (Jøkov et al., 2007). FTIR analyses were conducted on samples ground as described in section 5.3 above; however, due to COVID-19 related restrictions on travel it was necessary to use a different unit for analysis. For the archaeological samples a PerkinElmer Spectrum Two FTIR unit was used to produce FTIR spectra as controlled and interpreted by the Spectrum software package. Readings were taken with a Spectrum Two Universal ATR module accessory equipped with a diamond crystal with an operational range of 50,000 cm^{-1} to 50 cm^{-1}. Measurements were taken in the 2000-400 cm^{-1} range with a resolution of 4 cm^{-1}. Thirty-two scans were averaged to produce each spectrum and each sample was analysed in triplicate. Statistical significance was determined by the Kolmogorov-Smirnov test and the Mann-Whitney U test, as discussed in section 5.3.8 above.

Chapter 6: Controlled Heating Experiment Results:

6.1 Introduction:

This chapter presents the results from the controlled heating experiment as laid out in section 5.3. Sections of cow bone were heated under controlled conditions to temperatures between 100°C and 400°C, at 50°C intervals. Three samples were heated to each temperature for half an hour, one hour and two hours and three samples were retained unheated as controls for a total of 66 samples. The control samples were considered as having been exposed to room temperature, 23°C, before collagen extraction and after collagen extraction at 70°C, as this is the temperature that was used to denature the collagen; see section 5.3.6. This experiment was designed to determine the threshold temperatures at which $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ values no longer represent the biogenic isotope ratios of bone. This experiment should also determine whether the commonly used collagen quality indicators: %C, %N, %S, C:N ratio, C:S ratio, and N:S ratio – are sufficient to distinguish samples that have deviated from their biogenic isotope ratios due to heat exposure. Changes in the bone due to heat were also observed to create a metric by which to select bone samples exposed to unknown burning conditions for isotope analyses. This would allow researchers to select archaeological samples that have been exposed to low temperatures that would be likely to have viable collagen for isotope analyses.

The control of the temperature exposure is discussed in section 6.2. Observations of the changes in bone due to heat are discussed in section 6.3, specifically: changes in mass, colour, and FTIR absorption spectra. Collagen was extracted as laid out in section 5.3.6 and the resulting yields are discussed in section 6.4. Finally, the results of the isotope analyses are discussed in section 6.5.

6.2 Temperature Fluctuation:

A muffle furnace was used to heat the bone samples to the target temperatures, as discussed in chapter 5, the furnace was set to the target temperature for at least one hour before introducing bone samples to allow the furnace to reach a stable temperature. However, the introduction of bone samples, crucibles, and the heating tray caused fluctuations in the furnace temperature. Additionally, the opening of the furnace door to remove samples after half an hour, and again after one hour caused minor temperature fluctuations. These temperature fluctuations

are shown in figures 6.1 and 6.2, with the raw data provided in Appendix 2. In the following results sections, the 'experimental temperature' refers to the target temperature; however, the fluctuation shown here should be considered when interpreting the later results.

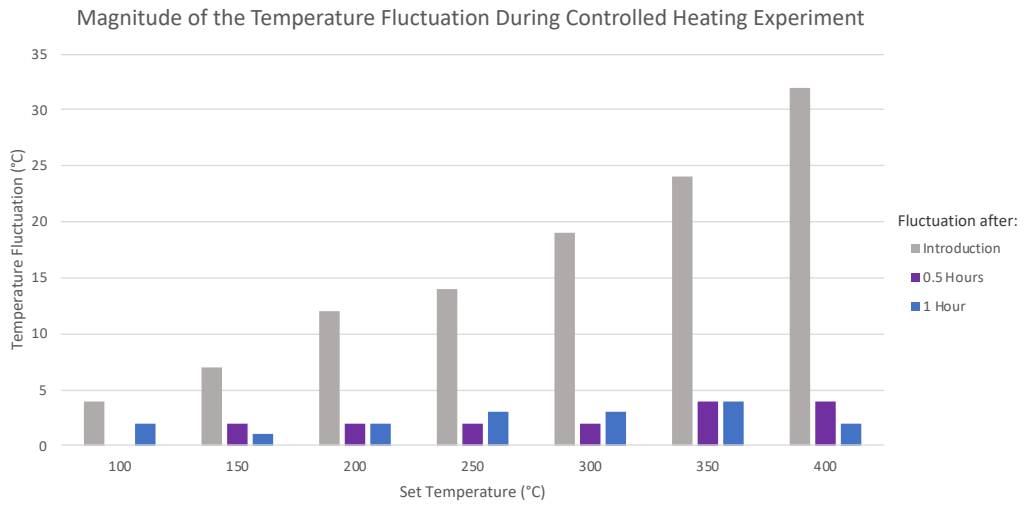


Figure 6.1: Bar graph showing the magnitude of the temperature fluctuation experienced by the muffle furnace at each temperature setting. The grey bars show the fluctuation after the initial introduction of the bone samples. The purple after the removal of samples at 0.5 hours. The blue after the removal of samples at one hour.

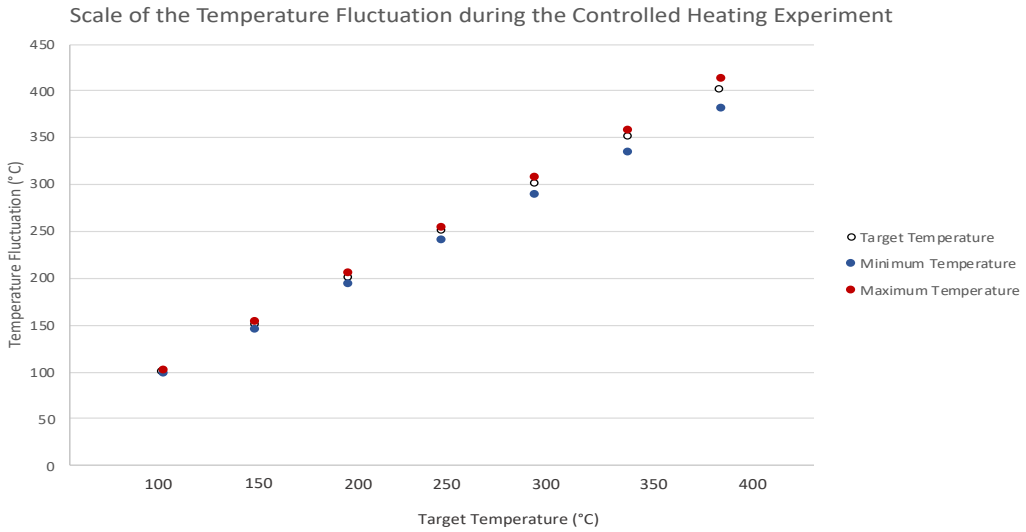


Figure 6.2: Scatterplot showing the fluctuation of the temperature of the muffle furnace to scale compared against the target temperature setting.

The largest fluctuations in temperature were seen at the target temperature of 400°C, with the initial introduction of the bone samples resulting in a fluctuation of 32°C. However, these fluctuations were relatively minor when compared against the target temperatures. Furthermore, at no point were the temperature fluctuations sufficient to cause samples from any target temperatures to enter the adjacent temperature range.

6.3 Changes in Bone due to Heat Exposure:

Bone undergoes four phases of primary changes, as discussed in section 3.4.2a. While the exact temperature ranges for each phase are debated, only the first two: dehydration and decomposition, would be expected in bones heated to a maximum of 400°C. In order to infer the primary changes occurring in the experimentally heated bone samples observations of secondary changes were taken. Three main observations, as discussed in section 5.3, were used to examine the changes in bone when exposed to various temperatures: mass, colour, and chemical changes as observed through FTIR analysis.

6.3.1: Change in Mass:

As discussed in section 3.4.2.b, bone is expected to lose mass at several stages during heating events relating to the loss of water, organic material, and carbonates. Water is expected to evaporate mainly between 105°C and 300°C and organic material begins to pyrolyse at 300°C; however, the loss of carbonates is not expected below 700°C (Thompson, 2005). The observed change in mass, as a percentage of the total mass of the bone sample, as related to temperature and duration of exposure is presented in figure 6.3. As discussed in section 5.3 bone samples were weighed before and after heating. The change in mass was expressed as a percentage of the initial mass to eliminate noise in the data caused by variation in the mass of the samples, the raw data is provided in Appendix 3.

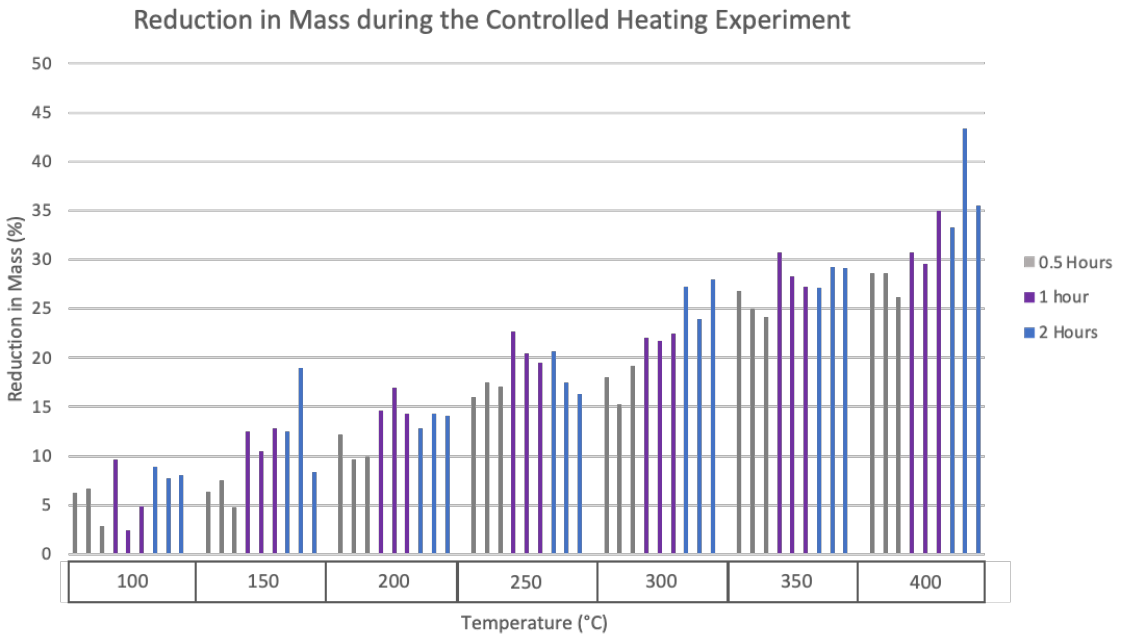


Figure 6.3: Reduction in mass during the controlled heating experiment as related to temperature and duration of exposure. Colour coded to show exposure times.

Figure 6.3 shows that as temperature increased the reduction in mass also increases. In most cases, longer exposure times were also correlated with the highest reductions in mass. This follows expectations from previous literature (Mayne Correia, 1997, Gonçalves et al., 2015). However, exposure time was less important than temperature in affecting the mass of the bone samples and in some cases, bones exposed for shorter time intervals lost proportionally more mass. One of the samples heated to 400°C for two hours appears to have lost 43% of its mass during heating, which is unexpectedly high and likely due to measurement or recording error. As such, this data point should be eliminated from further consideration.

6.3.2: Colour Change:

Colour was recorded by spectrophotometer in CIEL*a*b* colour space, spectrophotometer settings are outlined in section 5.3.3. The colour data from the bone samples taken before the heating experiment are presented in table 6.1.

Table 6.1: Colour analysis data of bone samples prior to burning. The picture in the top left corner roughly matches the mean values represented in this data set, photograph by Jeff Veitch.

	Mean	Standard Deviation	Maximum	Minimum	Range
SCI L*	75.08	7.12	88.10	53.29	34.81
SCI a*	1.75	1.19	9.03	-1.03	10.06
SCI b*	10.76	1.75	16.73	5.48	11.25
G	70.47	6.56	93.00	53.00	40.00

The colour data from the bone samples taken after heating are presented in table 6.2. Colour change with increased temperature exposure followed the expected patterns from the cream/ivory colour of unaffected bone through yellow, brown, and black as charring became evident and finally to grey-brown as the organic char begins to be lost. Photographs of each bone sample before and after heating are provided in Appendix 4.

Table 6.2: The colour data from bone samples measured after the controlled heating experiment. Photographs by Jeff Veitch.

Sample		Control-1-p	Control-2-c	Control-3-d	100-0.5-1	100-0.5-2	100-0.5-3	100-1-1	100-1-2	100-1-3	100-2-1	100-2-2	100-2-3	150-0.5-1	150-0.5-2
Measure	L*	65.87	77.64	76.51	73.59	65.30	80.25	80.31	84.24	85.25	84.64	82.98	80.04	80.92	75.17
	a*	3.41	1.96	3.63	2.85	1.92	2.24	1.33	1.99	1.81	1.90	2.64	2.97	2.74	3.48
	b*	10.85	11.83	12.04	9.84	8.37	8.69	8.40	10.05	10.14	10.15	9.59	9.22	9.81	9.47
	G	76.10	73.55	67.50	72.55	79.90	66.50	66.15	65.00	63.40	63.40	65.70	67.95	65.55	71.55
Image															
Sample		150-0.5-3	150-1-1	150-1-2	150-1-3	150-2-1	150-2-2	150-2-3	200-0.5-1	200-0.5-2	200-0.5-3	200-1-1	200-1-2	200-1-3	200-2-1
Measure	L*	75.94	79.78	78.55	83.83	81.68	72.00	84.33	75.83	77.45	82.32	64.90	63.40	73.42	64.51
	a*	1.92	0.89	1.38	1.00	1.57	0.95	0.65	2.73	1.52	0.58	4.44	4.05	5.55	9.02
	b*	9.83	9.40	8.81	10.34	14.96	12.68	14.73	14.73	9.25	11.90	21.17	21.91	25.45	21.96
	G	72.05	65.85	69.35	63.35	67.00	76.35	65.40	70.25	72.30	66.85	81.40	82.00	75.00	80.95
Image															
Sample		200-2-2	200-2-3	250-0.5-1	250-0.5-2	250-0.5-3	250-1-1	250-1-2	250-1-3	250-2-1	250-2-2	250-2-3	300-0.5-1	300-0.5-2	300-0.5-3
Measure	L*	65.26	68.83	68.20	56.57	52.74	42.55	44.79	43.41	41.98	42.08	46.33	42.57	45.10	41.38
	a*	9.47	8.03	6.99	9.03	7.56	2.49	3.66	3.34	2.89	2.67	5.77	1.77	3.01	1.30
	b*	23.96	25.27	22.62	20.56	12.14	2.47	4.51	3.55	2.40	2.05	6.43	2.45	4.15	1.17
	G	84.30	79.55	80.10	84.80	89.30	93.25	91.85	92.75	93.55	95.00	90.95	93.55	89.45	95.95
Image															
Sample		300-1-1	300-1-2	300-1-3	300-2-1	300-2-2	300-2-3	350-0.5-1	350-0.5-2	350-0.5-3	350-1-1	350-1-2	350-1-3		
Measure	L*	41.71	41.33	41.82	41.31	41.03	40.51	40.79	40.47	43.15	44.80	43.82	43.34		
	a*	0.21	0.16	0.09	0.46	0.37	0.68	0.12	0.32	-0.22	-0.45	-0.34	-0.32		
	b*	-0.45	-0.58	-0.78	1.05	-0.34	0.45	-0.69	-0.42	-1.37	-1.54	-1.48	-1.71		
	G	100.25	102.55	95.05	93.30	90.70	89.75	88.90	88.70	93.55	103.20	101.00	102.05		
Image															
Sample		350-2-1	350-2-2	350-2-3	400-0.5-1	400-0.5-2	400-0.5-3	400-1-1	400-1-2	400-1-3	400-2-1	400-2-2	400-2-3		
Measure	L*	43.67	42.93	42.20	43.43	42.59	46.08	44.07	44.57	47.21	58.34	59.08	49.66		
	a*	-0.34	-0.31	-0.18	-0.27	-0.19	-0.53	0.64	0.84	1.56	2.97	3.17	3.33		
	b*	-1.77	-1.84	-1.50	-1.32	-1.60	-1.66	-0.54	0.34	2.87	7.86	8.84	5.96		
	G	103.55	99.25	102.15	98.90	101.75	104.20	102.40	91.85	86.80	81.15	78.90	89.75		
Image															

As the CIEL*a*b* colour space can be understood as a physical sphere, it is possible to measure the distance between the colour coordinate measured before the heating experiment and the colour coordinate measured after heating. This data is presented in figure 6.3. As can be seen in the images in table 6.2, there was little colour change below 200°C as reflected in the low y-values in figure 6.4. The highest amount of colour change was observed in the samples heated to 300°C and 350°C, which appear black in the images in table 6.2. Raw data of colour measurements can be found in Appendix 5.

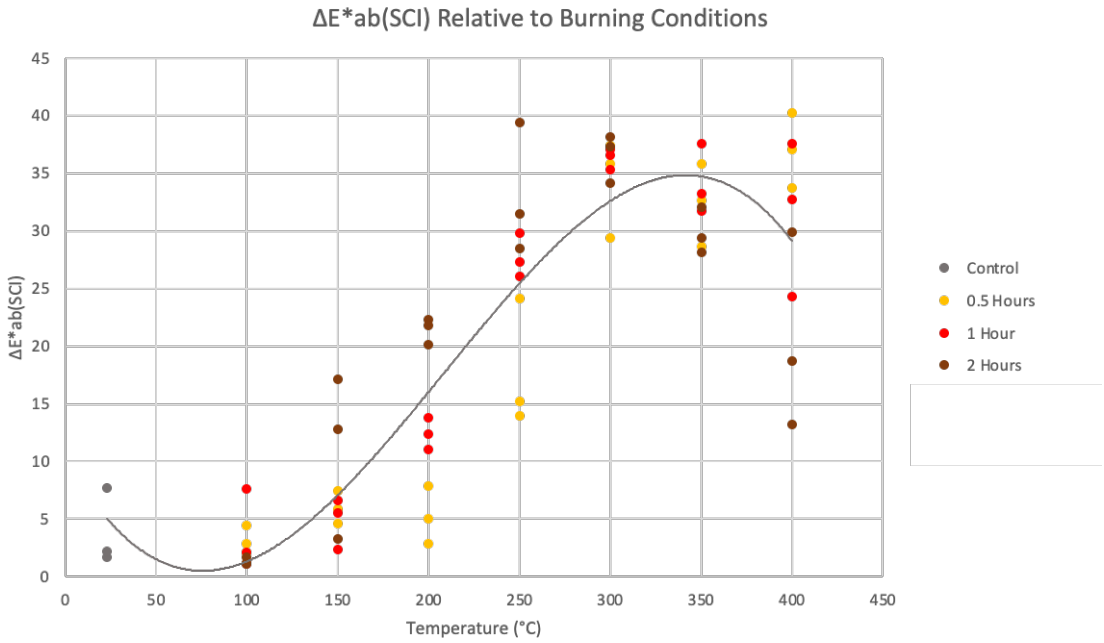


*Figure 6.3: Euclidean distance between the before and after colour coordinates (ΔE*ab) presented relative to the burning conditions. Data points are colour coded for exposure time (hours) and plotted against temperature (°C).*

To convey the colour data that was measured here, as it fits into the CIEL*a*b* colour space, the before and after colour coordinates have been plotted in figure 6.5. The blue data points, which represent the colour analysis values before heating, are tightly clustered. The orange data points, representing the colour data after heating, are more widely spread. However, when interpreting the a* and b* data presented below, it is important to recognise that the central scatter plot in figure 6.5 represents only a small area of the a*b* space; whereas, the L* scatter plot covers the entire range of L* space.

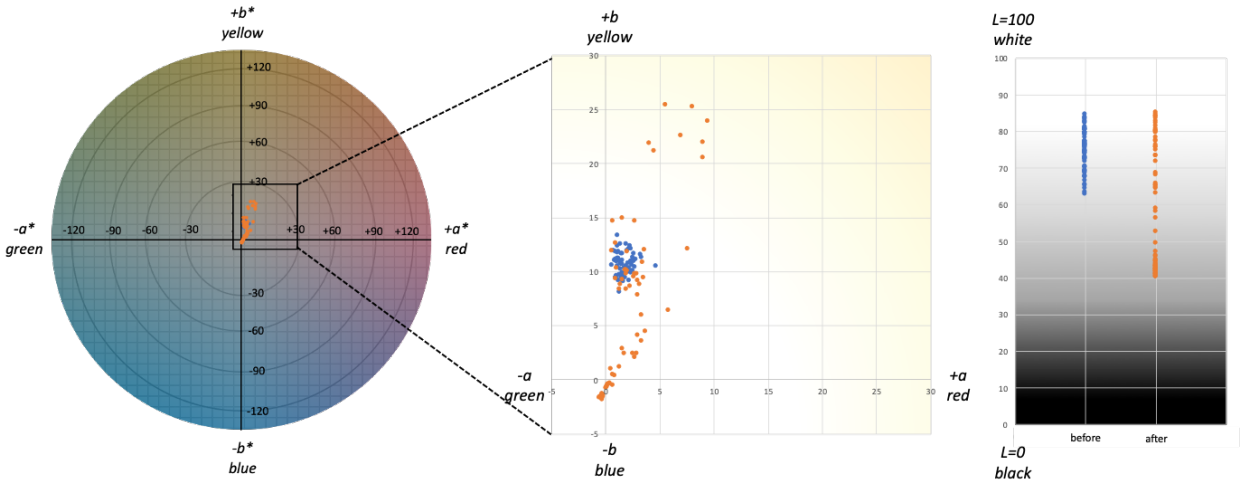


Figure 6.5: The circular plot on the left represents two dimensions (a: red-green and b*: yellow-blue) of CIEL*a*b* colour space (reproduced from Mouw, 2018). The black square on the circular plot is equivalent to the central scatter plot which shows the colour analysis data from the controlled heating experiment, with blue points showing values before heating and orange points showing values after heating. Finally, the scatter plot on the right shows the L* values of the bone samples before and after heating.*

Colour in this experiment, as in the literature, has been shown to correlate strongly with burning conditions (Shipman et al., 1984; Munro et al., 2007; Walker et al., 2008; Wahl, 2015). These colour changes were used to create a metric for selecting archaeological bone samples, with colour used as a broad indicator of past burning conditions.

6.3.3: Chemical Changes:

FTIR analysis can be used to observe some of the chemical changes that occur in bone during heat exposure. Absorption peaks have been correlated with specific functional groups of molecules, with changes in the relative height and width of several of these peaks have been correlated with low, middling, and high temperature exposures (Thompson et al., 2013). Figure 6.6 shows absorption spectra from the bones exposed to various temperatures during the controlled heating experiment normalised to the peak at 1035 cm^{-1}. Raw data from the FITR analyses can be found in Appendix 6. Significant changes in the spectra can be seen in the absorption bands between 1630 cm^{-1} and 1660 cm^{-1}, when analysing bone samples this area of the spectrum has been associated with water and organic tissue with the peak near 1660 cm^{-1} associated with the amide I band (Thompson et al., 2013; Ellingham et al., 2015a). Significant changes can also be seen around the peaks at 1415 cm^{-1} and 1450 cm^{-1}, these peaks have been associated with carbonate (CO_3) mineral and organic methylene (CH_2) inclusions in bone and at the peak at 900 cm^{-1} also associated with carbonate (Figueiredo et al., 2012). Further major changes can be seen around the absorption peaks at 605 cm^{-1} and 565 cm^{-1}, which have been related to phosphate (PO_4) mineral components in bone (Thompson et al., 2013).

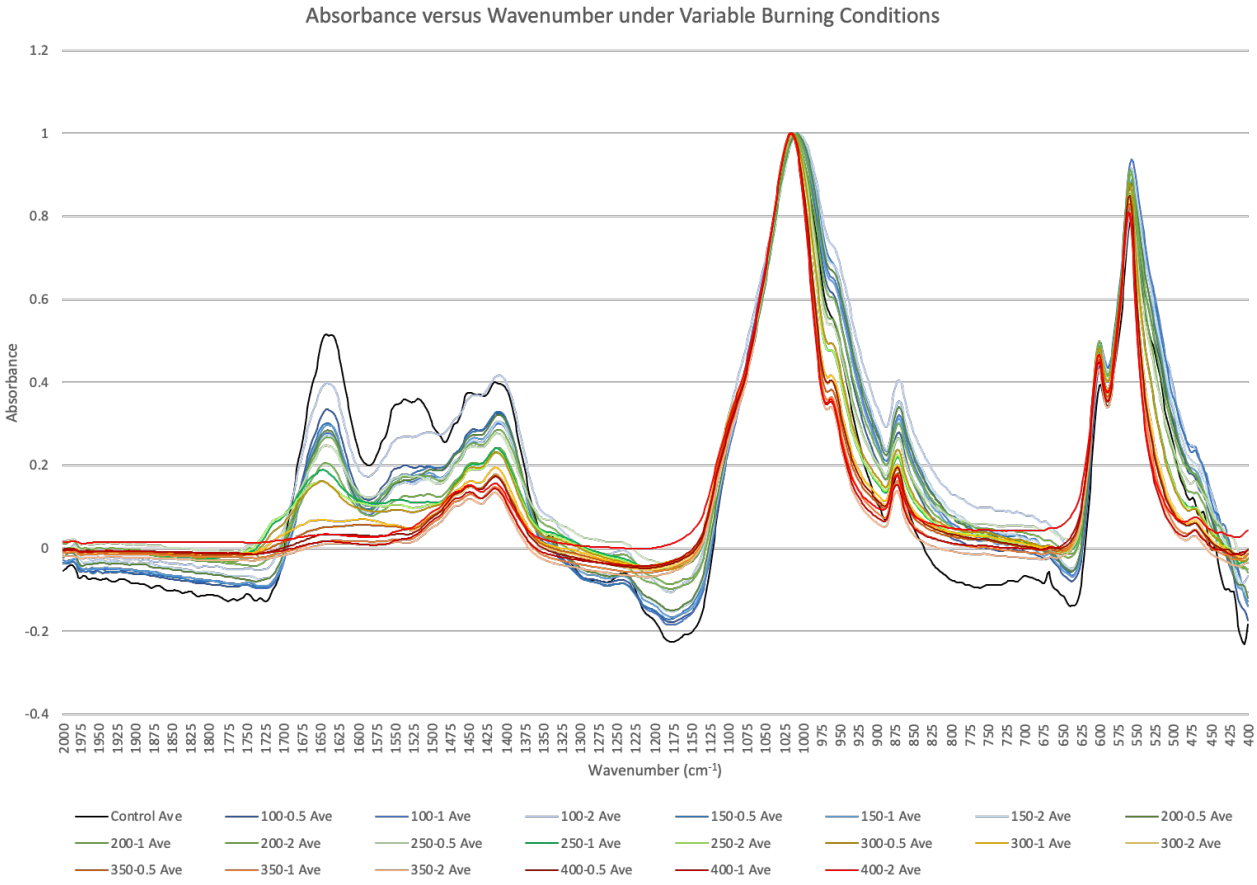


Figure 6.6: Absorbance by wavenumber (cm^{-1}) shown for different burning conditions, including temperature (°C) and length of exposure time (hours). FTIR data were normalised to the peak at 1035 cm^{-1}.

Most FTIR studies of bone, recovered from archaeological or forensic contexts, evaluate the crystallinity index or splitting factor, discussed in section 3.5.5a. The CI values of the bones heated in this experiment can be found in figure 6.7. However, this index is more useful for interpreting the changes in bone that occur at temperatures between 400°C and 700°C and the maximum temperature exposure in this experiment was 400°C (Thompson et al., 2013). Thus, unsurprisingly, this index is not effective in separating the chemical changes occurring in the samples presented here.

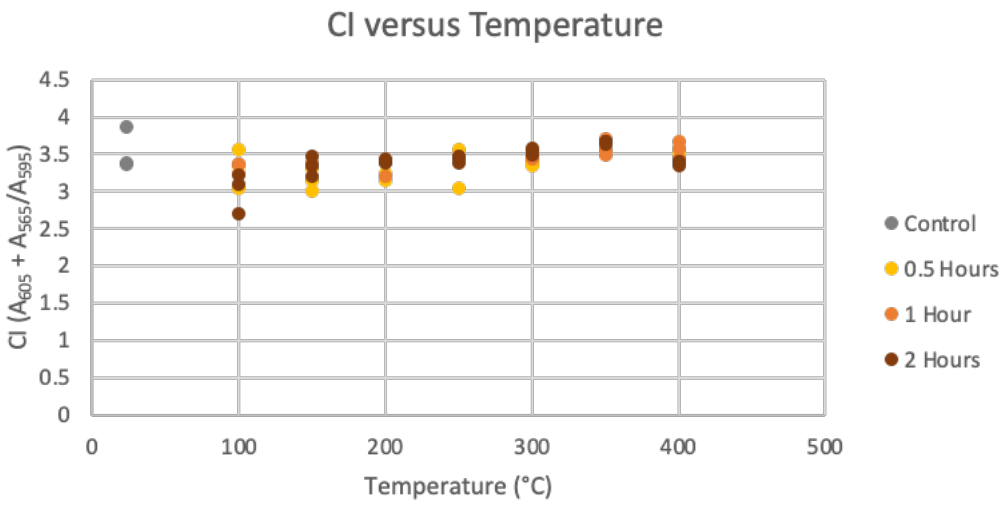


Figure 6.7: Crystallinity Index plotted against temperature (°C) showing samples heated for 0.5 hours, 1 hour and 2 hours.

Four ratios were identified by Thompson and colleagues as particularly useful for interpreting chemical changes occurring below 400°C: A_{1415}/A_{1035}, A_{1650}/A_{1415}, A_{900}/A_{1035}, and A_{1650}/A_{1035} (2013). Comparisons of these ratios against temperature are presented in figures 6.8 through 6.11. The chemical compounds associated with these ratios can be found in section 3.5.5a.

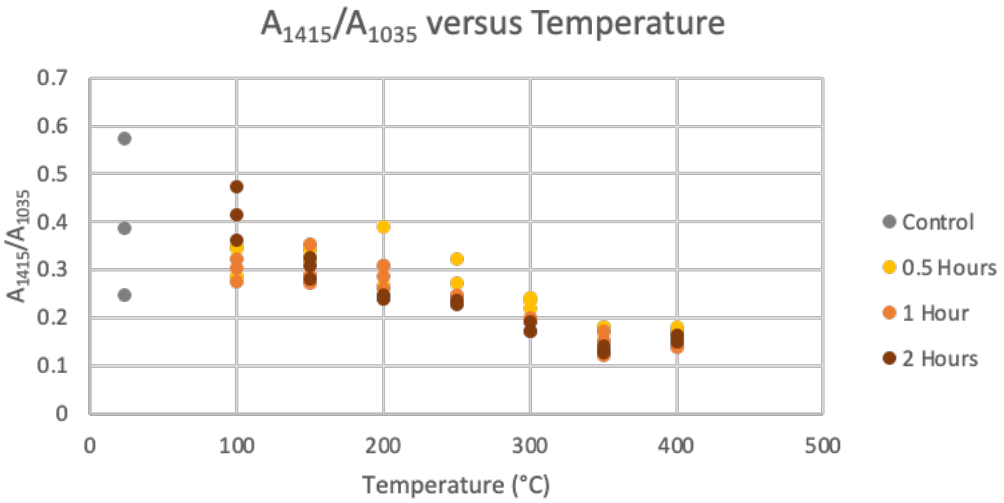


Figure 6.8: Ratio of peaks A_{1415}/A_{1035} related to carbonate/methylene and phosphate respectively, versus temperature (°C) showing samples heated for 0.5 hours, 1 hour and 2 hours.

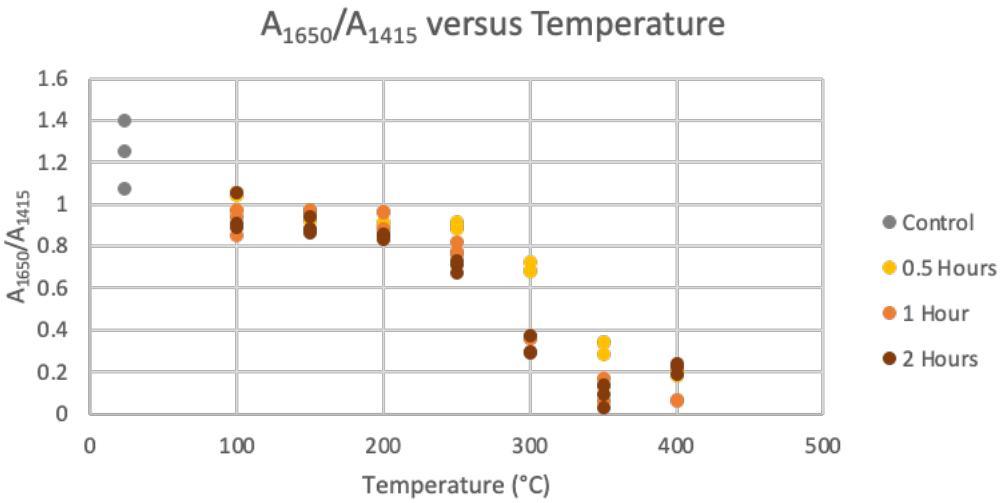


Figure 6.9: Ratio of peaks A_{1650}/A_{1415} related to carbonyl and carbonate/methylene respectively versus temperature (°C) showing samples heated for 0.5 hours, 1 hour and 2 hours.

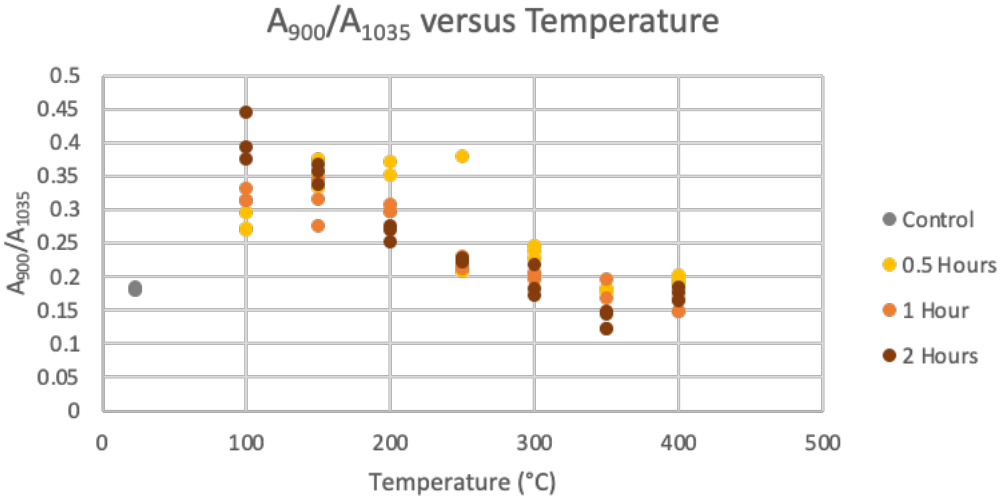


Figure 6.10: Ratio of peaks A_{900}/A_{1035} related to carbonate and phosphate respectively, versus temperature (°C) showing samples heated for 0.5 hours, 1 hour and 2 hours.

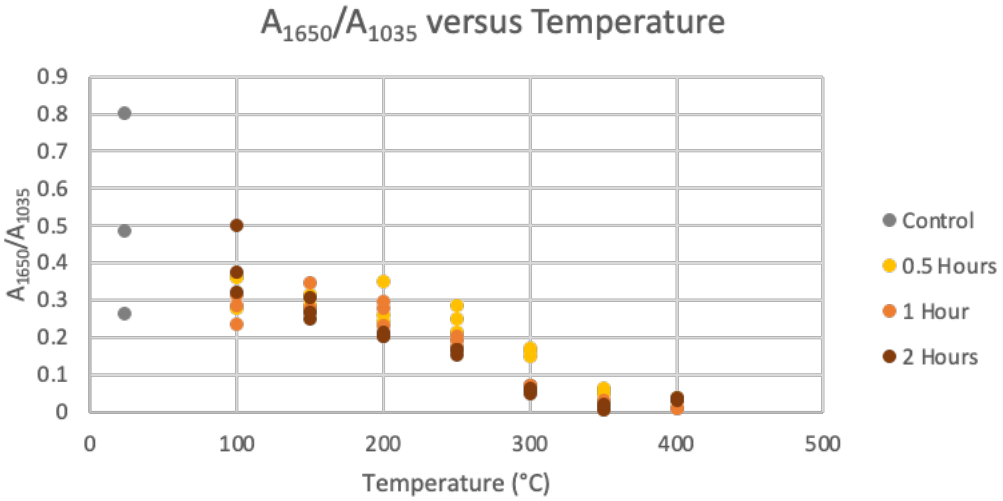


Figure 6.11: Ratio of peaks A_{1650}/A_{1035} related to carbonyl and phosphate respectively, versus temperature (°C) showing samples heated for 0.5 hours, 1 hour and 2 hours.

In order to create a model of the chemical changes ratios of absorption bands can be compared against each other. These models, developed from experimental data, can then be used to interpret the unknown burning conditions of bone from archaeological sources (Thompson et al., 2016). Ideally, these models will show significant changes around the previously identified threshold for collagen preservation, approximately 200°C. One of these models is shown in figure 6.12.

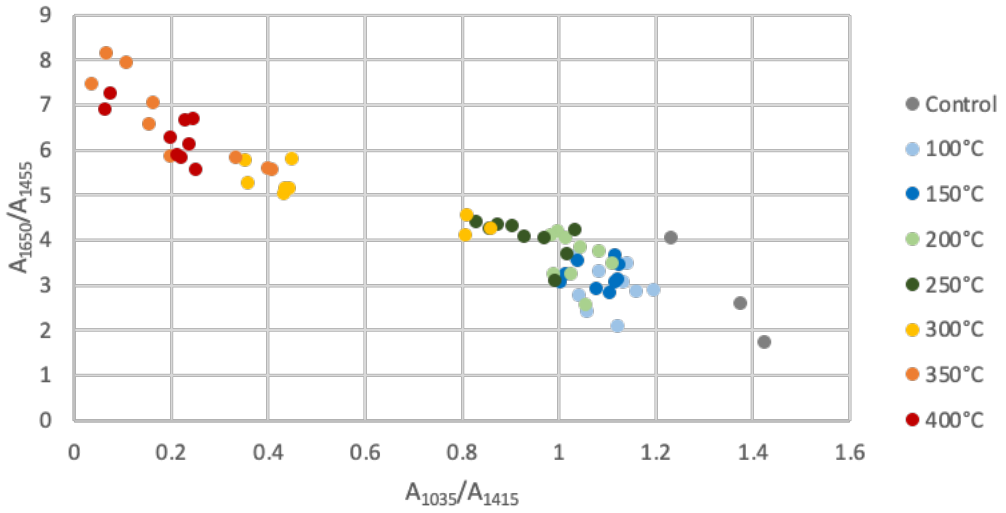


Figure 6.12: Temperature model using two ratios: the y-axis shows the ratio between absorption peaks at A_{1650}/A_{1455}, and the x-axis shows the ratio between absorption peaks at A_{1035}/A_{1415}. The peak at 1650 cm^{-1} has been associated with carbonyl and amide I, the peak at 1455 cm^{-1} with carbonate and methylene, the peak at 1035 cm^{-1} with phosphate, and the peak at 1415 cm^{-1} with carbonate and methylene. Experimental data is colour-coded to show temperature.

These models were used in the application of these results to burned bone from archaeological contexts. Colour, as discussed in section 6.3.2, was used as an indicator of past burning conditions. FTIR analyses was then used to confirm the temperature estimation, as broadly defined by colour.

6.4 Collagen Yield:

Collagen yield is typically expressed as a percentage by weight (wt. %) comparing the full weight of the bone sample before extraction to the weight of the extracted collagen that has been lyophilised. A full record of the collagen extraction procedure is given in Appendix 7. Fresh human bone is expected to yield approximately 22 wt. % collagen (van Klinken, 1999). However, interspecies comparisons have shown that cow bones have marginally higher levels of extractable proteins, thus, the average collagen yield of the control samples (24.4 wt. %) is not surprising. Collagen yields remain relatively consistent in samples heated to 100°C and 150°C but fall

significantly among samples heated to 200°C. These samples had an average collagen yields of 11.5 wt. %. Yields continue to drop steadily as temperatures increase with samples heated to 400°C, yielding an average of 2.4 wt. % collagen. However, as can be seen in figure 6.13, exposure times did not have a significant effect on collagen yields in this experiment. The minimum recorded collagen yield was 0.7 wt. %. When collagen yields drop below 0.5 wt. %, contamination of the sample becomes an issue.

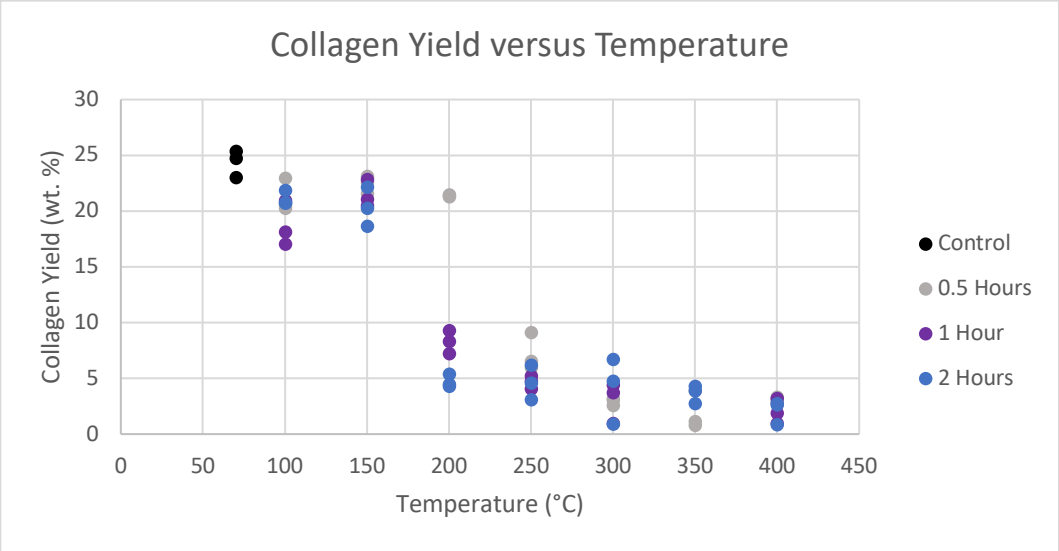


Figure 6.13: Scatterplot showing collagen yield (wt%) versus temperature (°C), exposure time is shown via the colour coding of the data points. The control samples were recorded as 70° as all samples were heated to this temperature during the collagen extraction procedure.

The data collected in this experiment suggests that samples heated below 200°C will produce viable collagen samples. At higher temperatures low collagen yields may indicate that exogenous contamination will overwhelm the collagen signal or that the breakdown of collagen may result in a deviation from biogenic isotope values (van Klinken, 1999).

To determine whether exposure times were a significant factor affecting the collagen yield from these samples a Kolmogorov-Smirnov test was conducted. The maximum difference in the distributions, as shown in figure 6.14, were compared against a critical value. The critical value of 0.08 was calculated for a population of 21 samples at a significance level of 0.05 using the formula presented in section 5.3.8. In order to reject the null hypothesis, that exposure time was not a significant factor affecting collagen yields, the maximum difference between the sample sets must exceed the critical value. The maximum difference between the samples heated for 0.5 hours and those heated for one hour was 0.24; the maximum difference between the samples heated for 0.5 hours and those heated for two hours was 0.19. In both cases the maximum difference exceeds

the critical value and the null hypothesis was rejected, suggesting that exposure time was a significant factor affecting collagen yields, at a level of 0.05. However, when comparing the samples heated for one hour to the samples heated for two hours the maximum difference was 0.05, which does not exceed the critical value. This suggests that during the first 0.5 hours of exposure to heat collagen is relatively protected from thermal degradation, but that exposure times between one and two hours produce similar levels of thermal alteration.

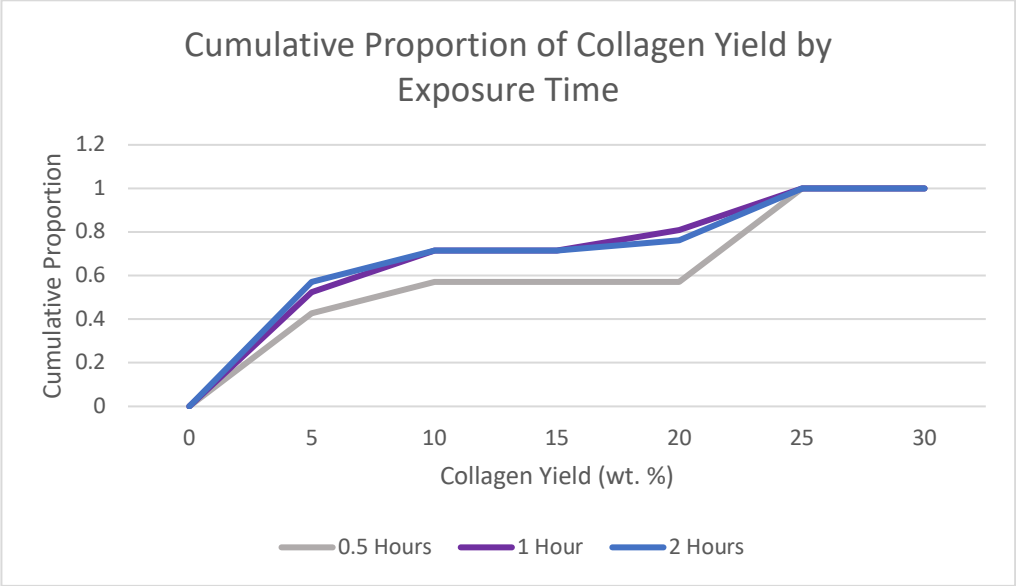


Figure 6.14: Graph showing the cumulative proportion of collagen yields (wt. %), colour coded for exposure times (hours): the grey line shows yields from exposures of 0.5 hours, the purple 1 hour, and the blue 2 hours.

As the statistical difference between the samples heated for 0.5 hours and the samples heated for 1 to 2 hours appeared to be driven by the three samples exposed to 200°C, further analysis of these data was conducted through the Mann-Whitney U test. The critical value for two populations of 21 samples at a significance level of 0.05 was 142. Neither the comparison between samples heated for 0.5 hours and 1 hour nor samples heated for 0.5 hours and 2 hours fell below this critical value. Thus, for both comparisons the null hypothesis was accepted, and the populations can be considered stochastically equal; see the data presented in table 6.3. While both tests are valid for this data set, the Mann-Whitney U test is less influenced by individual data points than the Kolmogorov-Smirnov test. Thus, for the data collected specifically from samples heated to 200°C there appears to be a significant difference between exposure times of 0.5 hours and longer exposures; however, this difference is not seen at other temperatures. As with the Kolmogorov-Smirnov test, no significant difference was found using the Mann-Whitney U test

between the samples heated for 1 hour and those heated for 2 hours. For the full range of heating conditions used in this experiment, exposure time is not a significant factor in the resultant collagen yield. However, further samples heated for a longer range of exposure times would be needed to determine the extent of this trend.

Value	Exposure Time		Value	Exposure Time		Value	Exposure Time	
	0.5 Hours	1 Hour		0.5 Hours	2 Hours		1 Hour	2 Hours
N	21	21	*N*	21	21	*N*	21	21
R	493	410	*R*	483	420	*R*	446	457
U	179	262	*U*	189	252	*U*	226	215
Min. U	179		*Min. U*	189		*Min. U*	215	
U_{crit}	142		U_{crit}	142		U_{crit}	142	
H_0	Accepted		H_0	Accepted		H_0	Accepted	

Table 6.3: Data from the Mann-Whitney U test comparing collagen yields (wt. %) from samples exposed for 0.5 hours and 1 hour on the left, 0.5 hours and 2 hours in the centre, and 1 hour and 2 hours on the right. In each test the null hypothesis (H_0) was accepted, and no statistical significance was found between exposure times.

6.5 Isotope Analyses:

6.5.1 Carbon and Nitrogen Isotope Analyses:

The collagen yield data from this experiment suggests that samples heated above 200°C should be examined further to determine whether the collagen is viable for isotope analyses. Both contamination from exogenous materials or the deterioration of autochthonous molecules may affect the percentage of carbon (%C) or nitrogen (%N) present in bone collagen; thus, %C and %N are used as indicator of collagen quality. Figures 6.15 and 6.16 show the %C and %N of the collagen extracted from bones heated to various temperatures.

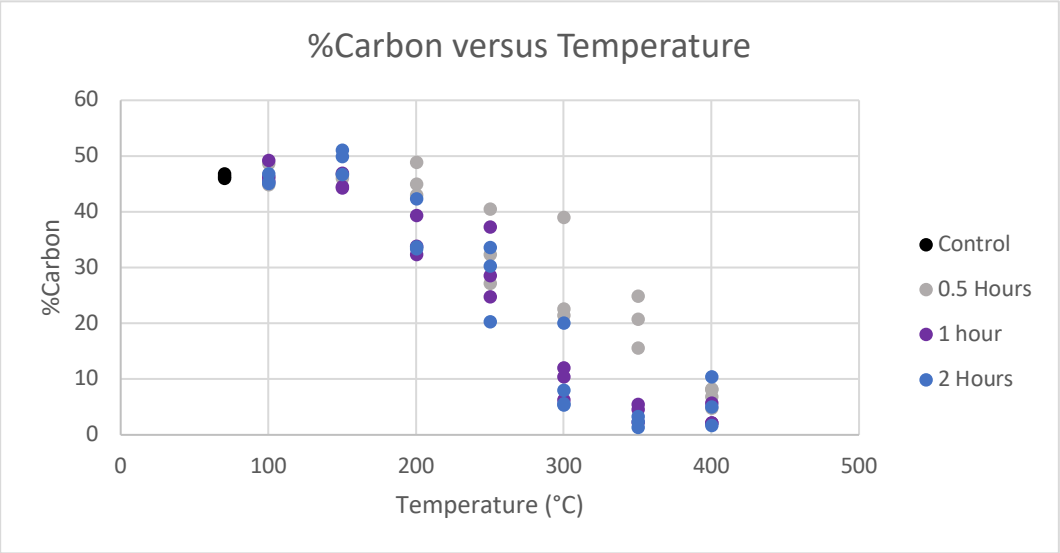


Figure 6.15: Scatterplot showing %carbon against temperature (°C), colour coding shows the exposure time.

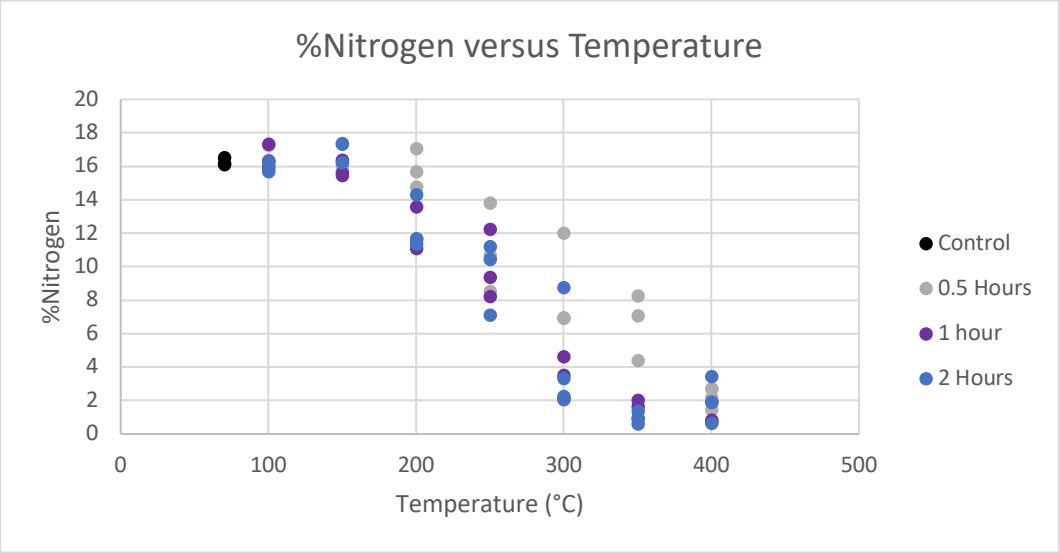


Figure 6.16: Scatterplot showing the %nitrogen against temperature, colour coding shows the exposure time.

Both the %C and %N are reduced as temperature is increased. Exposure time can be shown to have an effect as well, with samples heated for only 0.5 hours showing less reduction between 200°C and 350°C. The reduction in %C due to heat follows closely the reduction in %N, as can be seen in figure 6.17.

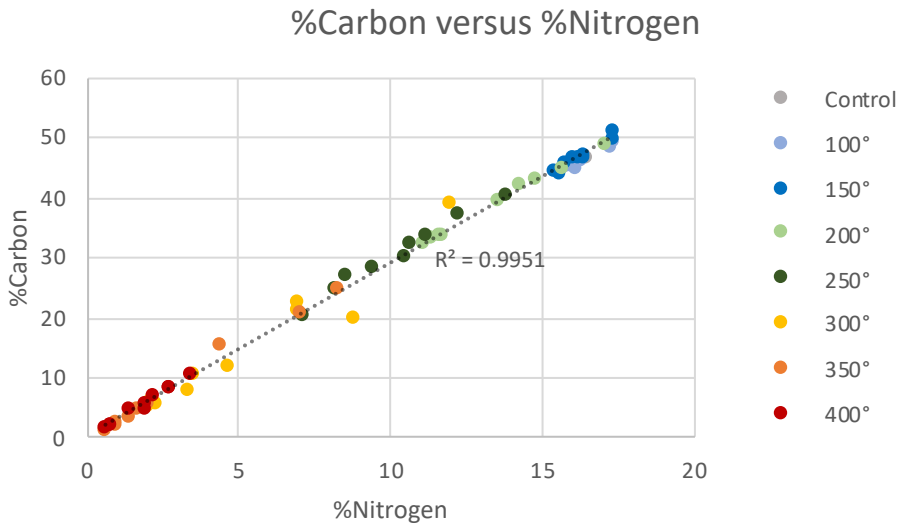


Figure 6.17: Scatterplot showing the relationship between %carbon and % nitrogen, colour coded to show temperature (°C) exposure.

The r^2 value (0.9951) in figure 6.17 shows that the correlation between %C and %N is strong. Both of these values show a negative correlation with temperature. In observations made on archaeological human bone %C levels below 30% are considered suspicious. Regarding the data presented here samples heated to 250°C and above begin to enter this area of compromised collagen (van Klinken, 1999). Nitrogen contents are expected to fall between 11% and 16%, again those samples heated to 250°C and above begin to fall below this expected range (van Klinken, 1999).

The atomic ratio between carbon and nitrogen (C:N) is an established collagen quality indicator. With the boundaries for good quality collagen established as 2.9-3.6 by DeNiro and Hastorf in 1985. However, later research has contested these boundaries and instead suggested a narrower range of 3.1-3.5 (van Klinken, 1999). Figure 6.18 below shows the atomic C:N ratio for the collagen extracted from the bones heated to various temperatures for this experiment. Up to 250°C the atomic C:N ratios are relatively consistent, at 300°C and above the ratios become increasingly scattered. However, some of the data points from samples heated to 400°C fall within the 3.1-3.5 boundaries. These data suggests that atomic C:N ratios alone cannot be used to verify the quality of collagen from burned bone samples. Instead, atomic C:N ratios should be evaluated with %C and %N to ensure that the collagen obtained from these bones is viable for analyses.

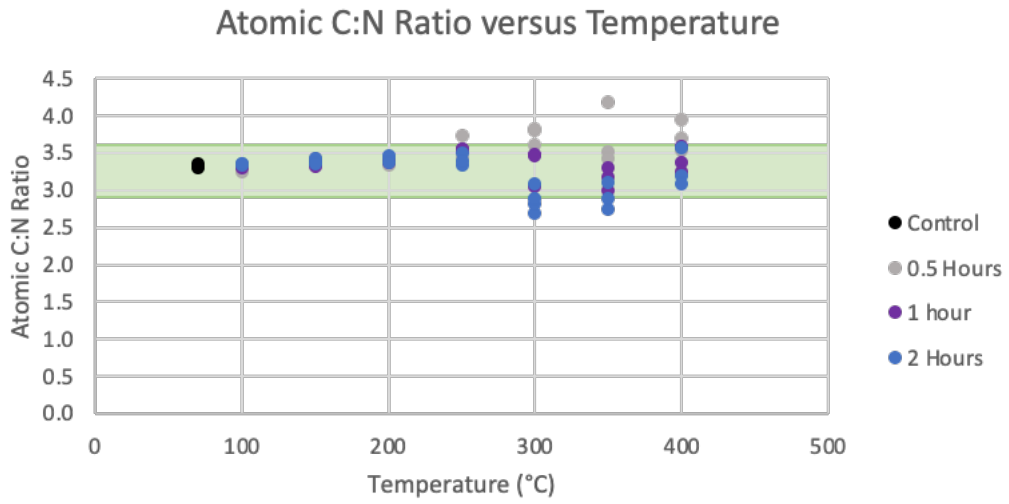


Figure 6.18: Scatterplot showing the variation in the atomic C:N ratio with temperature, colour coded to show exposure time. Green highlighted box shows 'good' collagen range of 2.9-3.6 (DeNiro and Hastorf, 1985).

Although collagen quality indicators suggest that isotope ratios from bone heated to 250°C or above may become questionable, experimental data shows that $\delta^{13}C$ values are minimally affecting by temperatures up to 400°C. There is some increased variation in the $\delta^{13}C$ values from the samples heated to 250°C and above, with a general increase in $\delta^{13}C$ values with increasing temperatures. However, the full range of $\delta^{13}C$ values found in this experiment fall between -24.4‰ and -22.5‰, as shown in figure 6.19.

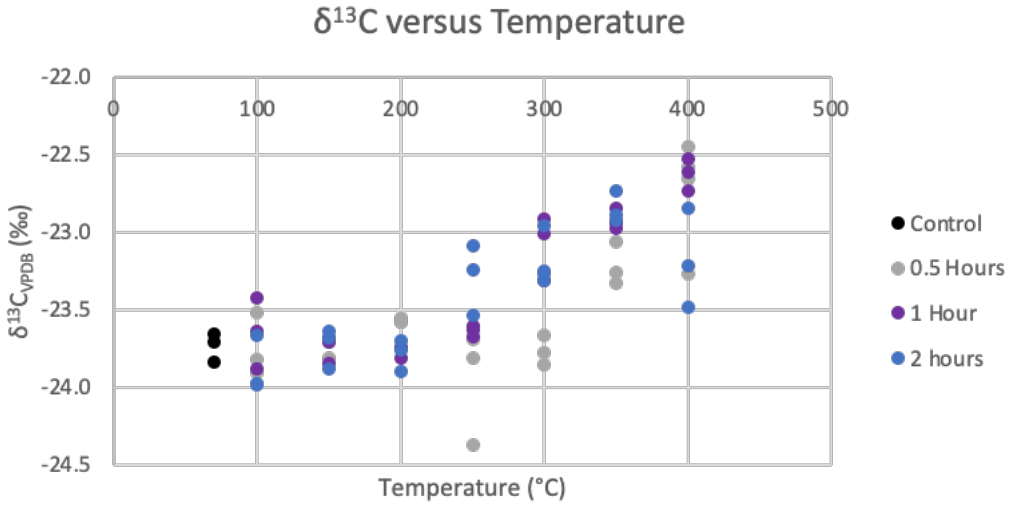


Figure 6.19: Scatterplot showing the variation in the $\delta^{13}C$ values (‰) with temperature, colour coded to show exposure time.

In comparison, $\delta^{15}N$ values are significantly influenced by temperature exposure. The $\delta^{15}N$ values measured in this experiment are consistent up to 200°C. Above this threshold $\delta^{15}N$ values increase with increased temperature exposure. Exposure time influences $\delta^{15}N$ as well, but to a

lesser extent. At 300°C exposure times of half an hour or less appear to have little effect on $\delta^{15}N$ values. The $\delta^{15}N$ values range from 6.1‰ to 14.0‰, as shown in figure 6.20. These results can be correlated with the collagen quality indicators discussed above. Samples heated up to approximately 250°C showed collagen yields, %C, %N, and atomic C:N ratios that suggest collagen is of sufficient quality for isotope analyses.

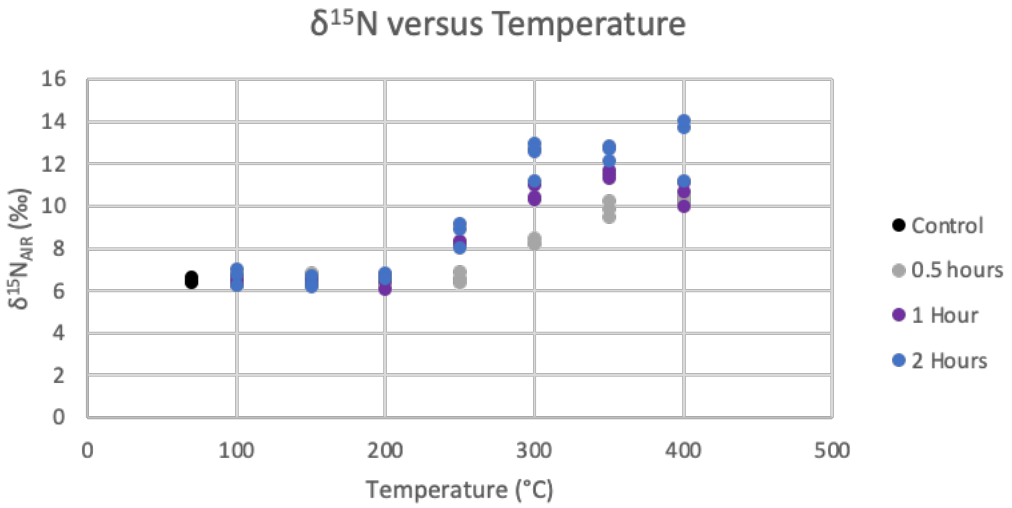


Figure 6.20: Scatterplot showing the variation in the $\delta^{15}N$ values (‰) with temperature, colour coded to show exposure time.

When the $\delta^{13}C$ and $\delta^{15}N$ values from this experiment are plotted together, as in figure 6.21 below, the potential influence of heat on the interpretation of isotope data can be seen. As discussed, the range of the $\delta^{13}C$ values found in this experiment is quite narrow; all of the $\delta^{13}C$ values here would fall within the expected range for animals raised on a diet of C_3 terrestrial plants, for reference see figure 4.8. Below 200°C the average $\delta^{15}N$ value is 6.5‰ ±0.5‰, within the range expected for terrestrial herbivores. Among the samples heated to 250°C the largest deviation from the mean is 2.7‰. However, above this temperature the deviation increases significantly: at 300°C the most elevated sample is 6.4‰ above the mean. The maximum $\delta^{15}N$ value, 14.0‰, would suggest the consumption of marine protein – fully distorting the actual diet of the individual studied. The comparison of the experimental data against the range of data expected from different food sources is shown in figure 6.22.

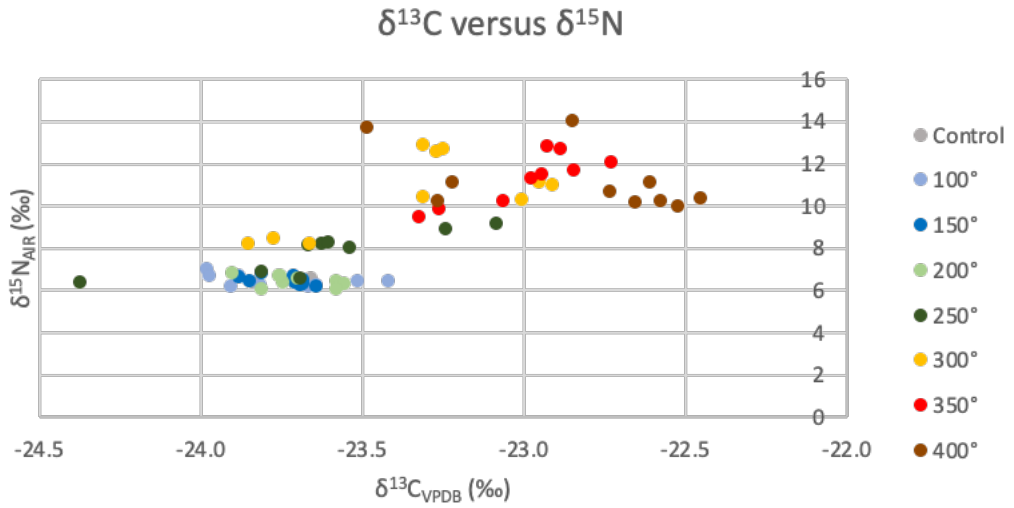


Figure 6.22: Scatterplot showing δ¹⁵N values (‰) plotted against δ¹³C values (‰), colour coding shows temperature (°C) exposure.

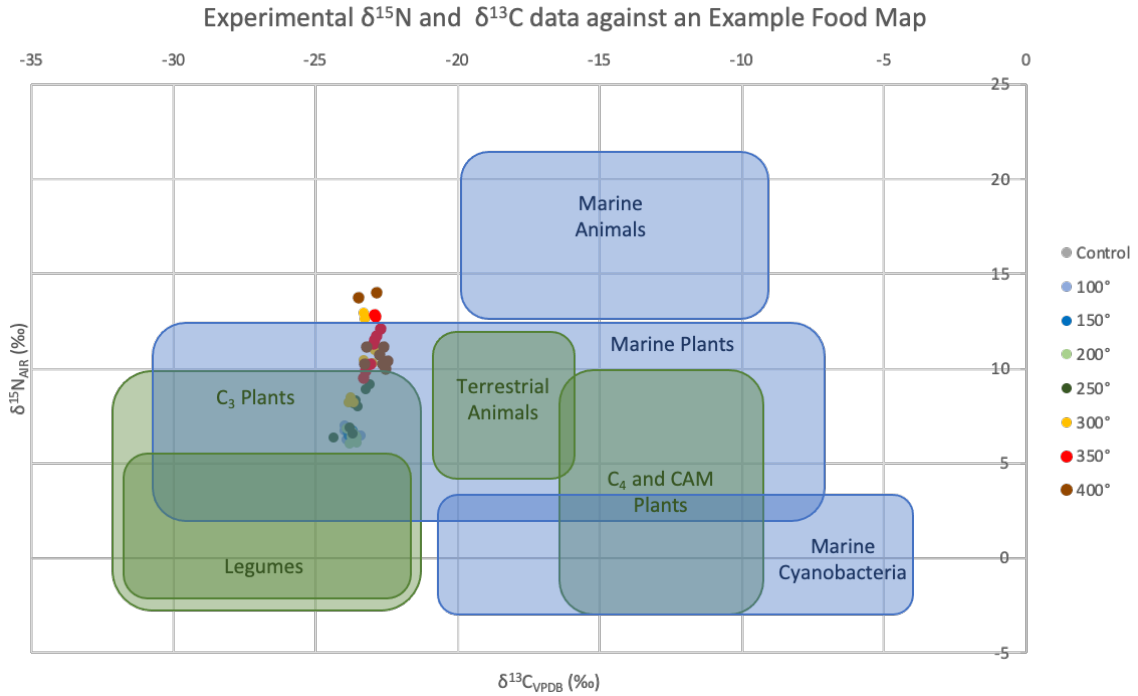
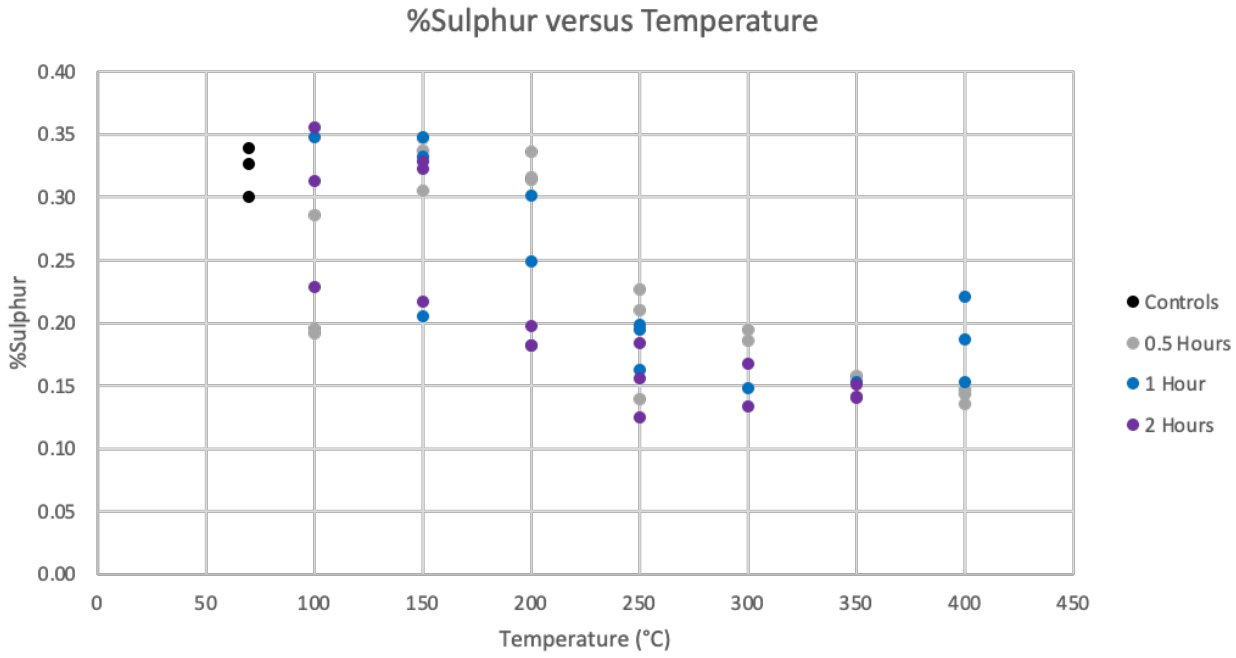


Figure 6.21: Scatterplot of δ¹³C (‰) and δ¹⁵N (‰) data from the controlled heating experiment, colour coded to show temperature (°C) exposure against a food map example. The ranges of isotopically distinct food were reproduced from DeNiro (1987).

6.5.2 Sulphur Analysis:

Sulphur analysis in archaeology is a relatively new technique, thus far no studies have published data on the thermal alteration of $\delta^{34}S$ values measured from bone collagen. The only sulphur containing amino acid in type I collagen is methionine, sulphur contents obtainable from bone collagen are low relative to carbon or nitrogen. General estimates for the sulphur content of

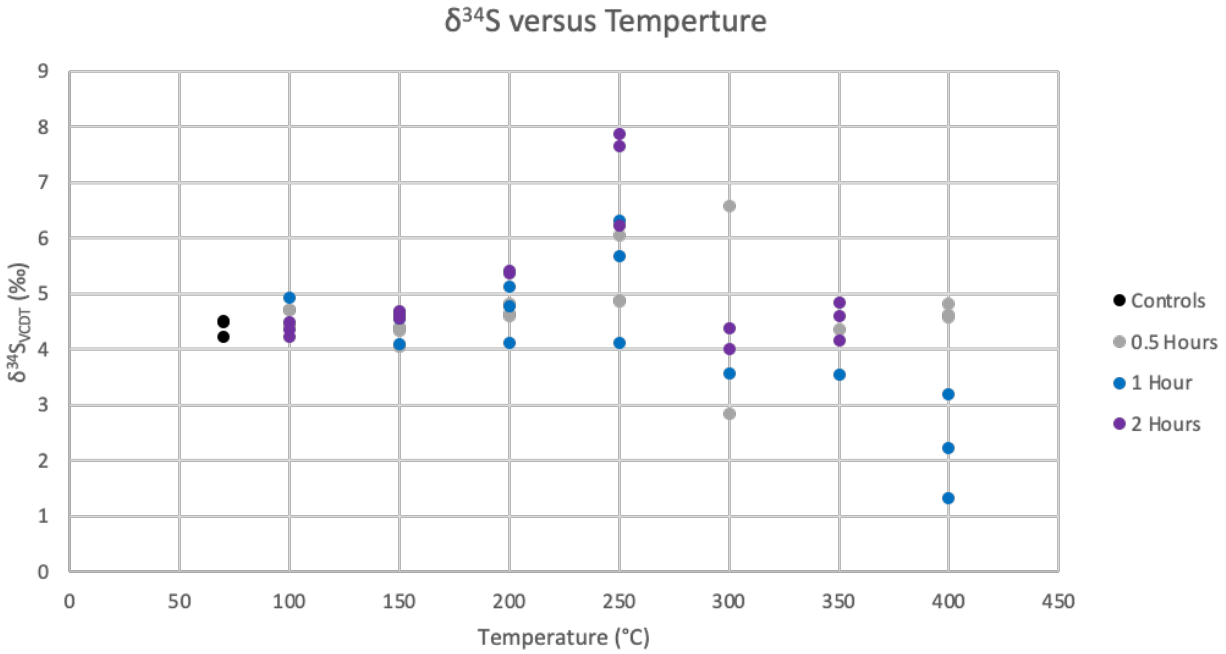
mammalian bone collagen fall between 0.21 wt. % and 0.35 wt. % (Nehlich and Richards, 2009), the mean sulphur content of the control samples from this experiment (0.32 wt. %) aligns with this previous research. Figure 6.23 shows the loss of sulphur with temperature exposure, falling to a mean sulphur content of 0.16 wt. % among samples heated to 400°C. Data from the isotope analyses including %C, $\delta^{13}C$, %N, $\delta^{15}N$, atomic C:N, %S and $\delta^{34}S$ measured from each sample are provided in Appendix 8.



%Sulphur	Control	100°	150°	200°	250°	300°	350°	400°
Mean	0.32	0.27	0.31	0.26	0.18	0.17	0.15	0.16
Maximum	0.34	0.36	0.35	0.34	0.23	0.19	0.16	0.22
Minimum	0.30	0.19	0.20	0.18	0.12	0.13	0.14	0.14
Range	0.04	0.16	0.14	0.15	0.10	0.06	0.02	0.09
Standard Deviation	0.02	0.07	0.05	0.07	0.03	0.03	0.01	0.03

Figure 6.23: Scatterplot (above) showing sulphur content (wt. %) against temperature (°C), colour coded to show exposure times. Table (below) shows basic descriptive statistics of sulphur contents seen at each target temperature.

Although some bone samples show a decreased sulphur content when heated to 100°C, the mean sulphur content remained relatively consistent up to 200°C. However, sulphur contents fell significantly when bone samples were heated to 250°C or higher. Similarly, $\delta^{34}S$ values remain relatively consistent up to 200°C, with all values falling between 4.1‰ and 5.4‰. Initially, $\delta^{34}S$ values increase with increasing temperatures, followed by a decrease in $\delta^{34}S$ values at temperature exposures of 350°C or higher; as shown in figure 6.24.



$\delta^{34}S$	Control	100°	150°	200°	250°	300°	350°	400°
Mean	4.41	4.56	4.45	4.87	5.96	4.28	4.30	3.39
Maximum	4.52	4.92	4.69	5.42	7.87	6.59	4.84	4.82
Minimum	4.23	4.22	4.06	4.13	4.11	2.85	3.55	1.32
Range	0.29	0.70	0.63	1.29	3.76	3.74	1.29	3.50
Standard Deviation	0.16	0.24	0.22	0.43	1.25	1.41	0.49	1.20

Figure 6.24: Scatterplot (above) showing $\delta^{34}S$ values against temperature (°C), colour coded to show exposure times. Table (below) shows basic descriptive statistics of $\delta^{34}S$ values seen at each target temperature.

The full range of $\delta^{34}S$ values observed in this experiment was between a low of 1.3‰ and a high of 7.9‰. This variation in $\delta^{34}S$ values would be sufficient to alter dietary inferences based on these data. Thus, similar to the pattern found in $\delta^{15}N$ values in this study, $\delta^{34}S$ values are reliable only for bone samples heated to 200°C or less. Comparisons of the $\delta^{34}S$ data against $\delta^{13}C$ data are shown in figure 6.25 and against $\delta^{15}N$ data in figure 6.26.

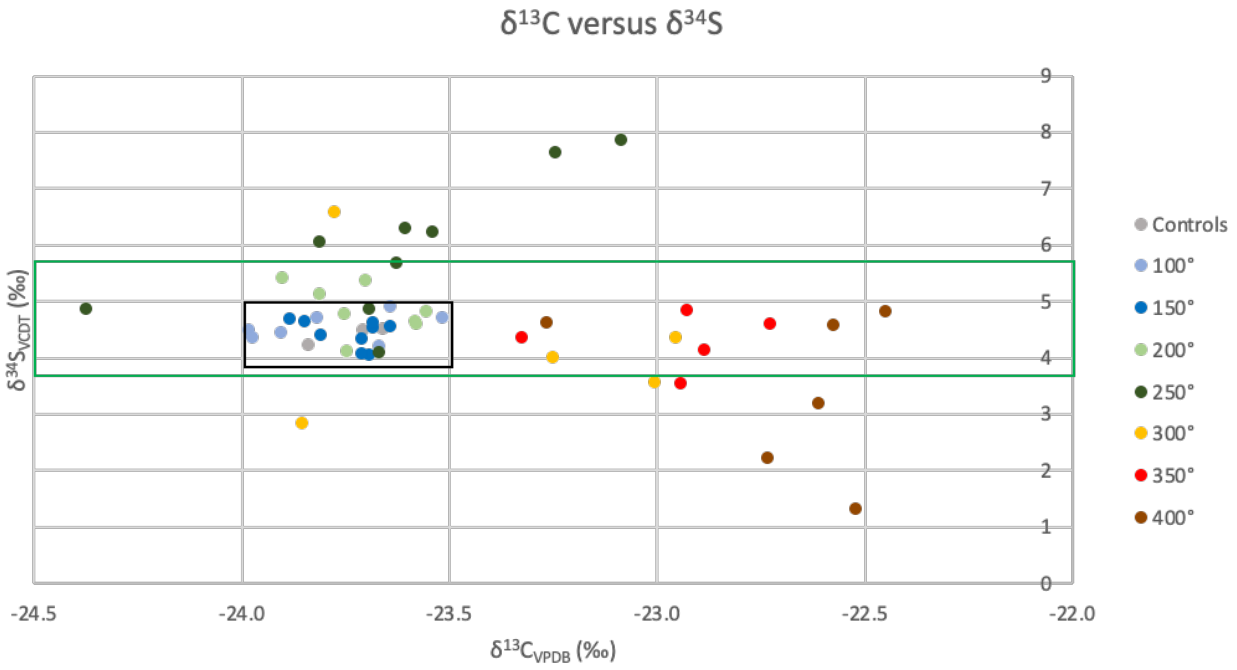


Figure 6.25: Scatterplot showing $\delta^{13}C$ values against $\delta^{34}S$ values colour coded to show temperature (°C) exposures. The black box imposed on the graph isolates data that are within the unaltered range of values, while the green box isolates an acceptable range of values. As there was little variation found in the $\delta^{13}C$ values observed in this experiment, the acceptable range extends across the plotted area.

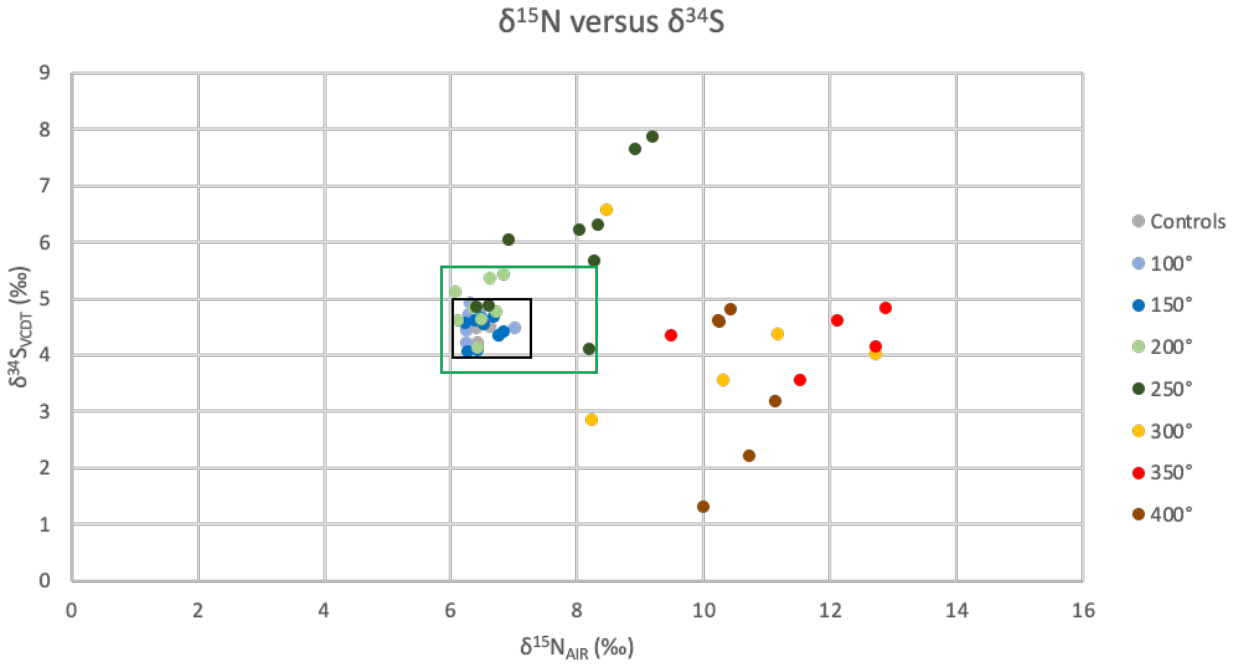


Figure 6.26: Scatterplot showing $\delta^{15}N$ values against $\delta^{34}S$ values colour coded to show temperature (°C) exposures. The black box imposed on the graph isolates data that are within the unaltered range of values, while the green box isolates an acceptable range of values.

6.6 Conclusions:

The results of these experiments are encouraging. Collagen was extractable from bone samples heated to 400°C for two hours, though yields were reduced above 200°C. The $\delta^{13}C$ values were minimally affected by all of the burning conditions tested in this experiment. The $\delta^{15}N$ values were stable up to 200°C, with minor increases at 250°C or at 300°C for exposure times of half an hour or less. Together these results suggest that isotope analysis of burned bones is possible if burning conditions can be established and fall below the threshold temperature of 250°C. Importantly, collagen quality indicators (%C, %N, and atomic C:N ratio) correlated well with the change in $\delta^{15}N$ values at increased temperatures. However, atomic C:N ratio is insufficient as the sole collagen quality criterion as some samples with divergent $\delta^{15}N$ values had atomic C:N ratios within the acceptable boundaries of 2.9-3.6 (DeNiro and Hastorf, 1985). The $\delta^{34}S$ values were stable up to 200°C but deviated from control values significantly above this threshold. Furthermore, observations of bone colour and FTIR absorption spectra suggest that both these measures can be well correlated with changes to the chemical signature of bone collagen. As such, bone colour appears to be an appropriate screening criterion for the selection of archaeologically burned bones for isotope analysis. FTIR analysis can then be used to verify the burning conditions experienced by the selected samples in order to determine whether isotope analysis would be viable. However, there are several additional factors that could affect the collagen preservation in burned bones from archaeological contexts and these will be explored further in later chapters.

Chapter 7: Results from Archaeological Application:

7.1 Introduction:

This chapter presents the results of temperature estimation and isotope analyses of carbon, nitrogen, and sulphur conducted on samples taken from inhumed and cremated individuals from two early Anglo-Saxon mixed rite cemeteries. Samples from forty individuals were taken for this experiment: four inhumed and ten cremated individuals were selected from Elsham cemetery and sixteen inhumed and ten cremated individuals were selected from Cleatham cemetery; see section 5.4.4 for specifics. One sample was taken from each inhumed individual and three samples were taken from each cremated individual.

Two methods of estimating the maximum temperature exposure of the bone samples are presented in section 7.2. The first method, colour analysis, has a long history as an indicator of the thermal history of bone (Shipman et al., 1984; Munro et al., 2007; Walker et al., 2008; Wahl, 2015). Whilst colour can be analysed with precision, it can provide only a broad indication of the maximum temperature exposure experienced by bone and can also be influenced by the burial environment (Taylor et al., 1995; Dupras and Schultz, 2013). Thus, a second method of temperature estimation was employed: Fourier Transform Infrared (FTIR) spectroscopic analysis. FTIR absorption spectra and ratios derived from them have been successfully used to indicate burning intensity experienced by bone samples (Thompson et al., 2009; Thompson et al., 2013; Ellingham et al., 2015a). Section 7.3 presents the collagen yields from the archaeological samples examined here and compares this data against the temperature estimations produced in section 7.2. The results of ^{13}C, ^{15}N, and ^{34}S analyses are presented in section 7.4.

7.2 Temperature Estimation:

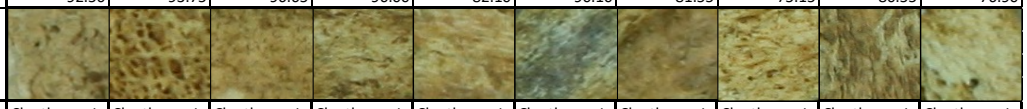
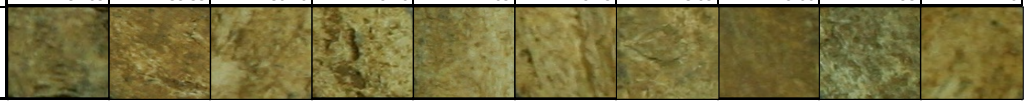
The controlled heating experiment suggested that $\delta^{13}C$ values were relatively stable in bone samples heated up to 400°C for two hours, while $\delta^{15}N$ values were affected at temperatures of 250°C and above; see section 6.5.1 for details. As such, in order to assess

whether isotope ratios from bone samples taken from archaeological cremations represent biogenic values it is necessary to determine the thermal history of the bone samples analysed. Cremation pyres have been measured as exceeding 1000°C; however, unlike modern crematory ovens, traditional pyres do not provide a uniform burning environment (McKinley, 2015; Ward and Tayles, 2015). The temperature exposure of bone is influenced by proximity to the centre of the pyre and the shielding provided by pyre goods, clothing, and overlying flesh (McKinley, 2015; Symes et al., 2015; Wahl, 2015). The burning intensity experienced has been recorded as variable across the skeleton and across individual bones (Mayne Correia, 1997; McKinley, 2015; Symes et al., 2015). Due to this variation, it is necessary to estimate the temperature exposure of each bone sample, even among samples taken from a single individual. Two methods were used to estimate the thermal history of the bone samples taken from archaeological cremations for use in this experiment: colour analysis and FTIR analysis. Colour was used as a broad indicator of burning intensity and used as a selection criterion for the bone samples taken from each cremated individual. Colour was recorded by spectrophotometer for objectivity and precision. FTIR analysis was then used to produce a more exact temperature estimation.

7.2.1 Colour Analysis:

Colour was recorded by spectrophotometer in CIEL*a*b* colour space; see section 5.3.3 for details. Photographs of all the samples selected for analysis from both Elsham and Cleatham are provided in Appendix 9. Both the specular component included (SCI) and specular component excluded (SCE) values were measured and recorded; however, in the interest of clarity only the SCI values are reported here and discussed, while the SCE values are included in the raw data provided in Appendix 10. The results from the colour analysis of the bone samples selected from inhumed individuals from both Elsham and Cleatham are presented in table 7.1.

Table 7.1: The colour data from bone samples taken from inhumed individuals from Elsham and Cleatham early Anglo-Saxon cemeteries. Photographs by Simon Hughes.

Site/Type		Elsham - I	Elsham - I	Elsham - I	Elsham - I	Cleatham - I	Cleatham - I	Cleatham - I	Cleatham - I	Cleatham - I	Cleatham - I
Sample		**EL75EN**	**EL76AL**	**EL76AK**	**EL76JO(a)**	**Grave 10**	**Grave 11**	**Grave 18**	**Grave 19**	**Grave 25**	**Grave 29**
Measure	L*	64.58	60.77	65.43	63.57	61.33	54.41	61.71	70.86	63.77	69.63
	a*	6.39	7.33	6.91	7.30	5.66	3.05	6.39	7.05	5.92	6.40
	b*	19.48	20.97	21.95	20.92	18.80	12.59	19.47	24.98	18.95	22.28
	G	92.50	93.75	96.65	96.00	82.10	90.10	81.55	75.15	80.55	76.90
Image											
Site/Type		Cleatham - I	Cleatham - I	Cleatham - I	Cleatham - I	Cleatham - I	Cleatham - I	Cleatham - I	Cleatham - I	Cleatham - I	Cleatham - I
Sample		**Grave 31**	**Grave 37**	**Grave 38**	**Grave 40**	**Grave 45**	**Grave 48**	**Grave 49**	**Grave 50**	**Grave 54**	**Grave 57**
Measure	L*	57.85	59.76	64.17	62.56	64.78	62.98	61.45	60.66	63.07	63.98
	a*	5.72	6.54	7.04	7.35	6.64	6.43	5.69	6.44	4.32	8.11
	b*	16.59	19.27	21.11	21.40	20.84	19.56	19.68	19.12	17.58	23.49
	G	84.05	83.55	80.20	79.40	77.05	79.75	78.65	79.60	77.95	77.40
Image											

The colour data from the bone samples selected from cremated individuals from Elsham are presented in table 7.2; equivalent data from the samples selected from cremated individuals from Cleatham are presented in table 7.3.

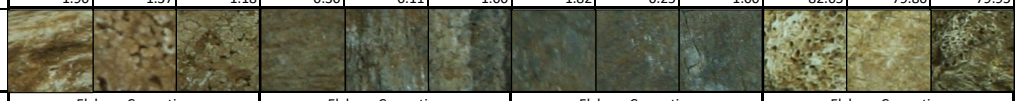
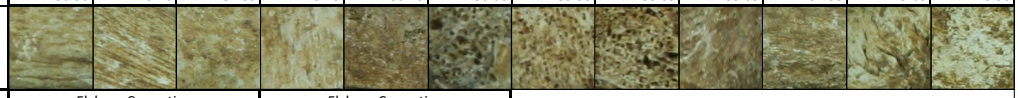
Site/Type		Elsham Cremation			Elsham Cremation			Elsham Cremation			Elsham Cremation		
Urn Number		**EL75AP**			**EL75DW**			**EL75DX**			**EL75ES**		
Sample		**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
Measure	L*	56.64	51.17	51.23	47.83	44.28	46.51	35.99	43.56	42.37	61.42	65.08	63.23
	a*	7.24	5.91	6.00	3.61	4.04	1.86	2.80	3.81	1.62	5.12	5.54	4.01
	b*	21.37	17.93	18.20	13.13	12.57	8.18	9.61	11.81	8.26	14.39	16.40	12.75
	G	1.90	1.37	1.18	0.30	0.11	1.00	1.82	0.25	1.00	82.65	79.80	79.95
Image													
Site/Type		Elsham Cremation			Elsham Cremation			Elsham Cremation			Elsham Cremation		
Urn Number		**EL75LW**			**EL76IL**			**EL76MN**			**EL76NN**		
Sample		**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
Measure	L*	65.37	64.93	60.34	70.11	59.96	57.54	55.44	51.82	57.23	63.43	61.11	63.05
	a*	4.44	4.19	5.05	4.86	3.94	3.28	3.85	3.84	4.65	4.32	4.15	4.55
	b*	14.84	13.55	14.46	17.09	12.36	11.85	12.29	10.46	12.48	13.74	13.14	14.38
	G	80.50	79.10	81.35	75.25	83.75	86.60	89.95	88.65	83.65	82.55	79.65	78.50
Image													
Site/Type		Elsham Cremation			Elsham Cremation								
Urn Number		**EL76PY**			**EL76PZ**								
Sample		**1**	**2**	**3**	**1**	**2**	**3**						
Measure	L*	61.98	60.59	55.65	62.07	54.19	54.20						
	a*	4.17	5.11	4.35	5.52	5.36	5.23						
	b*	12.67	14.26	11.81	15.82	12.16	12.20						
	G	75.15	78.40	80.55	78.25	81.10	80.80						
Image													

Table 7.2: Colour data from bones taken from cremated individuals from Elsham early Anglo-Saxon cemetery. Photographs by Simon Hughes.

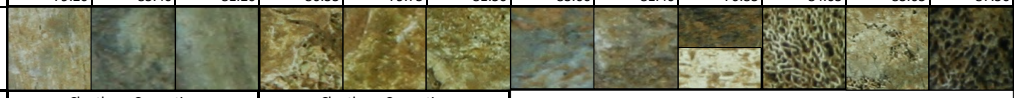
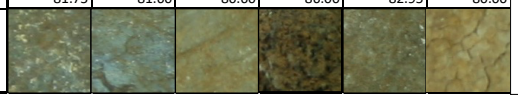
Site/Type		Cleatham Cremation			Cleatham Cremation			Cleatham Cremation			Cleatham Cremation		
Urn Number		MT84FT			MT84IT			MT84KJ			MT85AQ		
Sample		1	2	3	1	2	3	1	2	3	1	2	3
Measure	L*	52.44	55.04	53.00	49.07	52.62	54.47	55.48	56.33	59.24	63.61	58.26	58.87
	a*	3.44	1.15	2.02	0.61	2.25	3.75	0.90	2.21	-0.24	5.55	4.14	4.69
	b*	9.51	5.25	7.45	3.23	7.01	8.96	6.65	9.44	4.36	17.84	14.51	14.57
	G	81.30	80.10	80.85	85.15	83.55	82.45	83.25	81.85	80.30	78.25	81.10	81.20
Image													
Site/Type		Cleatham Cremation			Cleatham Cremation			Cleatham Cremation			Cleatham Cremation		
Urn Number		MT85AR			MT85BH			MT86TR			MT88AAA		
Sample		1	2	3	1	2	3	1	2	3	1	2	3
Measure	L*	60.05	52.87	57.70	62.33	60.52	58.19	55.84	57.50	62.53	54.60	55.24	47.76
	a*	-0.80	1.46	1.72	3.91	4.75	4.69	1.27	2.70	1.98	2.28	3.23	1.70
	b*	1.29	6.33	8.43	15.15	15.68	14.10	6.76	10.86	9.60	9.32	10.62	6.06
	G	79.20	85.40	81.20	80.35	79.75	81.50	83.00	81.40	76.85	84.05	83.05	87.50
Image													
Site/Type		Cleatham Cremation			Cleatham Cremation								
Urn Number		MT88ALD			MT89BBT								
Sample		1	2	3	1	2	3						
Measure	L*	54.52	53.20	53.84	44.26	52.48	58.46						
	a*	0.21	0.55	1.99	1.81	3.10	5.12						
	b*	3.27	4.68	7.96	4.77	8.91	13.80						
	G	81.75	81.60	80.60	86.00	82.95	80.00						
Image													

Table 7.3: Colour data from bones taken from cremated individuals from Cleatham early Anglo-Saxon cemetery. Two samples (MT84FT-1 and MT86TR-3) showed distinct bands on colour and are therefore represented by two photos each to show this variation. Photographs by Simon Hughes.

The bone samples from cremated individuals were selected on the basis of colour and therefore do not represent the full range of colours that were present among the bones of each individual. Instead, most of the cremated bone samples fall into brown, black, or grey colour profiles. Brown samples were expected to represent temperature exposures between 200°C and 300°C, black samples between 300°C and 400°C. Grey samples were likely exposed to temperatures above 400°C on the exterior surface but several of these samples showed darker colouration below the surface suggesting the internal temperature of the bone did not exceed 400°C. Sample MT86TR-3 shows a white calcined exterior surface that suggests a temperature exposure of 650°C or above, but a black charred internal surface suggesting temperature below 400°C (Wahl, 2015). These expectations are derived from the experimental data presented in section 6.3.2 and previously published literature (Munro et al., 2007; Walker et al., 2008; Wahl, 2015). However, there are several other factors that may lead to colour changes in bone as discussed in section 3.5.2; thus, while bone colour was used as a screening criterion in the selection of bone samples, temperature estimates based solely on bone colour are not considered robust.

The colour data in CIEL*a*b* space is shown in figure 7.1. Importantly while the scatter plot to the right of figure 7.1 covers the entire range of L* space, the central plot shows only a small sub-section of a*b* space as reflected by the circular plot to the left.

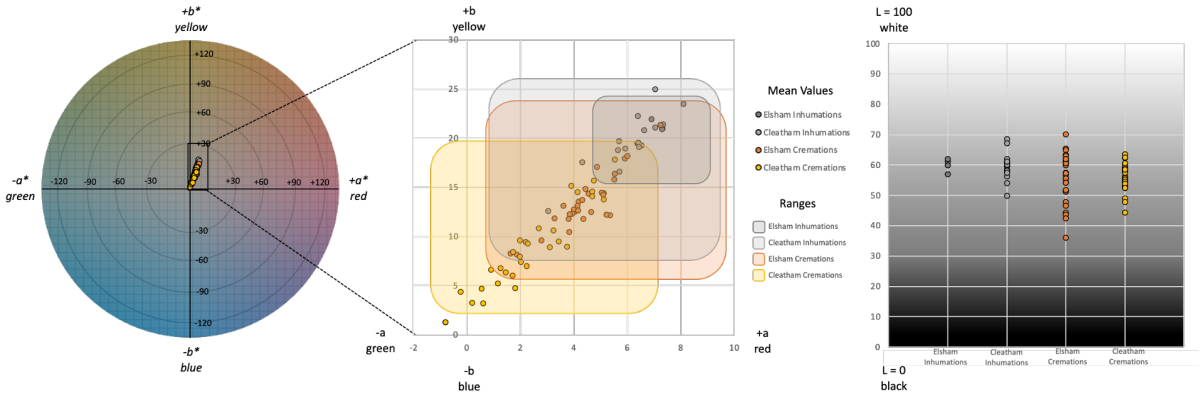


*Figure 7.1: Colour data in CIEL*a*b* space. The circular plot to the left represents the a* (red-green) and the b* (yellow-blue) axes (reproduced from Mouw, 2018). The black square on the circular plot is equivalent to the area shown in the central scatterplot showing colour data from the archaeological samples. The scatterplot on the right shows the L* axis (black-white). The data is colour coded to show site and burial type: dark grey points represent Elsham inhumations (n=4), light grey points represent Cleatham inhumations (n=16), orange points represent Elsham cremations (n=30) and yellow points represent Cleatham cremations (n=30).*

7.2.2 Fourier Transform Infrared (FTIR) Spectroscopic Analysis:

As discussed in section 3.5.5.a, FTIR analysis produces absorption spectra that reflect the chemical composition of a bone sample, this raw data is presented in Appendix 11. Previous research has established the expected changes in the absorption spectra for bone subjected to a variety of burning conditions. Lower temperature exposures cause changes in absorption peaks influenced by organic compounds such as those at 1650 cm^{-1}, 1550 cm^{-1}, 1455 cm^{-1}, 1415 cm^{-1}, and 1250 cm^{-1}. Higher temperature exposures affect absorption peaks that are influenced by mineral compounds, observed particularly at 1035 cm^{-1}, 900 cm^{-1}, 605 cm^{-1}, and 565 cm^{-1} (Thompson et al., 2013, Ellingham, 2015a). The FTIR data, normalised to the peak at 1035 cm^{-1}, from the samples taken from individuals interred at Elsham and Cleatham cemeteries are presented in figure 7.2.

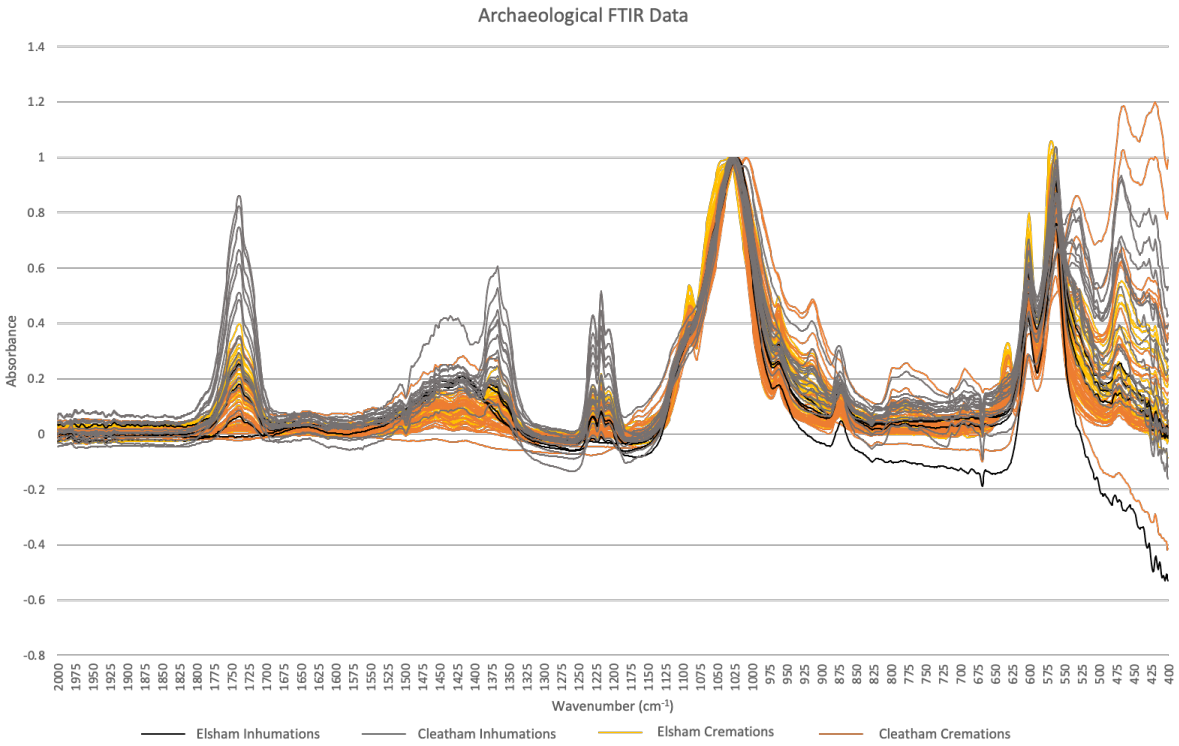


Figure 7.2: Absorption spectra produced via FTIR analyses conducted on archaeological samples of human bone, normalised to the peak at 1035 cm^{-1}. Black lines are samples from inhumed individuals from Elsham cemetery (n=4), grey lines are samples from inhumed individuals from Cleatham cemetery (n=16), yellow lines are samples from cremated individuals from Elsham cemetery (n=30), and orange lines are samples from cremated individuals at Cleatham cemetery (n=30).

Samples taken from inhumed individuals produced spectra that show some indication of collagen conservation in the region between 1250 cm^{-1} and 1650 cm^{-1}, as expected from unheated samples. The cremated samples from both cemeteries show smaller peaks in the region between 1250 cm^{-1} and 1650 cm^{-1}, though the remnants of peaks in these areas indicate that organic materials remain present in these samples. To better illustrate the comparison between peak values of samples from cremated and inhumed individuals these values were plotted against collagen yield; several of these comparisons are shown in figure 7.3.

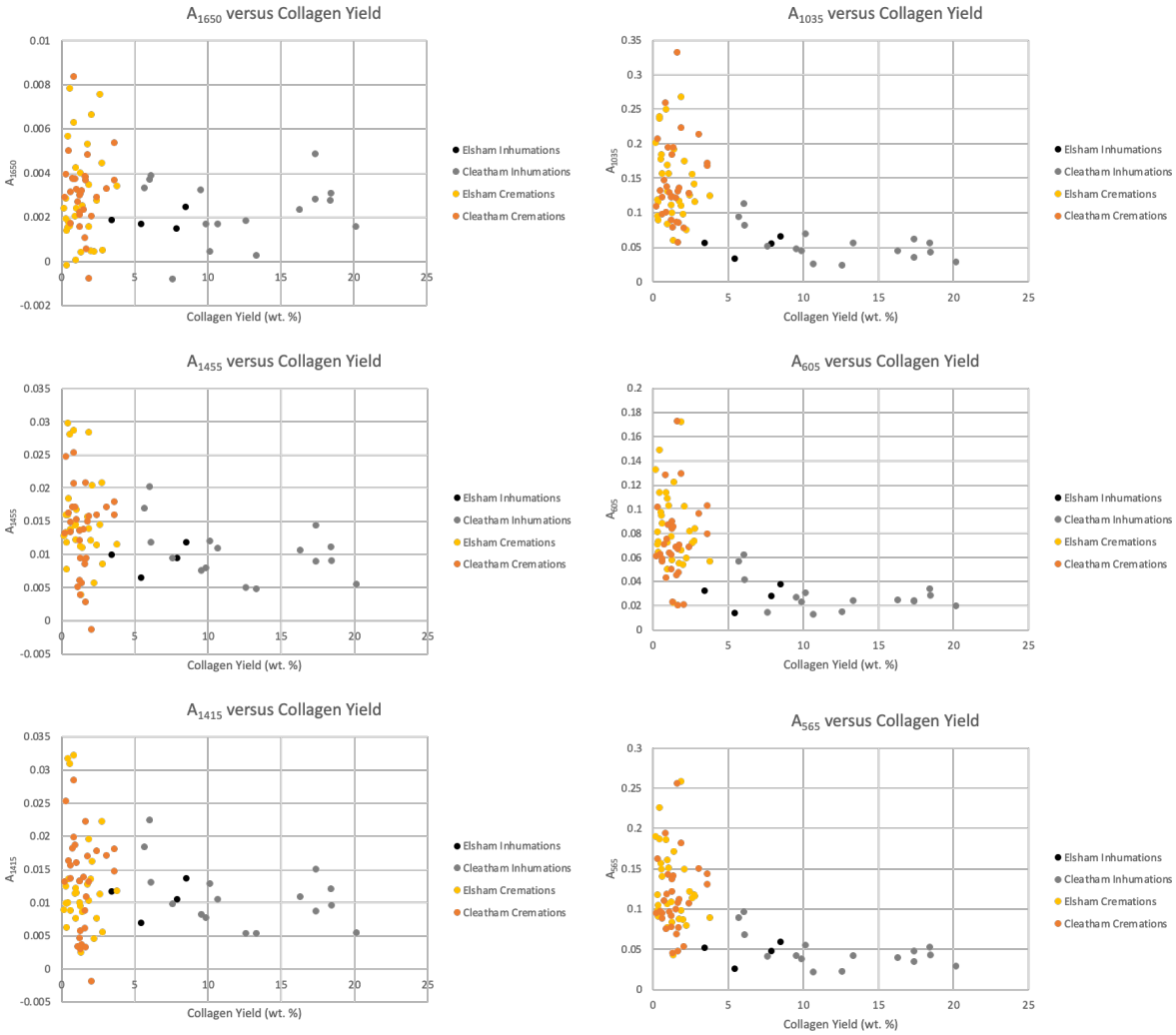


Figure 7.3: Absorption peak values plotted against collagen yield, in percentage by weight (%). In each plot samples from inhumed individuals from Elsham cemetery (n=4) are in black, samples from inhumed individuals from Cleatham (n=16) are in grey, samples from cremated individuals from Elsham (n=30) are in yellow and samples from cremated individuals from Cleatham (n=30) are in orange. Scatterplots in the left-hand column represent absorption peaks that are associated with organic components of bone, from top to bottom these are the peaks at 1650 cm^{-1}, 1455 cm^{-1} and 1415 cm^{-1}. Scatterplots in the right-hand column represent absorption peaks that are associated with mineral components of bone, from top to bottom these are the peaks at 1035 cm^{-1}, 605 cm^{-1} and 565 cm^{-1}.

The graphs presented in the left column of figure 7.3 show considerable overlap in the absorption data between cremated and inhumed individuals, an overlap that is not reflected in the collagen yields. Collagen yields will be discussed in more detail in section 7.3, but here yields are used as a proxy for the thermal modification of the bone samples. Unmodified human bone samples yield approximately 22 wt.% collagen when extracted; thus, as yields trend toward zero bone samples are increasingly modified – either by thermal alterations or diagenetic changes (van Klinken, 1999). The graphs in the right column of figure 7.3 show good separation of samples from inhumed individuals and those

from cremated individuals both in collagen yield and in absorption values. Thus, the chemical differences between samples that produced high collagen yields and those that produced low collagen yields are best reflected by the peaks at 1035 cm^{-1}, 605 cm^{-1} and 565 cm^{-1}; these three absorption peaks have been associated with changes in the mineral phase of bone in previous research (Thompson et al., 2013). To eliminate issues of background noise, FTIR data are often reported as ratios between peaks rather than as individual peaks. The most commonly reported is the Crystallinity Index (CI), which is shown relative to collagen yield in figure 7.4. The formula for CI is included in section 3.5.5.a.

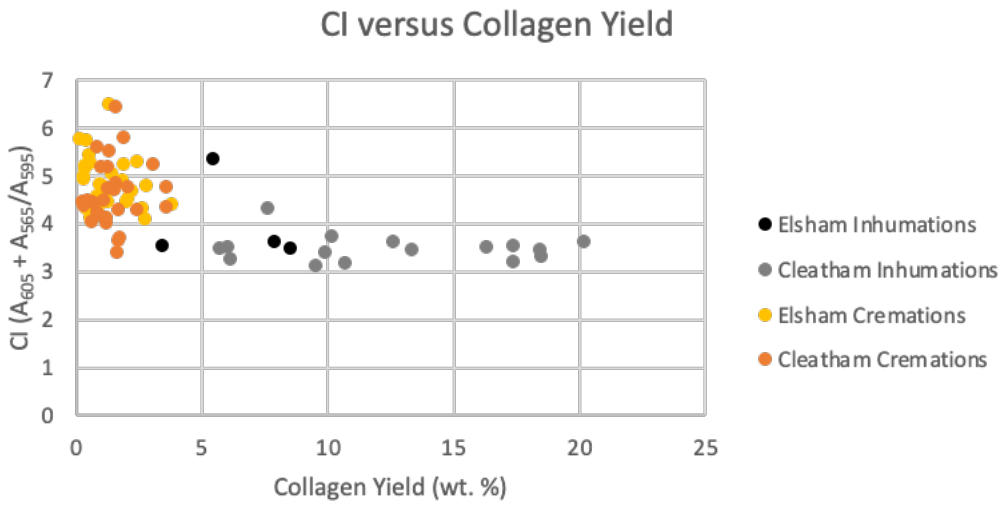


Figure 7.4: Crystallinity Index (CI) versus collagen yield, in weight percentage (%). Samples from inhumed individuals from Elsham cemetery (n=4) are in black, samples from inhumed individuals from Cleatham cemetery (n=16) are in grey, samples from cremated individuals from Elsham cemetery (n=30) are in yellow and samples from cremated individuals from Cleatham cemetery (n=30) are in orange.

The samples taken from inhumed individuals, regardless of collagen yield, produced CI values that cluster around three, while the samples taken from cremated individuals showed elevated CI values. In past research, as well as in the results presented from the controlled heating experiment in section 6.3.3, CI was not effective in separating samples exposed to low temperatures from unheated control samples (Thompson et al., 2013). However, CI was effective in distinguishing samples heated between 400°C and 700°C. The distinct separation seen in figure 7.4 suggests that the samples taken from cremated individuals from Cleatham and Elsham cemeteries likely were heated to temperatures within this range (Thompson et al., 2013). The most effective separation between samples taken from cremated individuals versus those taken from inhumed individuals were ratios

that included the phosphate peak at 1035 cm^{-1}; an example is shown in figure 7.5. This comparison shows the phosphate peak at 1035 cm^{-1} compared against the peak at 1650 cm^{-1} which has been related to organic compounds in bone, both carbonyl and amide I (Thompson et al., 2013). Thus, the ratio shown in figure 7.5 compares a mineral compound against an organic compound resulting in a distinct separation between the samples taken from cremated individuals and those taken from inhumed individuals. Conversely, ratios that included only peaks related specifically to organic molecules present in bone failed to produce significant separation; an example is shown in figure 7.6. This reflects the loss of organic material from the samples taken from cremated individuals as both the 1415 cm^{-1} peak and the 1455 cm^{-1} peak are related to methylene (Ellingham et al., 2015a).

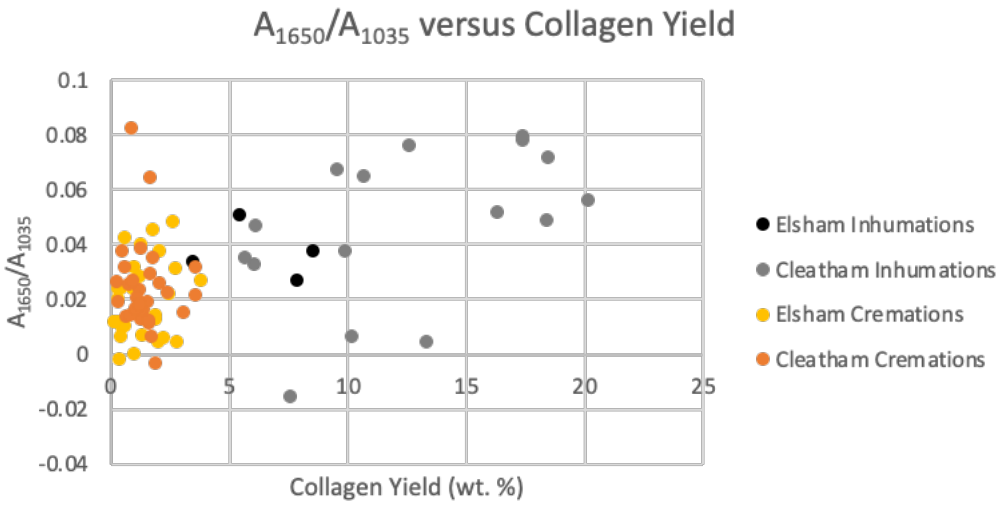


Figure 7.6: Ratio between peaks related to carbonate (CO_3) and methylene (CH_2) at 1455 cm^{-1} and 1415 cm^{-1}. Samples from inhumed individuals from Elsham cemetery (n=4) are in black, inhumed individuals from Cleatham cemetery (n=16) are in grey, cremated individuals from Elsham cemetery (n=30) are in yellow and cremated individuals from Cleatham cemetery (n=30) are in orange.

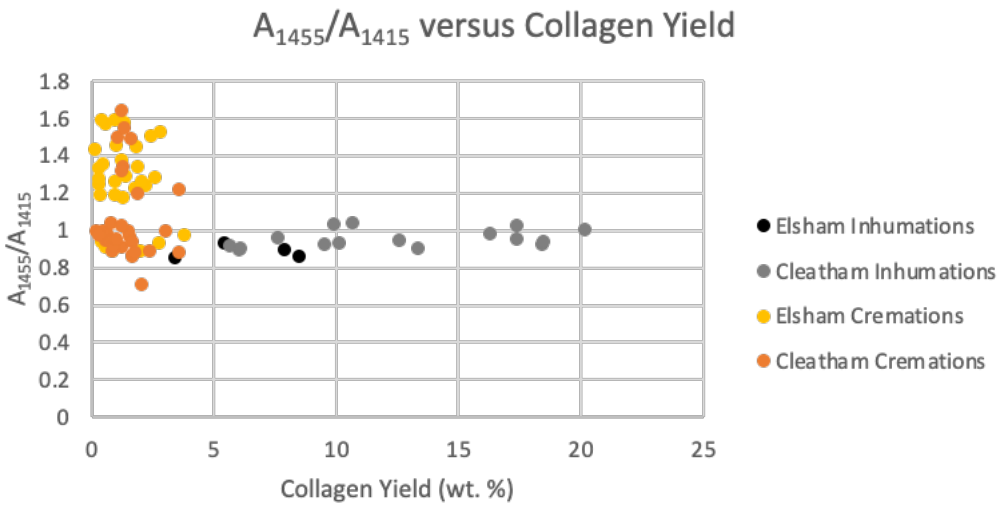


Figure 7.5: Ratio between the peak at 1650 cm^{-1} associated with carbonyl and amide I and the peak at 1035 cm^{-1} associated with phosphate. Samples from inhumed individuals from Elsham cemetery (n=4) are in black, inhumed individuals from Cleatham cemetery (n=16) are in grey, cremated individuals from Elsham cemetery (n=30) are in yellow and cremated individuals from Cleatham cemetery (n=30) are in orange.

As shown in figures 7.2 through 7.6, the FTIR data indicates that there is a difference in the mineral component of the bone samples taken from cremated individuals when compared against samples taken from inhumed individuals. Differences were also seen in comparisons between mineral and organic components of bone samples from cremated and inhumed individuals, as in figure 7.5. Changes in the mineral components of bone are not expected in thermal exposures of under 500°C (Thompson, 2005). Unfortunately, this suggests that despite the exterior appearance indicating lower temperatures, these samples have been exposed to temperatures in excess of 500°C. Alternatively, these changes may be associated with interactions with the burial environment. The same changes that occur in bone as it is heated, the loss of organic material and the increase in the crystallinity of bone mineral, occur via diagenesis (Surovell and Stiner, 2001).

7.3 Collagen Yield:

As stated in section 6.4, collagen yield is commonly expressed as a percentage by weight and fresh human bone is expected to yield approximately 22 wt.% collagen extract relative to the weight of the original sample (van Klinken, 1999). Archaeological samples rarely yield this level of collagen, as collagen breakdown occurs before death and continues at a rate dependent on burial conditions; see section 4.3 for details (Collins et al., 2002). A full record of the collagen extraction procedure for samples from inhumation burials is provided in Appendix 12, and for samples from cremation burials in Appendix 13. As seen in section 6.4, collagen yields are also expected to drop due to thermal degradation, particularly if bone reaches temperatures of 200°C or more. This pattern has also been found in previous research (DeNiro et al., 1985; Schurr and Hayes, 2008; Harbeck et al., 2011). The average collagen yield from the samples taken from inhumed individuals at Cleatham was 12.5 wt.% and at Elsham was 6.3 wt.%; however, this should not be considered definitive evidence of differential preservation between the two sites due to the small sample size available from Elsham. The average collagen yield from the samples taken from cremated individuals was 1.4 wt.% at Cleatham and 1.3 wt.% at Elsham; see table 7.4. These low yields may reflect thermal degradation of collagen within the samples; see distribution in figure 7.7. However, soil inclusions may have affected the initial weight of the bone samples, especially the samples taken from cremated individuals. While the samples from inhumed individuals were cortical bone samples, which can effectively be cleaned of soil contamination by removing the superficial layer of bone with a dental burr, several of the samples taken from cremated individuals involved trabecular bone that cannot entirely be rid of soil inclusion prior to collagen extraction. Therefore, the collagen yields from these samples may be artificially low as these values are measured as a weight percentage.

Table 7.4: Collagen yields as weight percentage from cremated and inhumed individuals from Cleatham and Elsham cemeteries.

Yield (wt.%)	Mean	Maximum	Minimum	Range
Elsham Inhumations	6.3	8.5	3.4	5.1
Cleatham Inhumations	12.5	20.1	5.7	14.5
Elsham Cremations	1.3	3.8	0.1	3.6
Cleatham Cremations	1.4	3.6	0.2	3.4
Inhumations	9.4	20.1	3.4	16.7
Cremations	1.4	3.8	0.1	3.6

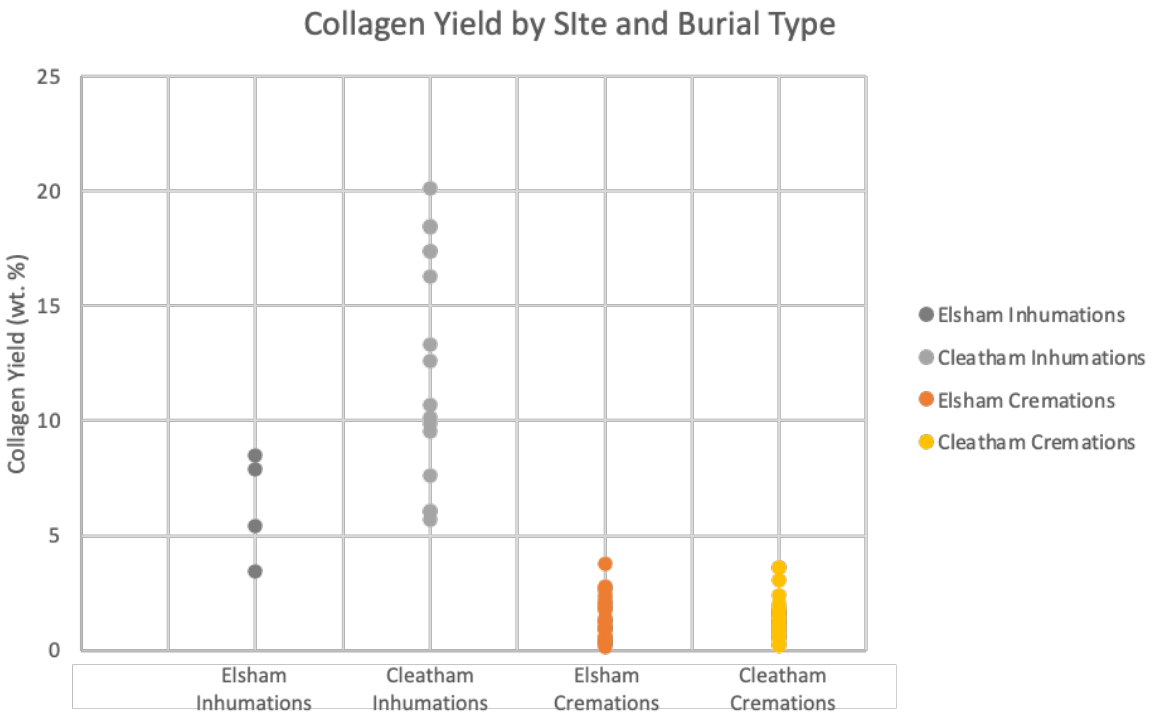


Figure 7.7: Collagen yields expressed as percentages by weight. Samples from inhumed individuals from Elsham cemetery are in black (n=4), samples from inhumed individuals from Cleatham cemetery (n=16) are in grey, samples from cremated individuals from Elsham cemetery (n=30) are in orange, and samples from cremated individuals from Cleatham cemetery (n=30) are in yellow.

The low collagen yields seen in the samples taken from cremated individuals necessitate the careful consideration of collagen quality indicators in the interpretation of stable isotope data from these samples.

A Kolmogorov-Smirnov test was used to determine whether the difference between the collagen yields (wt. %) of inhumations and cremations was significant. A critical value of 0.35 was calculated using the formula presented in section 5.3.8 for a significance level of 0.05 for populations of $N_1 = 20$ and $N_2 = 60$. The maximum difference, 0.95, between the distributions shown in figure 7.8 exceeded the critical value and the null hypothesis, that mortuary rite would have no effect on collagen yield, was rejected. The inhumation and cremation burials were then examined as separate populations and a Kolmogorov-Smirnov test was conducted to determine whether the collagen yields were influenced by site. These distributions are also shown in figure 7.8. For the inhumed individuals a critical value of 0.42 was calculated for a significance level of 0.05 for populations of $N_1 = 4$ and $N_2 = 16$. The maximum difference between the distributions was 0.75 and the null hypothesis was rejected, suggesting that for the inhumed individuals location was a significant factor

affecting collagen yields. For the cremated individuals a critical value of 0.06 was calculated for a significance level of 0.05 and a population size of 30. The maximum difference between the distributions was 0.17; therefore, the null hypothesis was rejected suggesting that for the cremated individuals location was also a significant factor affecting collagen yield.

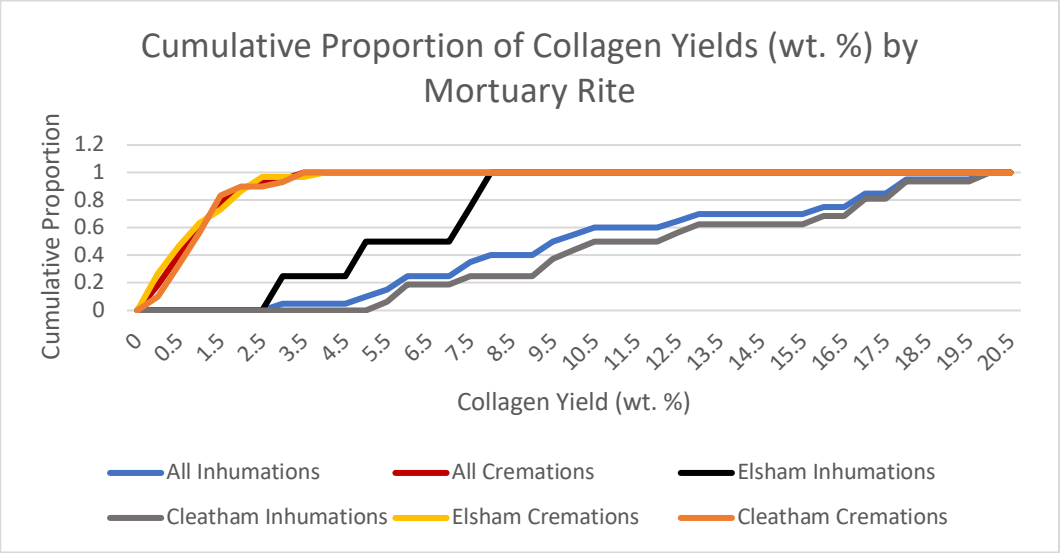


Figure 7.8: Graph showing the cumulative proportion of collagen yields (wt. %) from archaeological samples. The combined populations of inhumed individuals (n=20) are shown in blue, the combined population of cremated individuals (n=60) in red, the Elsham inhumation burials (n=4) in black, the Cleatham inhumation burials (n-16) in grey, the Elsham cremation burials (n=30) in yellow and the Cleatham cremated burials (n=30) in orange.

Further analysis of these data was conducted through the Mann-Whitney U test. For the comparison of all the inhumed individuals against all the cremated individuals a *z* value of 3.67 was calculated, as 60 cremated individuals were sampled for this study. The equation for the calculation of the *z* value is given in figure 5.6. This was compared against a critical *z* value of 1.96. As the critical value was exceeded the null hypothesis was rejected; see the data presented in table 7.5. The two data sets can therefore be considered statistically different according to both the Kolmogorov-Smirnov test and the Mann-Whitney U test. When comparing the inhumed individuals interred at Elsham ($N_1 = 4$) against those interred at Cleatham ($N_2 = 16$) the critical value was 11. The U_{min} for these data fell below this value and therefore the null hypothesis was rejected; see the data in table 7.5. Both tests indicate that the difference in collagen yield (wt. %) between the

inhumed individuals interred at Elsham and those interred at Cleatham was significant. When comparing the cremated individuals interred at Elsham (N_1 = 30) and those interred at Cleatham (N_2 = 30) the critical value was 317. The U_{min} for these data exceeded this value and the null hypothesis was accepted; see the data presented in table 7.5. This result contradicts the Kolmogorov-Smirnov test for these data. Thus, while there is a difference in the distribution of collagen yields (wt. %) between cremated individuals from Elsham and Cleatham, this difference is not sufficient to significantly affect the mean collagen yields (wt. %) from these sites; see table 7.4.

Table 7.5: Data from the Mann-Whitney U test comparing collagen yields (wt. %) from samples taken from cremated and inhumed individuals interred at Elsham and Cleatham cemeteries. When comparing all inhumed individuals and all cremated individuals the null hypothesis (H_0) was rejected, the null hypothesis was also rejected when comparing inhumed individuals from Elsham cemetery against those from Cleatham cemetery. In both cases the difference between populations was found to be significant. However, when comparing cremated individuals from the two cemeteries the null hypothesis was accepted and no statistical significance was found.

Value	All Individuals		Value	Inhumations		Value	Cremations	
	Inhumations	Cremations		Elsham	Cleatham		Elsham	Cleatham
N	20	60	*N*	4	16	*N*	30	30
U	3	1197	*R*	18	192	*R*	879	951
Min. U	3		*U*	56	8	*U*	486	414
z_U	3.67		*Min. U*	8		*Min. U*	414	
z_{crit}	1.96		U_{crit}	11		U_{crit}	317	
H_0	Rejected		H_0	Rejected		H_0	Accepted	

7.4 Isotope Analyses:

7.4.1: Carbon and Nitrogen Analyses:

7.4.1.a Inhumed Individuals:

The collagen extracted from inhumed individuals falls in line with previously published collagen quality indicators. The expected carbon content (%C) for bone samples from Western Europe should fall between 26.0% and 43.6%. All the samples taken from inhumed individuals from Cleatham and Elsham cemeteries conform to this standard; see figure 7.9 (van Klinken, 1999). The expected nitrogen content (%N) falls between 11% and 16%, from the same cohort (van Klinken, 1999). Two samples from Elsham fall below this standard, those taken from EL75EN and EL76AK; these samples had nitrogen contents of 10.4% and

10.3% respectively. All raw data from the isotope analyses conducted on archaeological samples are presented in Appendix 14.

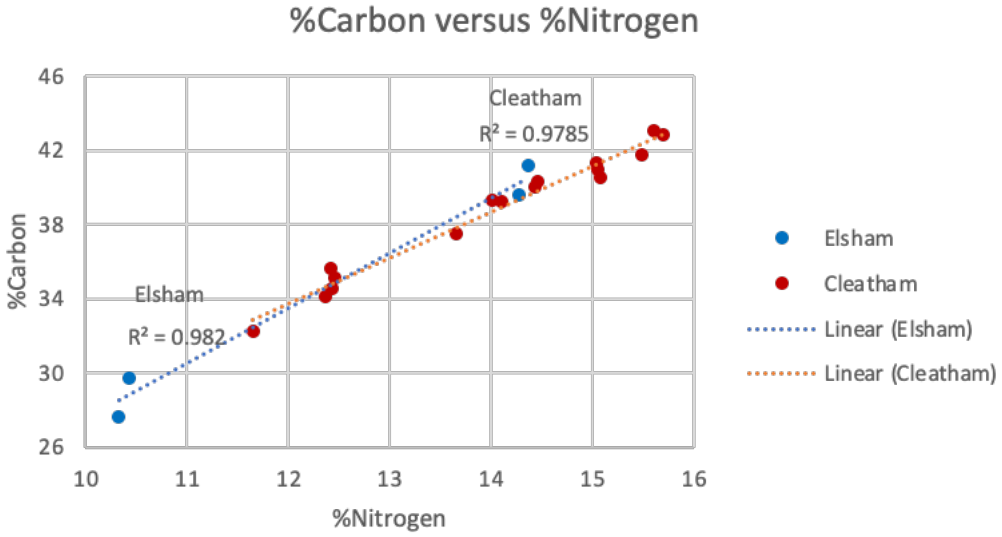


Figure 7.9: Carbon content (%) versus nitrogen content (%) from collagen extracted from inhumed individuals from Elsham cemetery (n=4) in blue and Cleatham cemetery (n=16) in red.

The two samples, EL75EN and EL76AK, also show low carbon yields. As such, these samples have C:N ratios that fall within the accepted range of 2.9-3.6 and the narrowed range of 3.1-3.5; see figure 7.10 (DeNiro, 1985; van Klinken, 1999). However, the isotope results from these individuals should still be interpreted with caution, especially due to the small sample size available from Elsham cemetery.

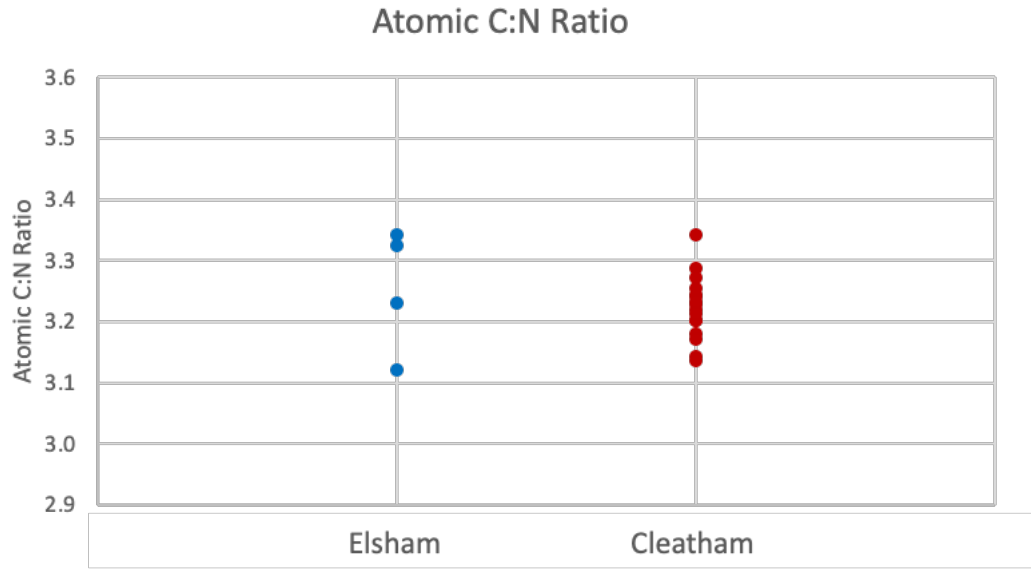


Figure 7.10: Atomic C:N ratios from collagen extracted from inhumed individuals from Elsham cemetery (n=4) in blue and Cleatham cemetery (n=16) in red. Plotted area covers range of 'good' collagen established by DeNiro and Hastorf in 1985.

The stable isotope ratios fall in line with expected values from this time period: C_3 terrestrial based diets with contributions from terrestrial mammalian protein; see figure 7.11. The range of $\delta^{13}C$ values from the two sites is from -23.9‰ to -20.5‰, well within a C_3 signature. The range of $\delta^{15}N$ values from the two sites is from 9.4‰ to 11.6‰, a range that can be explained by consumption of terrestrial proteins. While the two lowest $\delta^{15}N$ values are from individuals interred at Elsham cemetery, only one of these individuals had a low nitrogen content that would lend uncertainty to the data point.

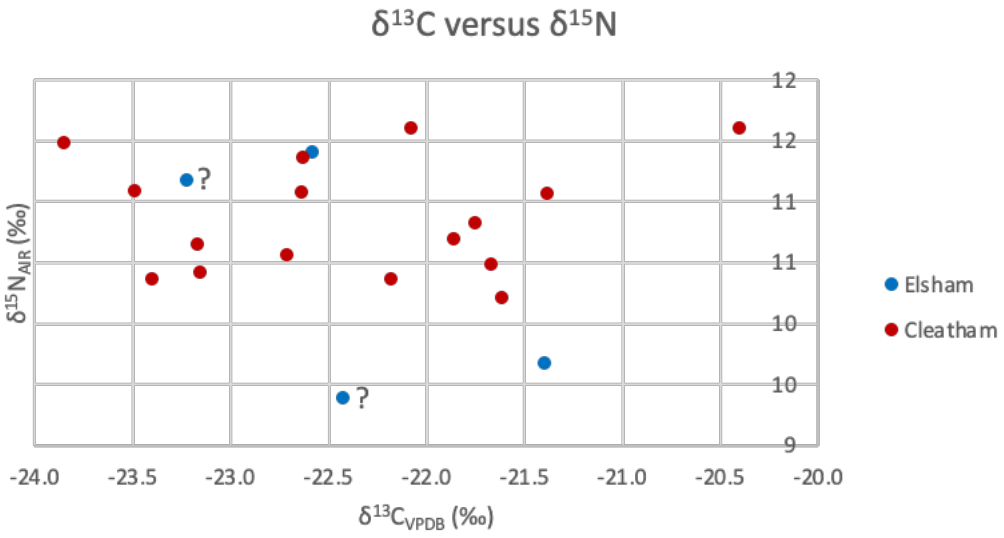


Figure 7.11: Stable isotope data from collagen extracted from inhumed individuals from Elsham cemetery (n=4) in blue and Cleatham cemetery (n=16) in red, $\delta^{13}C_{VPDB}$ plotted against $\delta^{15}N_{AIR}$. The two Elsham samples with low nitrogen contents are marked with question marks (?).

A Kolmogorov-Smirnov test was used to determine if location was a significant factor in the distribution of isotope data at Elsham and Cleatham; carbon and nitrogen were evaluated separately. A critical value 0.42 was calculated using the formula laid out in section 5.3.8 at a significance value of 0.05 for populations of $N_1 = 4$ and $N_2 = 16$. The maximum difference in the $\delta^{13}C$ values between Elsham and Cleatham was 0.13, as shown in figure 7.12; this did not exceed the critical value. The null hypothesis was accepted and location does not appear to have been a factor in the distribution of $\delta^{13}C$ values at Elsham and Cleatham. The test was repeated for $\delta^{15}N$ values and a maximum difference of 0.50

was found, as shown in figure 7.13; this exceeded the critical value suggesting that location was a significant factor in the distribution of $\delta^{15}N$ values at Elsham and Cleatham. Though, with the Elsham group represented by only four individuals this comparison cannot be considered robust.

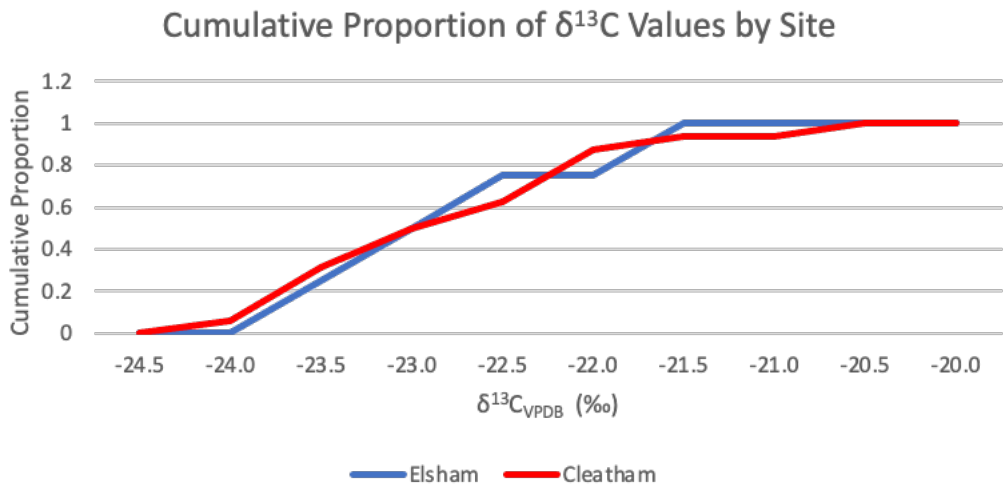


Figure 7.12: Graph showing the cumulative proportion of $\delta^{13}C$ values from individuals inhumed at Elsham (n=4) in blue and Cleatham (n=16) in red.

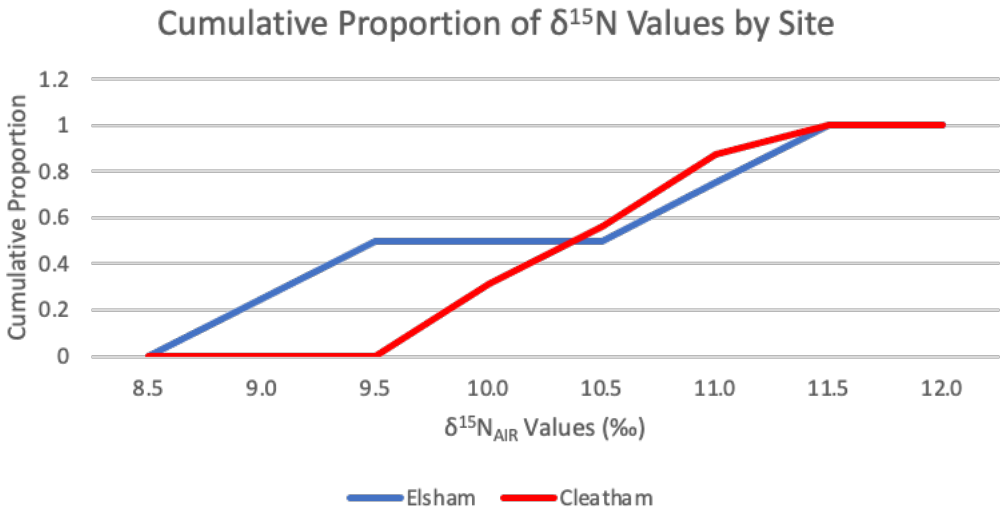


Figure 7.13: Graph showing the cumulative proportion of $\delta^{15}N$ values from individuals inhumed at Elsham (n=4) in blue and Cleatham (n=16) in red.

A Mann-Whitney U test was run to confirm the Kolmogorov-Smirnov results. For the populations of Elsham ($N_1 = 4$) and Cleatham ($N_2 = 16$) the critical value was 11. Neither the $\delta^{13}C$ data or the $\delta^{15}N$ data exceeded this value and the null hypothesis was accepted for both data sets; see table 7.6. For the $\delta^{13}C$ data this agrees with the Kolmogorov-Smirnov

results; however, for the $\delta^{15}N$ data this contradicts the Kolmogorov-Smirnov results. Considering the small size of the Elsham population, the results of the Kolmogorov-Smirnov test should be viewed with caution as this test is influenced by outlying data points.

Table 7.6: Data from the Mann-Whitney U test comparing $\delta^{13}C$ and $\delta^{15}N$ values from samples taken from inhumed individuals interred at Elsham and Cleatham cemeteries. When comparing both the $\delta^{13}C$ and $\delta^{15}N$ values from Elsham against those from Cleatham the null hypothesis (H_0) was accepted and neither comparison was found to be significant.

Value	$\delta^{13}C$ Values		Value	$\delta^{15}N$ Values	
	Elsham	Cleatham		Elsham	Cleatham
N	4	16	*N*	4	16
R	43	167	*R*	35	175
U	31	33	*U*	39	25
Min. U	31		*Min. U*	25	
U_{crit}	11		U_{crit}	11	
H_0	Accepted		H_0	Accepted	

Due to the small sample size, the data from Elsham and Cleatham were combined to determine if any demographic patterns could be identified in the distribution of the $\delta^{13}C$ and $\delta^{15}N$ values. Of the 20 individuals sampled there were 19 for whom sex had previously been estimated (females n=9, males n=10). Only the lower limbs of inhumation EL76AK from Elsham cemetery were recovered and sex estimation was not possible from these remains (Squires, 2011). The female mean values were -22.7‰ for $\delta^{13}C$ and 11.1‰ for $\delta^{15}N$; the male mean values were -22.1‰ for $\delta^{13}C$ and 10.7‰ for $\delta^{15}N$, resulting in a difference of 0.6‰ and 0.5‰ respectively. The female and male distribution of $\delta^{13}C$ and $\delta^{15}N$ values overlap, as shown in figure 7.14.

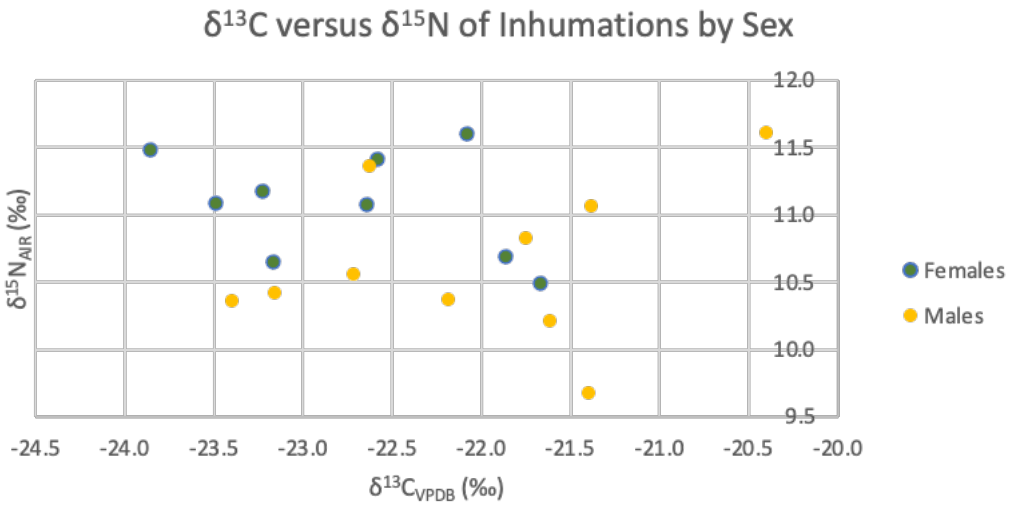


Figure 7.14: Stable isotope data from collagen extracted from inhumed individuals from Elsham and Cleatham cemeteries, colour coded by sex: females (n=9) in green and males (n=10) in yellow.

A Kolmogorov-Smirnov test was conducted to determine whether the difference in the isotope data from the females and males was significant; carbon and nitrogen data were considered separately. A critical value of 0.30 was calculated using the formula presented in section 5.3.8 at a significance value of 0.05 for populations of $N_1 = 9$ and $N_2 = 10$. The maximum difference in the distributions of $\delta^{13}C$ values, 0.30, did not exceed the critical value and the null hypothesis was accepted; see distribution in figure 7.15. This suggests that sex was not a factor in the distribution of $\delta^{13}C$ values at Elsham and Cleatham. The maximum difference in the distribution of $\delta^{15}N$ values was 0.39, exceeding the critical value such that the null hypothesis was rejected; see distribution in figure 7.16. Therefore, while sex does not appear to have been a factor in the distribution of $\delta^{13}C$ values it does appear to have been a factor in the distribution of $\delta^{15}N$ values for inhumed individuals.

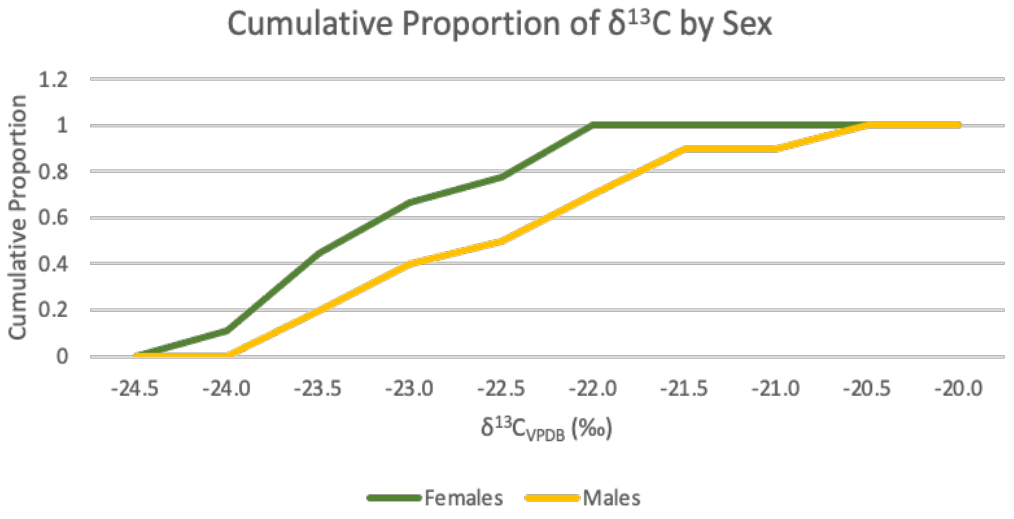


Figure 7.15: Graph showing the cumulative proportion of $\delta^{13}C$ values observed from inhumed individuals at Elsham and Cleatham cemeteries, colour coded to indicated sex: females (n=9) in green and males (n=10) in yellow.

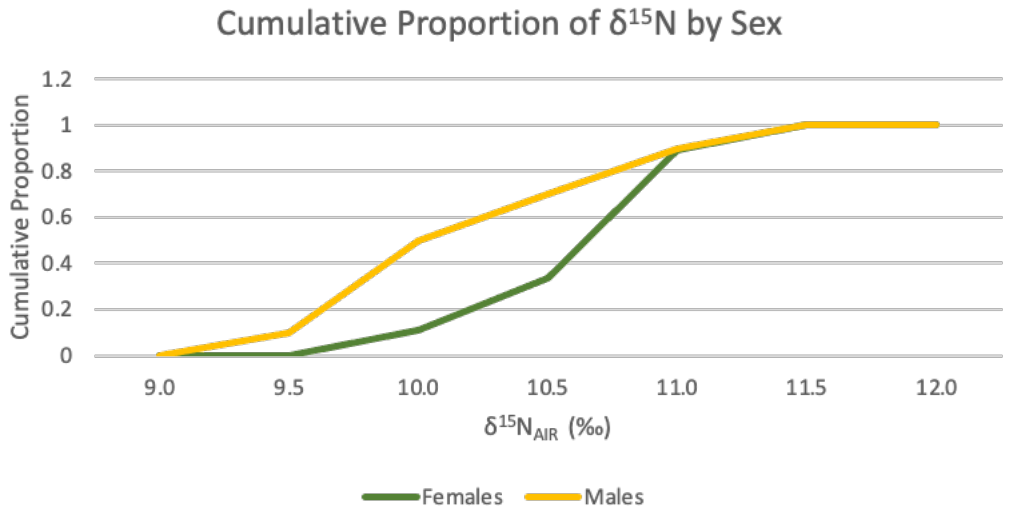


Figure 7.16: Graph showing the cumulative proportion of $\delta^{15}N$ values observed from inhumed individuals at Elsham and Cleatham cemeteries, colour coded to indicate sex: females (n=9) in green and males (n=10) in yellow.

A Mann-Whitney U test was run to confirm the Kolmogorov-Smirnov results. For the populations of females ($N_1 = 9$) and Males ($N_2 = 10$) the critical value was 20. Neither the $\delta^{13}C$ data or the $\delta^{15}N$ data exceeded this value and the null hypothesis was accepted for both data sets; see table 7.7. For the $\delta^{13}C$ data this agrees with the Kolmogorov-Smirnov results; however, for the $\delta^{15}N$ data this contradicts the Kolmogorov-Smirnov results. Considering the difference in the female and male distributions is largely driven by the male

outlier EL76AL with a $\delta^{15}N$ value of 9.68, the results of the Kolmogorov-Smirnov test should be viewed with caution.

Table 7.7: Data from the Mann-Whitney U test comparing $\delta^{13}C$ and $\delta^{15}N$ values from samples taken from female and male individuals interred at Elsham and Cleatham cemeteries. When comparing both the $\delta^{13}C$ and $\delta^{15}N$ values from females against those from males the null hypothesis (H_0) was accepted and neither comparison was found to be significant.

Value	$\delta^{13}C$ Values		Value	$\delta^{15}N$ Values	
	Females	Males		Females	Males
N	9	10	*N*	9	10
R	70	120	*R*	113	77
U	65	25	*U*	22	68
Min. U	25		*Min. U*	22	
U_{crit}	20		U_{crit}	20	
H_0	Accepted		H_0	Accepted	

Over half of the individuals sampled for this analysis had age estimates of 19-25 years (n=11). Only four individuals had age estimates of over 25 years; from Elsham the inhumations EL76AL (male) and EL76JO(a) (female) were assigned to the 31-40 year category, and from Cleatham Grave 10 (male) was estimated to be 26-40 years of age and Grave 29 (male) aged 41+. A further five individuals were established as adults, but more precise age estimation was not possible (Squires, 2011). The mean values for the 19-25 age group were -22.6‰ for $\delta^{13}C$ and 10.9‰ for $\delta^{15}N$; the mean values for the older group were -21.8‰ for $\delta^{13}C$ and 11.0‰ for $\delta^{15}N$, resulting in a difference of 0.8‰ and 0.1‰ respectively. The small sample size of older adults precludes meaningful analysis of age-related variation in $\delta^{13}C$ and $\delta^{15}N$ values. However, it is interesting to note that the highest

values of both ^{13}C and ^{15}N (-20.4‰, 11.6‰) are from the oldest individual analysed in this dataset; see distribution in figure 7.17.

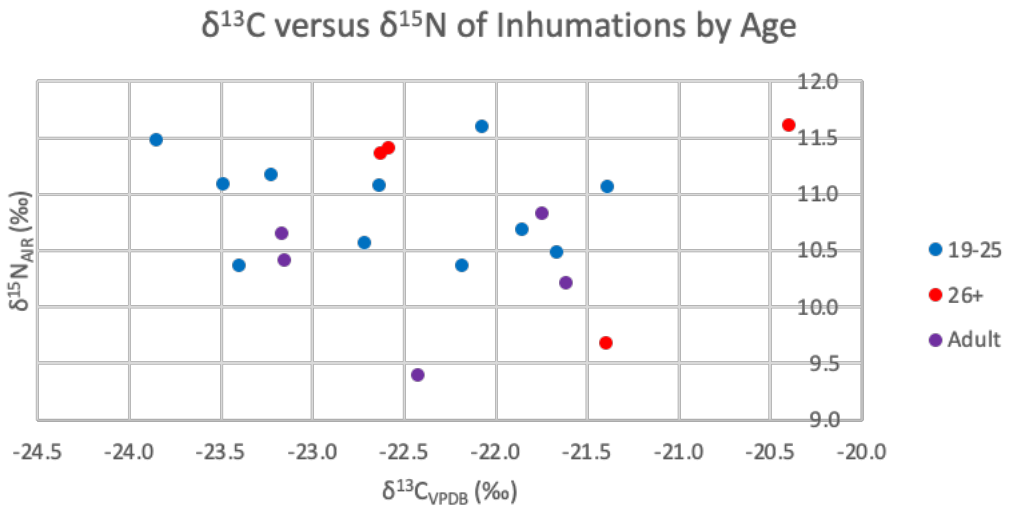


Figure 7.17: Stable isotope data from collagen extracted from individuals inhumed at Elsham and Cleatham cemeteries, colour coded by age: 19-25 years (n=11) in blue, 26+ years (n=4) in red, and adults without precise age estimates (n=5) in purple.

A Kolmogorov-Smirnov test was used to determine if age was a significant factor in the distribution of isotope data at Elsham and Cleatham; carbon and nitrogen values were evaluated separately. First, the age group consisting of individuals 19-25 years old was compared against all other individuals; for this comparison a critical value of 0.27 was calculated using the formula presented in section 5.3.8 at a significance level of 0.05 for populations of $N_1 = 11$ and $N_2 = 9$. The maximum difference between these distributions for $\delta^{13}C$ values, shown in figure 7.18, was 0.17. As the maximum difference did not exceed the critical value the null hypothesis, that age was not a significant factor in the distribution of $\delta^{13}C$ values at Elsham and Cleatham, was accepted. However, as five of the individuals were assigned only to an age range of 19 years or older and therefore cannot definitively be aged outside of the 19-25 year range, the test was run again with these individuals excluded. For this second test a critical value of 0.44 was calculated for populations of $N_1 = 11$ and $N_2 = 4$. The maximum difference between the distributions was 0.41, again insufficient to reject the

null hypothesis suggesting that age was not a factor in the distribution of $\delta^{13}C$ values at these sites.

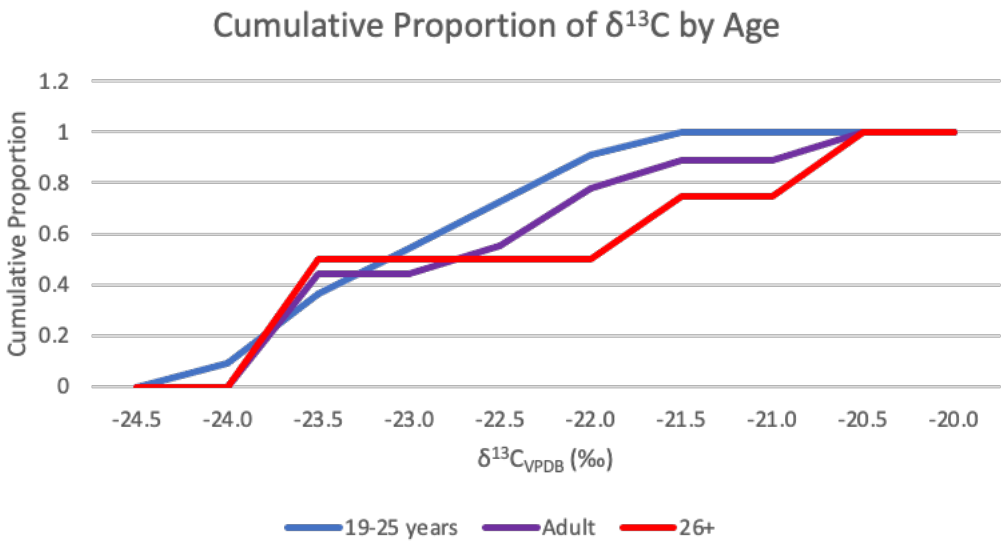


Figure 7.18: Graph showing the cumulative proportion of $\delta^{13}C$ values of individuals inhumed at Elsham and Cleatham cemeteries, colour coded to show age groupings: 19-25 year group (n=11) in blue, those aged 26+ (n=4) in red and a combined group of those aged 26+ years and those without precise age estimates (n=9) in purple.

The same two tests were run on the $\delta^{15}N$ values recorded from inhumed individuals at Elsham and Cleatham. When comparing the 19-25 year age group with all other individuals the maximum difference was 0.22, as shown in figure 7.19, which did not exceed the critical value of 0.27 determined above. When the 19-25 year age group was compared against only those adults aged 26 and older, the maximum difference was 0.25; again this was below the critical value of 0.44 calculated for this comparison. As such, in both cases the null hypothesis was accepted and the distribution of $\delta^{15}N$ values for inhumed individuals at Elsham and Cleatham do not appear to have been influenced by age.

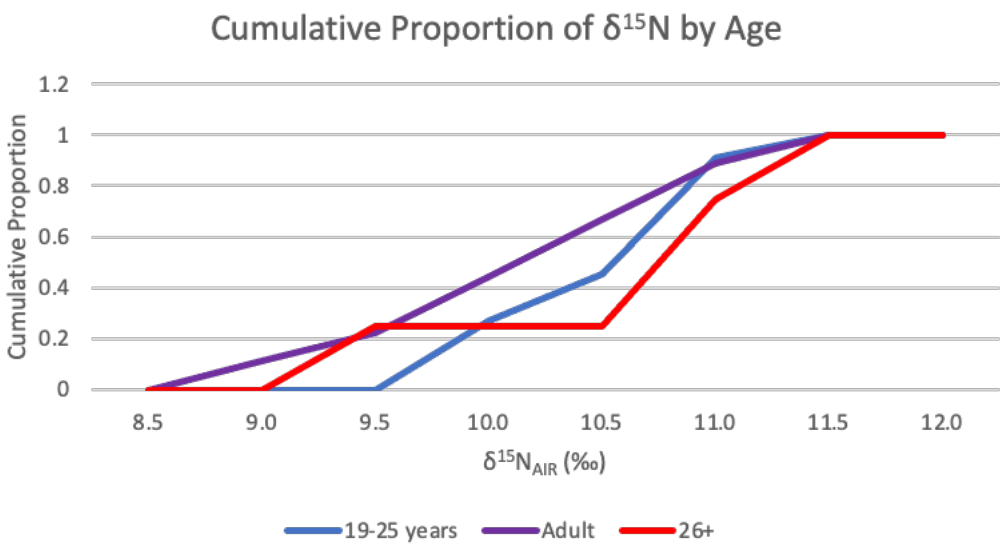


Figure 7.19: Graph showing the cumulative proportion of $\delta^{15}N$ values of individuals inhumed at Elsham and Cleatham cemeteries, colour coded to show age groupings: 19-25 year group (n=11) in blue, those aged 26+ (n=4) in red and a combined group of those aged 26+ years and those without precise age estimates (n=9) in purple.

A Mann-Whitney U test was run to confirm the Kolmogorov-Smirnov results. For the individuals aged 19-25 years ($N_1 = 11$) and those aged 26 year or older ($N_2 = 4$) the critical value was 6. Neither the $\delta^{13}C$ data or the $\delta^{15}N$ data exceeded this value and the null hypothesis was accepted for both data sets; see table 7.8. For both the $\delta^{13}C$ and $\delta^{15}N$ data this agrees with the Kolmogorov-Smirnov results. When the comparison is run between those individuals aged 19-25 years ($N_1 = 11$) and those in all other age categories ($N_2 = 9$) the critical value was 23. Again, neither the $\delta^{13}C$ data or the $\delta^{15}N$ data exceeded this value and the null hypothesis was accepted for both data sets; this data is also presented in table 7.8. For both the $\delta^{13}C$ and $\delta^{15}N$ data this agrees with the Kolmogorov-Smirnov results.

Table 7.8: Data from the Mann-Whitney U test comparing $\delta^{13}C$ and $\delta^{15}N$ values from samples taken from individuals aged 19-25 years and those aged 26 years or older, comparisons are also made between those aged 19-25 years and all other individuals. In each case the null hypothesis (H_0) was accepted, and no significant differences were found in $\delta^{13}C$ and $\delta^{15}N$ values according to age categories.

Value	$\delta^{13}C$ Values		Value	$\delta^{15}N$ Values	
	19-25 years	26+ years		19-25 years	26+ years
N	11	4	*N*	11	4
R	77	43	*R*	81	39
U	33	11	*U*	29	15
Min. U	11		*Min. U*	15	
U_{crit}	6		U_{crit}	6	
H_0	Accepted		H_0	Accepted	
Value	**$\delta^{13}C$ Values**		**Value**	**$\delta^{15}N$ Values**	
	19-25 years	Other		19-25 years	Other
N	11	9	*N*	11	9
R	99	111	*R*	125	85
U	66	33	*U*	40	59
Min. U	33		*Min. U*	40	
U_{crit}	23		U_{crit}	23	
H_0	Accepted		H_0	Accepted	

When compared against previously published medieval data, the $\delta^{13}C$ values from the individuals inhumed at Elsham and Cleatham cemeteries can be shown to between terrestrial animals and freshwater fish, shown in figure 7.20. Likely these individuals consumed mainly terrestrial plants and animals, possibly with some contributions from freshwater fish. Unsurprisingly, the omnivorous and carnivorous group plot similarly to the human data as this group includes dogs and cats that may have been fed on table scraps

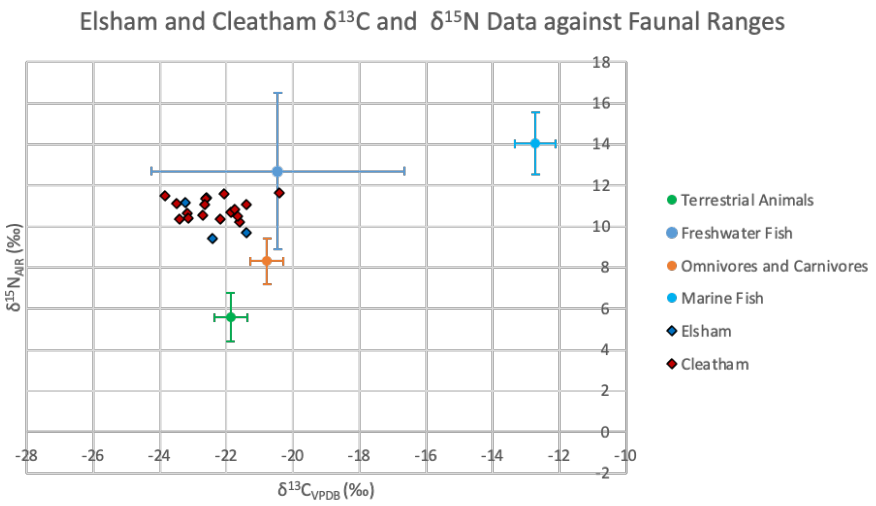


Figure 7.20: Stable isotope data from inhumed individuals from Elsham cemetery (n=4) in blue and Cleatham cemetery (n=16) red compared against faunal ranges. Terrestrial animals include samples from horses, cattle, sheep, and red deer from Berinsfield (5th-7th century Oxfordshire), St. Giles (12th-15th century Yorkshire) and Wharram Percy (10th-16th century Yorkshire). Freshwater fish include samples from eels, cyprinid, herring, pike and flatfish from Beverley (14th-15th century Yorkshire). Omnivores and carnivores include samples from cats, dogs and foxes from Berinsfield, and Wharram Percy. Marine fish include samples from Gadidae species, haddock, ling, ray and whiting from Beverley. Data from Berinsfield reproduced from Privet and colleagues (2002). Data from St. Giles, Wharram Percy and Beverley reproduced from Müldner and Richards (2005).

Stable isotope data from the individuals buried at Elsham and Cleatham cemeteries present a similar subsistence pattern to those inferred from previous carbon and nitrogen analyses conducted on individuals from other Anglo-Saxon cemeteries. However, as can be seen in figure 7.21, $\delta^{13}C$ values from Elsham and Cleatham are lower than other early Anglo-Saxon populations. Conversely, $\delta^{15}N$ values from Elsham and Cleatham are high relative to most other early Anglo-Saxon populations, with the exception of Westfield Farm (Lucy et al., 2009). At Westfield Farm, the relatively elevated $\delta^{15}N$ values were interpreted as indicative of freshwater fish consumption, especially without a corresponding increase in $\delta^{13}C$ values (Lucy et al., 2009). While this interpretation may apply here, the $\delta^{15}N$ values at Elsham and Cleatham are not as high as those recorded from samples taken from Westfield Farm and may instead be an artefact of the small population sizes evaluated (n=4, n=16 respectively).

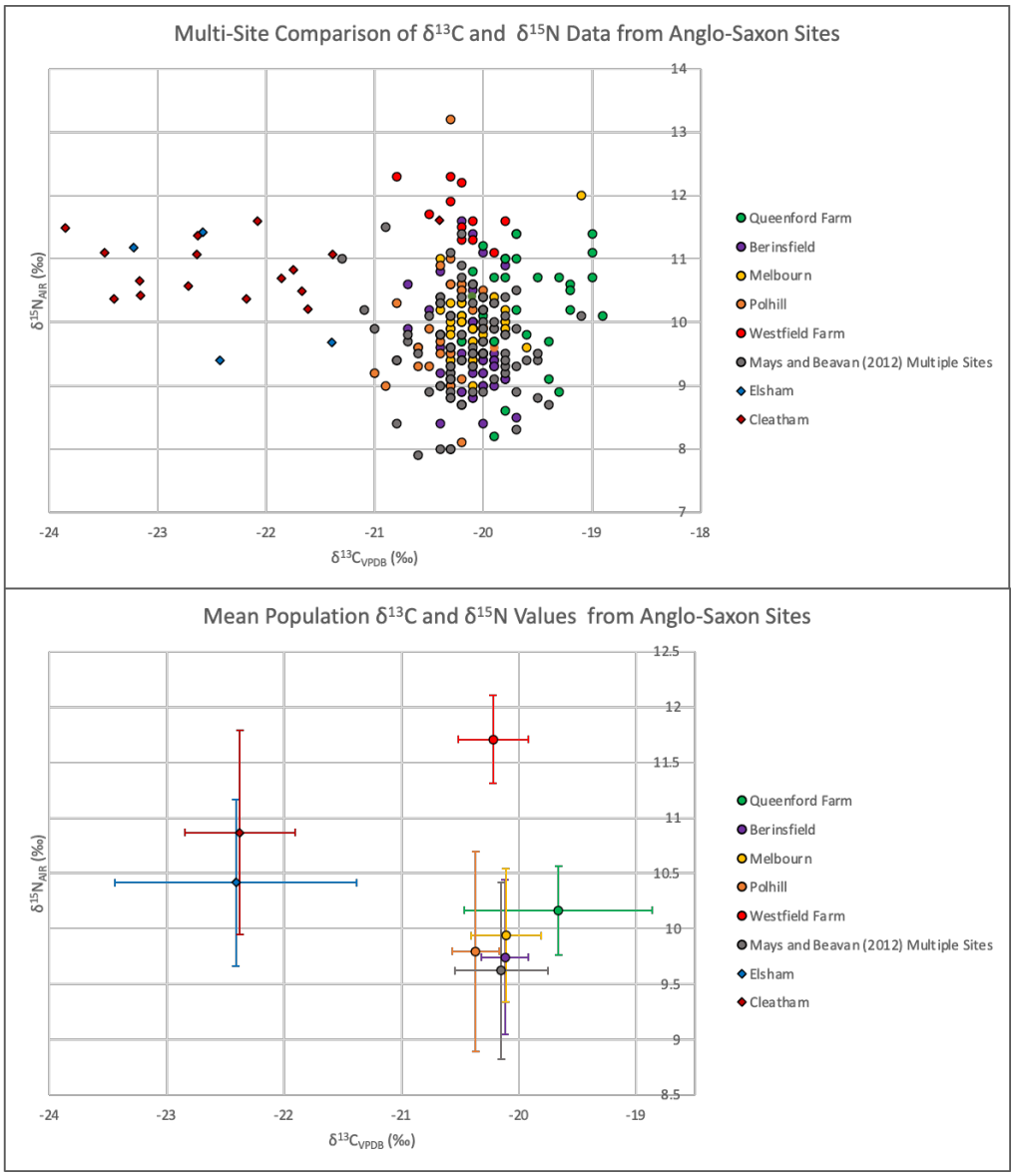


Figure 7.21: Above: Stable isotope data from Anglo-Saxon sites. Queenford Farm (4th-6th centuries, Oxfordshire) data reproduced from Fuller et al, 2006b. Berinsfield (5th-7th centuries, Oxfordshire) data reproduced from Privat et al., 2002. Melbourn (6th-7th centuries, Cambridgeshire) and Pollhill (7th-8th centuries, Kent) data reproduced from Hannah et al., 2018. Westfield Farm (7th century, Cambridgeshire) data reproduced from Lucy et al., 2009. Mays and Beavan (2012) investigated 18 different sites (5th-7th centuries), presented here as one population for clarity. Elsham and Cleatham (5th-7th centuries, Lincolnshire) original data. Below: Mean population values of δ13C and δ15N from the same populations as in the above scatterplot; error bars cover one standard deviation.

7.4.1.b Cremated Individuals

The collagen yield from samples taken from cremated individuals interred at Elsham and Cleatham cemeteries was very low, ranging from 3.8 wt.% to 0.1 wt.%. Only 33 of 60 samples provided sufficient carbon for analysis, while only 22 of 60 samples provided sufficient nitrogen for analysis when using 0.3 mg of extracted protein; however, the nitrogen data from these analyses was not reliable. The analyses were repeated using 3 mg

of extracted protein, only 12 samples retained sufficient collagen yield for these analyses. Two of these samples continued to produce unreliable nitrogen results, leaving a sample of 10 individuals for whom reliable carbon and nitrogen data was obtained. Collagen quality indicators from this data set suggest that the protein extracted does not represent biogenic human bone collagen. The carbon content of these samples ranges from 2.1 wt. %C to 5.5 wt. %C, while the nitrogen content ranged from 0.3 wt. %N to 0.9 wt. %N; these data are shown in figure 7.22.

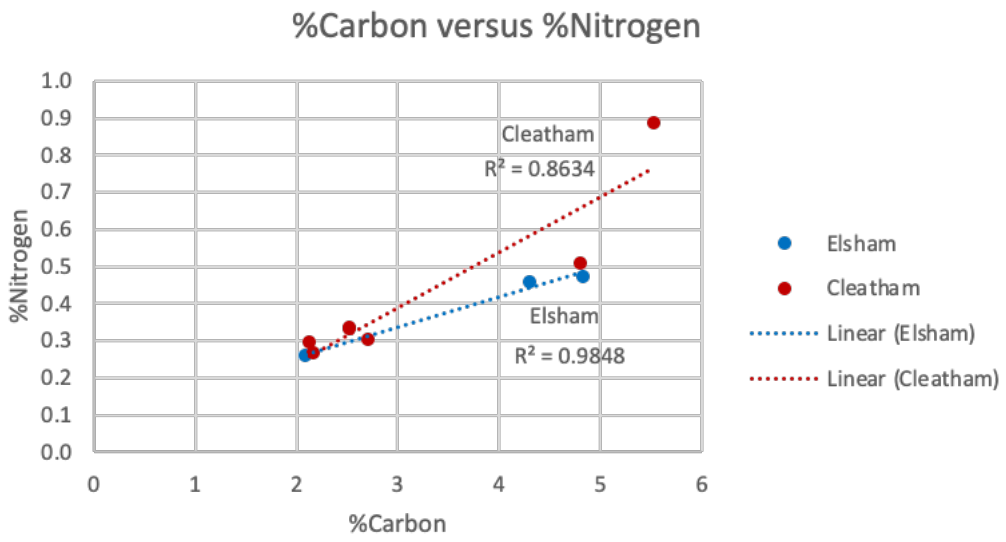


Figure 7.22: The carbon content (%C) versus nitrogen content (%N) of collagen extracted from samples of cremated bone taken from individuals interred at Elsham cemetery (n=3) in blue and Cleatham cemetery (n=7) in red.

Atomic C:N ratios from these samples also suggest an origin other than biogenic human bone collagen as they range from 7.3 to 11.9, well above the acceptable range of 2.9-3.6 (DeNiro, 1985). See figure 7.23 for atomic C:N ratio data.

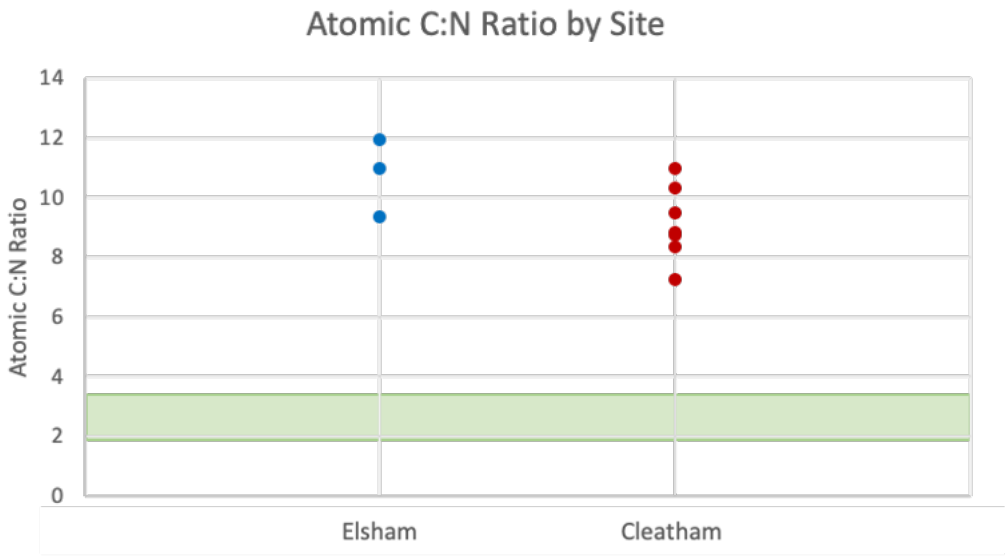


Figure 7.23: Atomic C:N ratios from collagen extracts taken from cremated bone samples from individuals interred at Elsham cemetery (n=3) in blue and Cleatham cemetery (n=7) in red. Green highlighted box shows range of 'good' collagen, 2.9-3.6 (DeNiro and Hastorf, 1985).

The $\delta^{13}C$ values from this data set ranged from -26.3‰ to -24.1‰, with a mean value of -25.3‰. The range of $\delta^{15}N$ values was from 6.1‰ to 9.6‰, with a mean value of 7.2‰, as shown in figure 7.24.

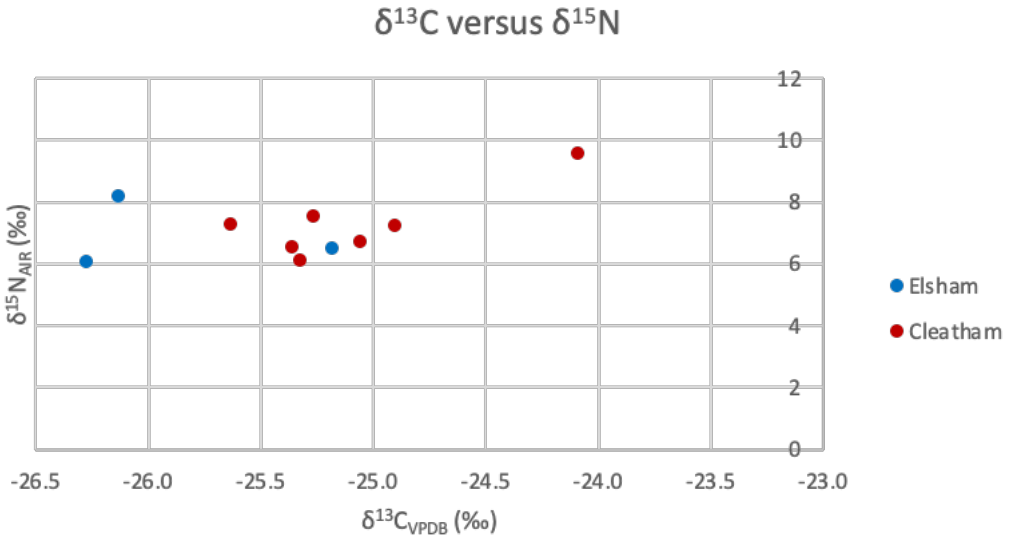


Figure 7.24: Stable isotope data from cremated human bone samples, $\delta^{13}C_{VPDB}$ (‰) versus $\delta^{15}N_{AIR}$ (‰). Data are presented colour coded by site with individuals interred at Elsham cemetery (n=3) in blue and those interred at Cleatham cemetery (n=7) in red.

Both $\delta^{13}C$ and $\delta^{15}N$ values are lower than expected in relation to the data obtained from inhumed individuals interred at the same cemeteries; see figure 7.25. This does not appear to represent a thermally-induced alteration. In experimentally heated bone both $\delta^{13}C$ and $\delta^{15}N$ values were higher at increased temperatures versus unheated controls; see figure 6.21. Instead, based on the low carbon content, low nitrogen content, and high atomic C:N ratios the collagen extract appears to originate from contamination rather than biogenic human bone collagen. The combination of high atomic C:N ratios and low $\delta^{13}C$ values has been interpreted in the past as indicative of contamination from plant matter (van Klinken, 1999). One sample taken from a cremated individual (urn number MT89BBT) interred at Cleatham cemetery approaches the range of $\delta^{13}C$ and $\delta^{15}N$ values seen among the samples taken from inhumed individuals. This sample also had the highest nitrogen content (0.9 wt. %), the highest carbon content (5.5 wt. %) and the lowest atomic C:N ratio (7.3).

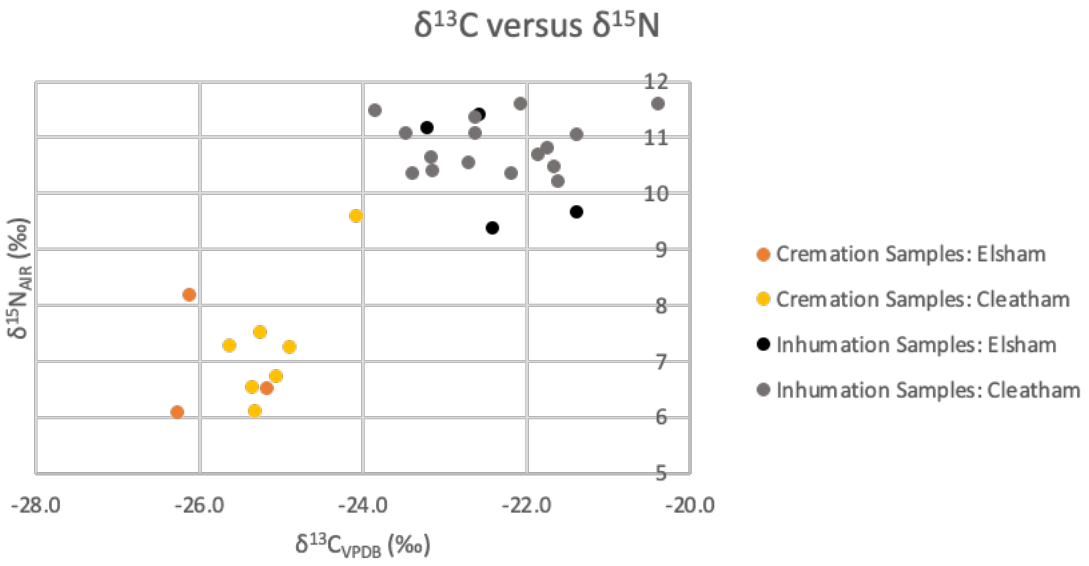


Figure 7.25: Comparing stable isotope data, $\delta^{13}C_{VPDB}$ (‰) and $\delta^{15}N_{AIR}$ (‰) values, from cremated and inhumed individuals from two early Anglo-Saxon cemeteries: Elsham with cremated individuals (n=3) in orange, inhumed individuals (n=4) in black; Cleatham with cremated individuals (n=7) in yellow and inhumed individuals (n=16) in grey.

7.4.2 Sulphur Analysis:

Sulphur isotope analysis was possible only for inhumed individuals from Elsham and Cleatham; samples taken from cremated individuals interred at these cemeteries failed to

produce sufficient collagen for sulphur analysis. The sulphur content for these samples, presented in figure 7.26, ranged from 0.2 wt. % to 0.3 wt. %.

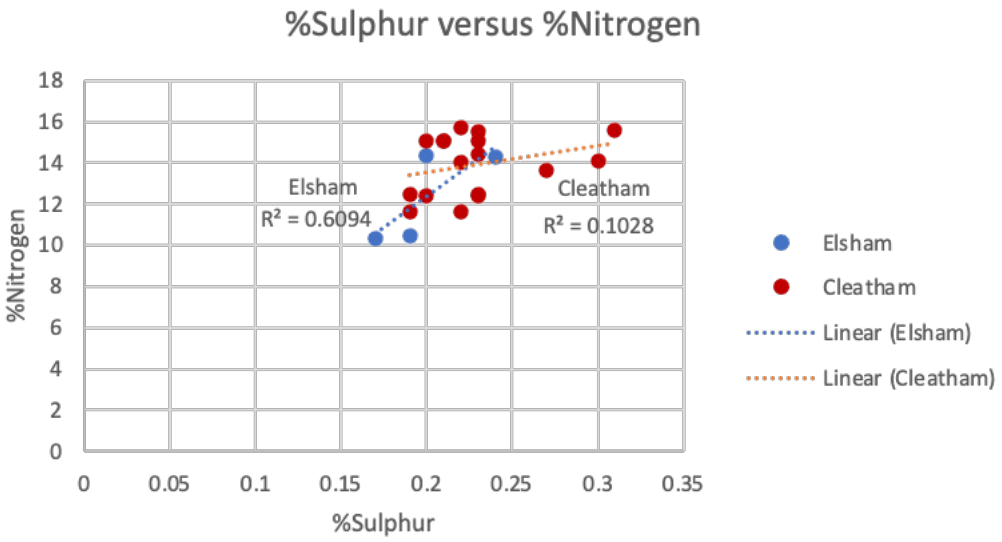


Figure 7.26: The sulphur content (%S) versus nitrogen content (%N) of collagen extracted from samples of bone taken from individuals interred at Elsham cemetery (n=4) in blue and Cleatham cemetery (n=15) in red.

The $\delta^{34}S$ values for these individuals ranged from -5.0‰ to 9.2‰; these data are presented plotted against $\delta^{13}C$ values in figure 7.27 and against $\delta^{15}N$ values in figure 7.28. One individual from the Cleatham population was removed as the data from this sample were unreliable, thus n=4 from Elsham and n=15 from Cleatham. These $\delta^{34}S$ data are within the expected range for the areas surrounding Elsham and Cleatham cemeteries that may be influenced by chalk and Jurassic clay substrates, as well as coastal effects; see section 4.11 for details.

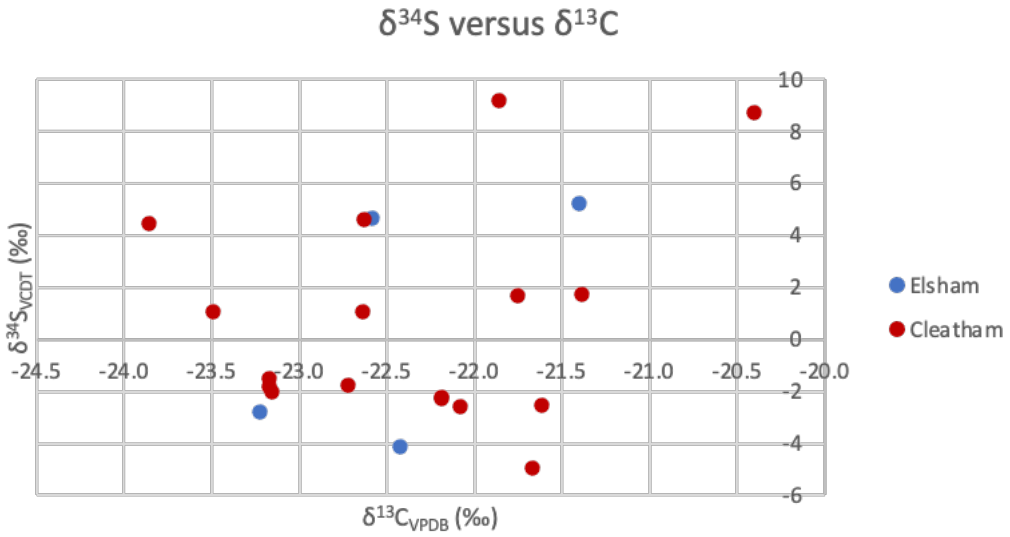


Figure 7.27: Stable isotope data from archaeological human bone samples, $\delta^{13}C_{VPDB}$ (‰) versus $\delta^{34}S_{VCDT}$ (‰). Data are presented colour coded by site with individuals interred at Elsham cemetery (n=4) in blue and those interred at Cleatham cemetery (n=15) in red.

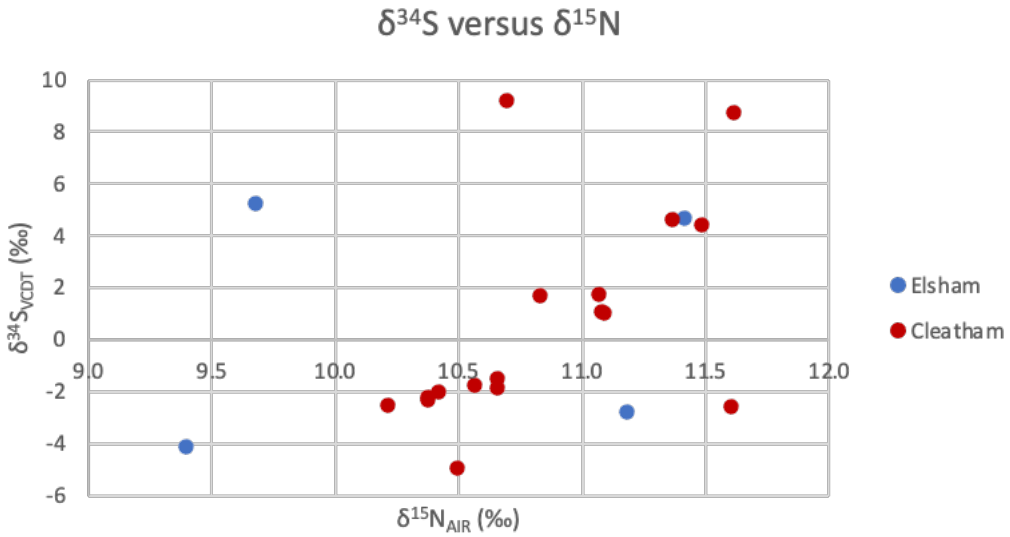


Figure 7.28: Stable isotope data from archaeological human bone samples, $\delta^{15}N_{AIR}$ (‰) versus $\delta^{34}S_{VCDT}$ (‰). Data are presented colour coded by site with individuals interred at Elsham cemetery (n=4) in blue and those interred at Cleatham cemetery (n=15) in red.

A Kolmogorov-Smirnov test was used to determine if location was a significant factor in the distribution of sulphur isotope data at Elsham and Cleatham. A critical value 0.76 was calculated using the formula laid out in section 5.3.8 at a significance value of 0.05 for populations of $N_1 = 4$ and $N_2 = 15$. The maximum difference in the $\delta^{34}S$ values between Elsham and Cleatham was 0.23, as shown in figure 7.29; this did not exceed the critical value. The null hypothesis was accepted; location does not appear to have been a factor in the distribution of $\delta^{34}S$ values at Elsham and Cleatham.

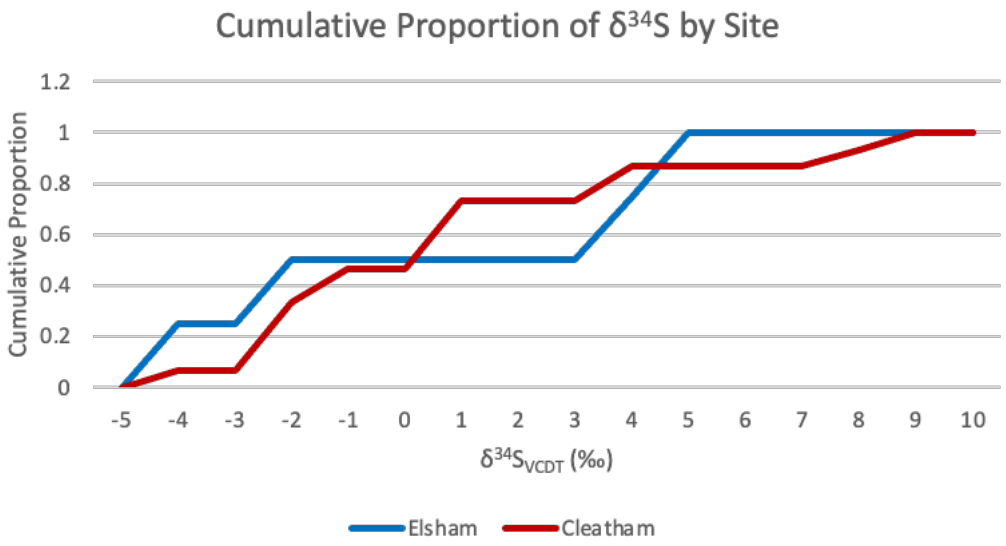


Figure 7.29: h showing the cumulative proportion of $\delta^{34}S$ values from individuals inhumed at Elsham (n=4) in blue and Cleatham (n=15) in red.

To confirm the Kolmogorov-Smirnov results for location a Mann-Whitney U test was run. For the populations of Elsham ($N_1 = 4$) and Cleatham ($N_2 = 15$) the critical value was 10. The $\delta^{34}S$ data did not exceed this value and the null hypothesis was accepted; see table 7.9. This agrees with the Kolmogorov-Smirnov results.

Table 7.9: Data from the Mann-Whitney U test comparing $\delta^{34}S$ values from samples taken from individuals interred at Elsham and Cleatham cemeteries. The null hypothesis (H_0) was accepted and no significant difference between the $\delta^{34}S$ values from these populations was found.

Value	$\delta^{34}S$ Values	
	Elsham	Cleatham
N	4	15
R	38	152
U	32	28
Min. U	28	
U_{crit}	10	
H_0	Accepted	

As there was no significant difference found between the distributions of $\delta^{34}S$ values between the Elsham and Cleatham populations, these data are combined and considered as one population for further comparisons by sex and age-at-death. The female (n=9) mean $\delta^{34}S$ value, 1.0‰, was lower than the male (n=9)[4] mean value, 1.5‰. As mentioned in section 7.4.1.a. there was one individual sampled for whom sex estimation was not possible. These data are shown plotted against carbon in figure 7.30 and against nitrogen in figure 7.31. As shown above in section 7.4.1.(a), females also had a lower $\delta^{13}C$ mean value and higher $\delta^{15}N$ mean value, although only the difference in $\delta^{15}N$ values was found to be significant. Figure 7.31, comparing $\delta^{34}S$ data to $\delta^{15}N$ data, shows an interesting linear pattern that will be investigated further during the age-at-death comparisons.

[4] Samples taken from the individual buried in Grave 49 at Cleatham cemetery, male, produced unreliable data during sulphur analysis. Thus, the male group has 10 individuals for carbon and nitrogen analyses but only 9 for sulphur analysis.

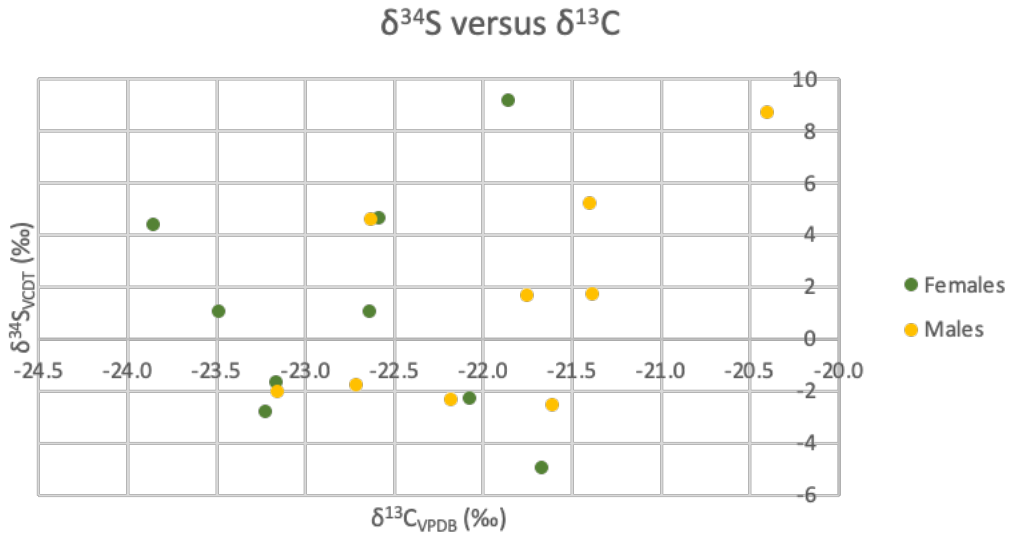


Figure 7.30: Stable isotope data from archaeological human bone samples, $\delta^{13}C_{VPDB}$ (‰) versus $\delta^{34}S_{VCDT}$ (‰). Data are presented colour coded by sex with female individuals (n=9) in green and male individuals (n=9) in yellow.

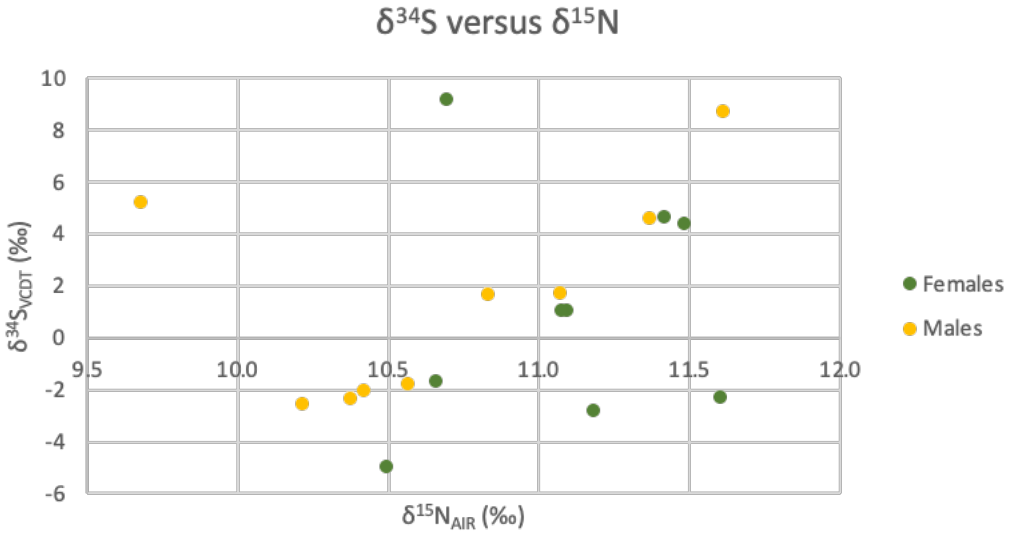


Figure 7.31: Stable isotope data from archaeological human bone samples, $\delta^{15}N_{AIR}$ (‰) versus $\delta^{34}S_{VCDT}$ (‰). Data are presented colour coded by sex with female individuals (n=9) in green and male individuals (n=9) in yellow.

A Kolmogorov-Smirnov test was used to determine if sex was a significant factor in the distribution of sulphur isotope data at Elsham and Cleatham. A critical value of 0.70 was calculated using the formula laid out in section 5.3.8 at a significance value of 0.05 for populations of $N_1 = 9$ and $N_2 = 9$. The maximum difference in the $\delta^{34}S$ values between Elsham and Cleatham was 0.11, as shown in figure 7.32; this did not exceed the critical

value. The null hypothesis was accepted; sex does not appear to have been a significant factor in the distribution of $\delta^{34}S$ values at Elsham and Cleatham.

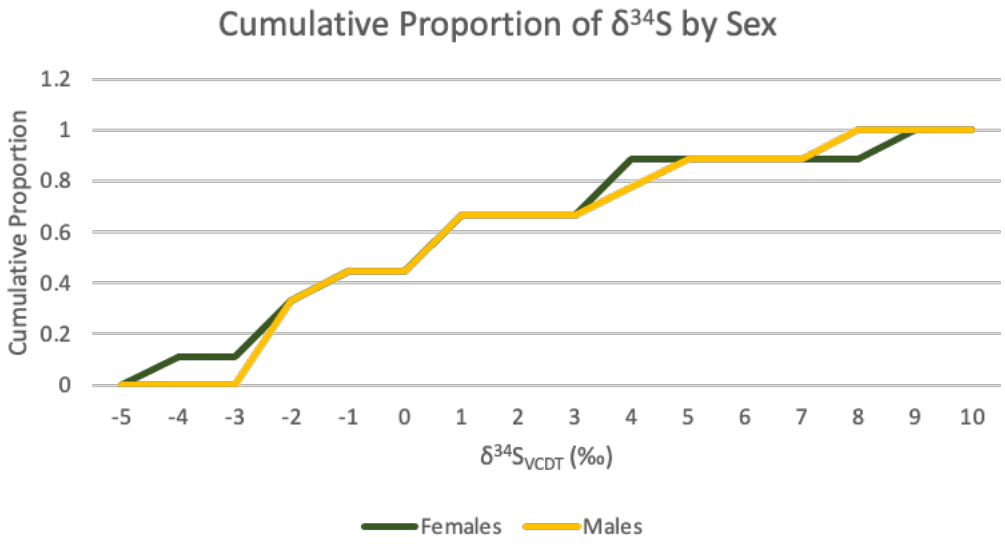


Figure 7.32: Graph showing the cumulative proportion of $\delta^{34}S$ values from female individuals in green and male individuals in yellow.

To confirm the Kolmogorov-Smirnov results for sex a Mann-Whitney U test was run. For the populations of females ($N_1 = 9$) and Males ($N_2 = 9$) the critical value was 17. The $\delta^{34}S$ data did not exceed this value and the null hypothesis was accepted; see table 7.10. This agrees with the Kolmogorov-Smirnov results.

Table 7.10: Data from the Mann-Whitney U test comparing $\delta^{34}S$ values from samples taken from female and male individuals. The null hypothesis (H_0) was accepted and there was no significant difference between the $\delta^{34}S$ values of the females and males from these populations.

Value	$\delta^{34}S$ Values	
	Females	Males
N	9	9
R	81	90
U	45	36
Min. U	36	
U_{crit}	17	
H_0	Accepted	

As discussed in section 7.4.1.(a), the distribution of ages-at-death among those selected for this analysis is uneven. There are ten individuals[5] whose ages have been estimated at 19-25 years old, four individuals whose ages have been estimated in excess of 26 years and five individuals for whom age could not be estimated more closely than 19+ years. As such, any implications from this data set must be interpreted with caution. However, there does appear to be somewhat of an age-related pattern in the $\delta^{34}S$ data from Cleatham and Elsham, with the mean $\delta^{34}S$ value among those aged 26+ years being 5.8‰ compared to the mean value of those aged 19-25 years being 0.3‰. The undifferentiated adult group (19+ years) showed the lowest mean $\delta^{34}S$ value at -1.7‰. Figure 7.33 shows these data compared against $\delta^{13}C$ values and figure 7.34 shows the comparison against $\delta^{15}N$ values. Interestingly, of the four older individuals with higher $\delta^{34}S$ values, three are male and only one is female. Among the lowest $\delta^{34}S$ values, those less than -2‰, there are four individuals aged 19-25 years and two individuals without precise age estimates; among these individuals three are female, two are male and one is unsexed.

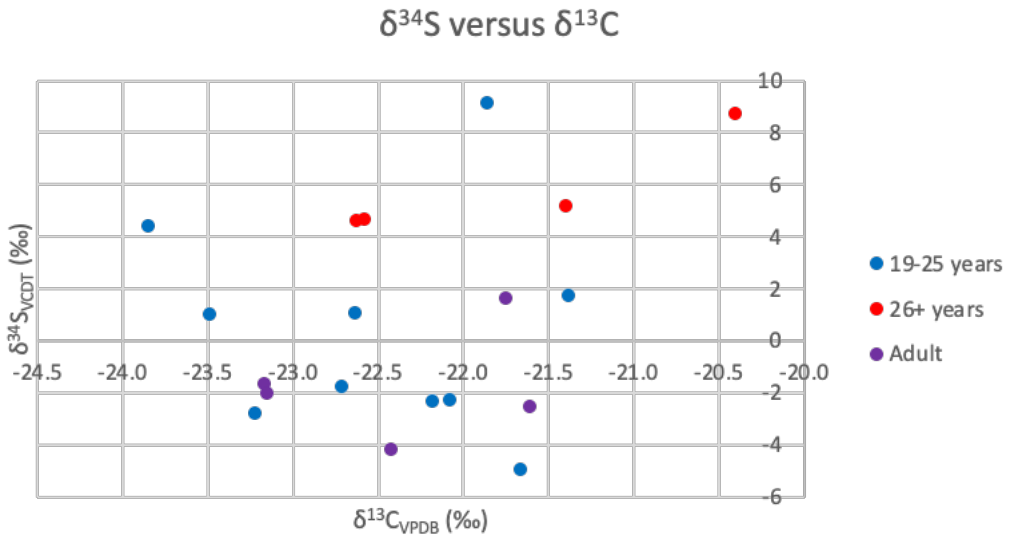


Figure 7.33: Stable isotope data from archaeological human bone samples, $\delta^{13}C_{VPDB}$ (‰) versus $\delta^{34}S_{VCDT}$ (‰). Data are presented colour coded by age with individuals aged 19-25 years (n=10) in blue, individuals aged 26 years or older (n=4) in red and adults without precise age estimates (n=5) in purple.

[5] Samples taken from the individual buried in Grave 49 at Cleatham cemetery, who was in the 19-25 year age group, produced unreliable data during sulphur analysis. Thus, the 19-25 year age group has 11 individuals for carbon and nitrogen analyses but only 10 for sulphur analysis.

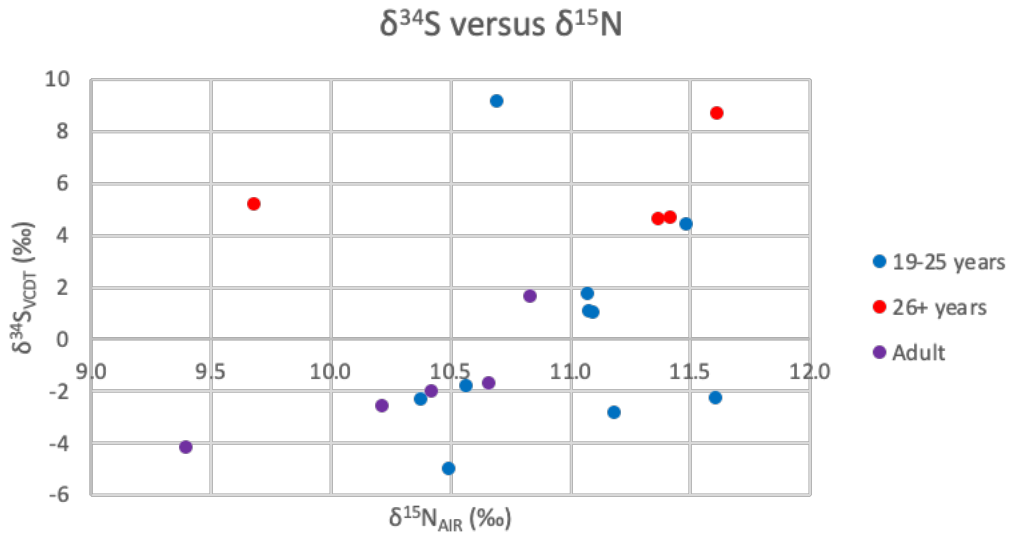


Figure 7.34: Stable isotope data from archaeological human bone samples, $\delta^{15}N_{AIR}$ (‰) versus $\delta^{34}S_{VCDT}$ (‰). Data are presented colour coded by age with individuals aged 19-25 years (n=10) in blue, individuals aged 26 years or older (n=4) in red and adults without precise age estimates (n=5) in purple.

A Kolmogorov-Smirnov test was used to determine if age-at-death was a significant factor in the distribution of $\delta^{34}S$ data at Elsham and Cleatham. First, the age group consisting of individuals 19-25 years old were compared against all other adults; for this comparison a critical value of 0.27 was calculated using the formula presented in section 5.3.8 at a significance level of 0.05 for populations of $N_1 = 10$ and $N_2 = 9$. The maximum difference between these distributions for $\delta^{34}S$ values, shown in figure 7.35, was 0.24. The maximum difference did not exceed the critical value to reject the null hypothesis: that age was not a significant factor in the distribution of $\delta^{34}S$ values at Elsham and Cleatham. Secondly, the test was repeated without those individuals without precise age estimates, comparing those aged 19-25 years with those aged 26 years or older. For this second test a critical value of 0.50 was calculated for populations of $N_1 = 10$ and $N_2 = 4$. The maximum difference between the distributions was 0.80, which was sufficient to reject the null hypothesis suggesting there was a significant difference between the $\delta^{34}S$ values of these two age groups. The disparity between these two comparisons shows the danger of making

interpretations from this data set without accounting for those without precise estimates of age-at-death.

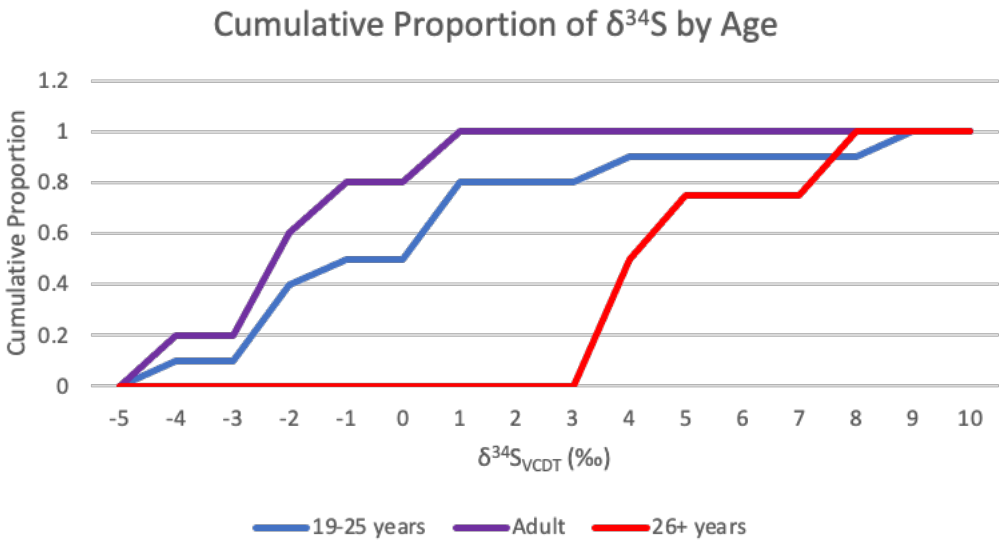


Figure 7.35: Graph showing the cumulative proportion of $\delta^{34}S_{VCDT}$ values (‰) of individuals inhumed at Elsham and Cleatham cemeteries, colour coded to show age groupings: 19-25 year group (n=11) in blue, those aged 26+ years (n=4) in red and combined group of those aged 26+ years and those without precise age estimates (n=9) in purple.

To confirm the Kolmogorov-Smirnov results for age Mann-Whitney U test was run. For the individuals aged 19-25 years (N_1 = 10) and those aged 26 year or older (N_2 = 4) the critical value was 5. The $\delta^{34}S$ data exceeded this value and the null hypothesis was rejected, indicating that age was a significant factor in the $\delta^{34}S$ values found at Elsham and Cleatham; see table 7.11. This agreed with the results of the Kolmogorov-Smirnov test. However, the comparison was also run between those individuals aged 19-25 years (N_1 = 10) and those in all other age categories (N_2 = 9) with a critical value of 20. In this case, the $\delta^{34}S$ data did not exceed the critical value and the null hypothesis was accepted. Again, this agrees with the result of the Kolmogorov-Smirnov test further emphasising the need to account for those individuals for whom precise age-at-death estimates were not possible.

Table 7.11: Data from the Mann-Whitney U test comparing $\delta^{34}S$ values from samples taken from female and male individuals. The null hypothesis (H_0) was accepted and there was no significant difference between the $\delta^{34}S$ values of the females and males from these populations.

Value	$\delta^{34}S$ Values		Value	$\delta^{34}S$ Values	
	19-25 years	26+ years		19-25 years	Other
N	10	4	*N*	10	9
R	59	46	*R*	90	100
U	36	4	*U*	55	35
Min. U	4		*Min. U*	35	
U_{crit}	5		U_{crit}	20	
H_0	Rejected		H_0	Accepted	

7.5 Conclusion:

The results of these analyses show, that while refinements need to be made, this method has the potential to allow for stable isotope analyses of cremated remains recovered from archaeological sites. Colour was a useful screening tool to narrow the selection of samples from cremated individuals; however, soil staining was a confounding factor. FTIR analyses were able to distinguish samples taken from cremated individuals from those taken from inhumed individuals. Unfortunately, the FTIR data indicates that the samples selected from cremated individuals were subject to burning intensities sufficient to alter the mineral portion of bone; from previous research this suggests temperatures in excess of 500°C. The FTIR data may have been influenced by diagenetic changes to the bone samples as well as thermal changes, which would potentially suggest lower burning temperatures followed by further chemical changes in the burial environment. Collagen yields were acceptable from all samples taken from inhumed individuals, but yields were marginal from all samples taken from cremated individuals. This result was expected from the FTIR data suggesting thermal degradation of the organic portion of the bone samples taken from cremated individuals. However, in the case of both FTIR data and collagen yields, the dearth of organic material may have resulted from either combustion during cremation or from decay after burial. Stable isotope analysis conducted on the samples taken from inhumed individuals fell in line with previous research on early Anglo-Saxon

populations, with $\delta^{13}C$ data suggesting a C_3 based terrestrial diet and $\delta^{15}N$ data suggesting contributions of terrestrial plants and terrestrial herbivores. There was minimal discernable patterning within the isotope data collected here; there were no significant inter- or intra-population patterns found among the $\delta^{13}C$ data. However, there were patterns within the $\delta^{15}N$ data: individuals interred at Cleatham had relatively higher $\delta^{15}N$ values than those at Elsham, significant at a level of 0.05. When the Cleatham and Elsham populations were combined, females showed higher average $\delta^{15}N$ values than males and this difference was found to be significant using a Kolmogorov-Smirnov test. Though this significance was not confirmed by the Mann-Whitney U test. Stable isotope analysis of the collagen extracted from cremated individuals suggested that these extracts were not biogenic in origin and likely arose from plant-derived contamination. Only inhumed individuals produced sufficient collagen yields for sulphur isotope analysis. These data showed that there was not a significant inter-population difference in $\delta^{34}S$ values. While there was an interesting sex-linked pattern in the $\delta^{34}S$ data when compared against the $\delta^{15}N$ data, with higher $\delta^{15}N$ values and lower $\delta^{34}S$ values found among female individuals, the difference in the distributions of the $\delta^{34}S$ data between males and females was not found to be significant. When comparing those aged 19-25 years of age against those aged 26 years or older there was a significant difference in $\delta^{34}S$ values at a significance level of 0.05, with the older individuals showing higher $\delta^{34}S$ values. This significance was found by both the Kolmogorov-Smirnov test and the Mann-Whitney U test. However, this difference is mitigated if the individuals without precise age estimates are included with the older individuals.

Chapter 8: Discussion

8.1 Introduction

This chapter comprises the discussion of two related experiments: a controlled heating experiment and subsequent archaeological application. Both experiments were designed to test methods of determining burning intensities experienced by bone fragments. Additionally, these experiments determined whether bone fragments retain sufficient, biogenic collagen for carbon, nitrogen, and sulphur isotope analyses used to infer diet after heating. The results of the controlled heating experiment are discussed in section 8.2, with particular attention to the variation in the results of previously published studies with a similar focus (DeNiro et al., 1985; Schurr and Hayes, 2008; Schurr et al., 2008; Harbeck et al., 2011). The results of the archaeological application are then discussed in section 8.3, including the isotope data from inhumed individuals from Elsham and Cleatham cemeteries compared against dietary information from other Anglo-Saxon sites (Privat et al., 2002; Fuller et al., 2006b; Lucy et al., 2009; Mays and Beavan, 2012; Hannah et al., 2018). The results of the controlled heating experiment are then compared against the results from the archaeological application in section 8.4. The wider research context is discussed in section 8.5 with particular attention to the scope of cremation rites used in Britain and the, as yet rarely exploited, potential of archaeologically cremated remains for research. Finally, a summary is provided in section 8.6.

8.2 Results from the Controlled Heating Experiment

8.2.1: Mass

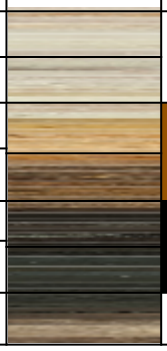
The change in mass of the samples from before to after heating in the controlled heating experiment followed expected patterns with a gradual increase from an average of 6% loss among samples heated to 100°C to an average of 32% loss among samples heated to 400°C. Two processes of thermal alteration are observed at these temperatures: dehydration below 300°C and pyrolysis of organic compounds at and above 300°C (Thompson, 2005; 2013). Exposure time was a less important variable affecting the change

in mass during heating. However, this effect may be more significant in experiment designs using whole bone samples, whereas this experiment used bone sections during heating.

8.2.2 Colour Analysis

Colour change in experimentally heated bone followed the expected pattern from the original cream or ivory colour through yellow, brown, and black; the black char appears in samples heated to 300°C for at least one hour suggesting pyrolysis of organic materials had begun in these samples. The loss of char among those samples heated to 400°C for one hour or more, linked to the oxidation of charred material, aligns with research by McCutcheon (1992) and Walker and colleagues (2008). However, the loss of charring was not found until higher temperatures in the research by Munro and colleagues (2007) and Wahl (2015); see table 8.1. The variation between these studies relates to the conflation of burning conditions and temperature. While exposure temperatures are a major factor in the chemical changes experienced by bone when heated, other factors including exposure times and oxygen availability will also impact the chemistry of bone samples.

Table 8.1: Comparison of colour data from this experiment against previously published research. The photographs used to display colour data from this experiment courtesy of Jeff Veitch. Temperatures in °C. Figure by author.

	Bone Colour Changes						
Temperature	Morrison	Bonucci and Graziani (1975)	Shipman et al. (1984)	McCutcheon (1992)	Munro et al. (2007)	Walker, Miller and Richman (2008)	Wahl (2015)
100°			Pale yellow or very pale brown (below 285°)	Pale brown and black up to 340°	No Change	Gradual shift to dark brown	Yellowish white
150°							
200°		Ochraceous and brown			Dark Brown		
250°							Ivory, glassy light grey
300°		Black	Dominant colours: pink and black Secondary: very dark greyish brown and brown (285°-525°)				
350°					Black	Black to tan	Brown, dark brown
400°				Light brownish grey			Black

8.2.3 Fourier Transform Infrared Spectroscopy (FTIR)

The general trends in the FTIR data collected from the samples used in the controlled heating experiment follow expectations. Peaks reflecting mineral components of bone were sharper and clearer at higher temperatures; these were the peaks found at wavenumbers 1035 cm^{-1}, 605 cm^{-1} and 565 cm^{-1} – all of which are associated with phosphate (PO_4)

functional groups (Thompson, 2013). All of these peaks appeared sharper due to a decrease in noise surrounding the observed peak with increased temperatures and all also showed increased absorbance with increasing temperatures. The peak at 900 cm^{-1} associated with carbonate (CO_3) similarly appeared increasingly sharper with higher temperature exposures. Peaks reflecting organic components were gradually lost from the absorption spectra of samples heated to higher temperatures. The peaks related to amide II (1550 cm^{-1}) and amide III (1250 cm^{-1}) were no longer discernable in the spectra of samples heated to 250°C or higher, while the peak related to amide I (1650 cm^{-1}) could be observed in the spectra of samples heated up to 300°C, as seen in figure 6.6 (Ellingham et al., 2015). As expected, the Crystallinity Index (CI) was not effective in separating the data produced in this experiment, as seen in figure 6.7; however, the C/P (1415 cm^{-1}/1035 cm^{-1}), CO/CO_3 (1650 cm^{-1}/1415 cm^{-1}), CO_3/P (900 cm^{-1}/1035 cm^{-1}) and CO/P (1650 cm^{-1}/1035 cm^{-1}) ratios provided good separation, as seen in figures 6.8 through 6.11, and allowed for modelling of the chemical changes experienced by bone samples exposed to temperatures below 400°C (Ellingham et al., 2015). Temperature models created by comparing pairs of these ratios showed distinct separations among the samples heated to 300°C, as can be seen in figure 6.12; this separation likely reflected the point at which pyrolysis of organic components began (Thompson, 2005; 2013).

8.2.4 Collagen Yield

Collagen yield of the unheated controls showed minimal loss during the extraction procedure, averaging a yield of 24 wt. %. The samples heated to 100°C and 150°C showed comparable collagen yields to the unheated controls, but at 200°C a significant drop in collagen yields was found, these samples producing an average of only 11 wt. %. Yields dropped steadily with the increase in temperatures above 200°C, and minimal yields were extracted from the samples heated to 400°C. While the significant drop in collagen yields at 200°C may suggest that pyrolysis of organic compounds had begun, this may instead reflect minor damage to the collagen fibrils that would be expected at these low temperatures (Koon et al., 2003; 2010). During low temperature heating, the collagen molecule is progressively broken along the fibril structure (Koon et al. 2003; 2010). The breaks in the fibril may increase the chances that collagen is lost during the extraction procedure, as the increased surface area causes the collagen to react more readily with the hydrochloric acid

used in extraction. Thus, the collagen yields reported do not represent the entire collagen content of the heated bone sample, but only that portion of the collagen content successfully retrieved by the extraction procedure. In previous research regarding collagen yields from experimentally heated bone, there was a consistent trend of reduced yields with increases in temperature (DeNiro et al., 1985; Schurr and Hayes, 2008; Schurr et al., 2008; Harbeck et al., 2011). In this experiment and in the research conducted by Harbeck and colleagues (2011) there was a distinct drop in collagen yields at 200°C followed by a gradual decline in yields at higher temperatures. However, Harbeck and colleagues saw low initial yields followed by a reduction to 1 wt.% collagen at 200°C, whereas in this experiment and in other previous research yields of 1 wt. % or less were not found until temperatures in excess of 300°C were reached; see figure 8.1 (DeNiro et al., 1985; Schurr and Hayes, 2008; Schurr et al., 2008). The lower yields seen by Harbeck and colleagues (2011) are likely a reflection of the collagen extraction procedure; the procedure cited involved ultrasonic cleaning, milling of bone to a fine powder, and incubation in NaOH – all of which may have reduced collagen yields (Grupe et al., 2009).

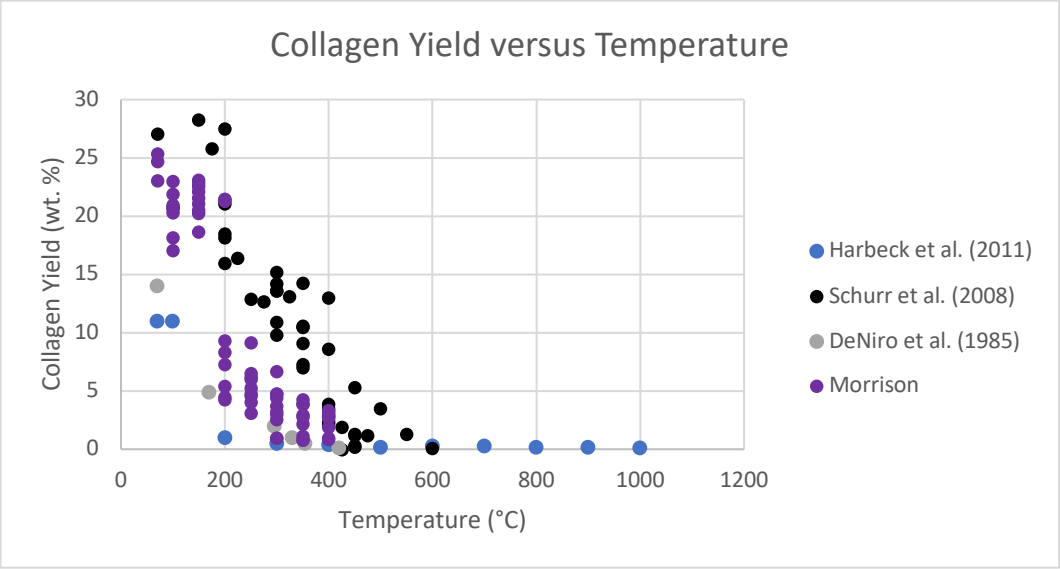


Figure 8.1: Collagen yield data in wt % from this experiment (purple) compared against previously published research.

8.2.5 Stable Isotope Analysis

This research and previously published studies agree on a threshold temperature for the conservation of *in vivo* isotope ratios of carbon and nitrogen at approximately 200°C

(DeNiro et al., 1985; Schurr and Hayes, 2008; Schurr et al., 2008; Harbeck et al., 2011). However, the trends found in the data above this threshold are divergent. This study showed a small increase in $\delta^{13}C$ values with increasing temperatures, but the effect was small and not sufficient to change dietary interpretation based on these data; see section 6.5.1. Conversely, both DeNiro and colleagues (1985) and Harbeck and colleagues (2011) found that $\delta^{13}C$ values were decreased with increasing temperatures; both studies showed changes in $\delta^{13}C$ values sufficient to obscure dietary interpretations. In both previous studies a larger range of temperatures are investigated; however, when the data is constrained to below 400°C to compare with the data collected in this project $\delta^{13}C$ values are still altered sufficiently to affect dietary interpretations (DeNiro et al., 1985; Harbeck et al., 2011). Schurr and Hayes (2008) found that $\delta^{13}C$ values increasingly diverged from the control sample with increasing temperatures but did not show a specific trend, nor were the changes of sufficient magnitude to affect dietary interpretations; see figure 8.2 for comparison. The changes in $\delta^{15}N$ values were also inconsistent. In this study $\delta^{15}N$ values were consistent up to 200°C, but thereafter $\delta^{15}N$ values increased as temperatures rose; those samples heated to 300°C for an hour or longer or heated to higher temperatures were altered enough to obscure diet reconstruction. The elevation seen in both $\delta^{13}C$ and $\delta^{15}N$ values with increased temperatures in this experiment follows theoretical expectations underlying the fractionation effect; ^{12}C and ^{14}N would be expected to react more readily during oxidation than ^{13}C and ^{15}N (van der Merwe, 1982). Schurr and Hayes (2008) found a similar enrichment in ^{15}N values among samples exposed to higher temperatures. However, DeNiro and colleagues (1985) found that samples were depleted in ^{15}N relative to controls when heated to 300°C, but further temperature increases resulted in ^{15}N enrichment relative to controls. This finding is most easily explained by the use of whole tali from different goats for the heating experiment conducted by DeNiro and Colleagues (1985); the talus heated to 300°C may have had a relatively low $\delta^{15}N$ value compared with other samples before heating. Harbeck and colleagues (2011) instead found that samples became depleted in ^{15}N with increasing temperatures. In all four previous studies the changes in $\delta^{15}N$ values were of sufficient magnitude to influence dietary interpretations (DeNiro et al., 1985; Schurr and Hayes, 2008; Schurr et al., 2008; Harbeck et al., 2011).

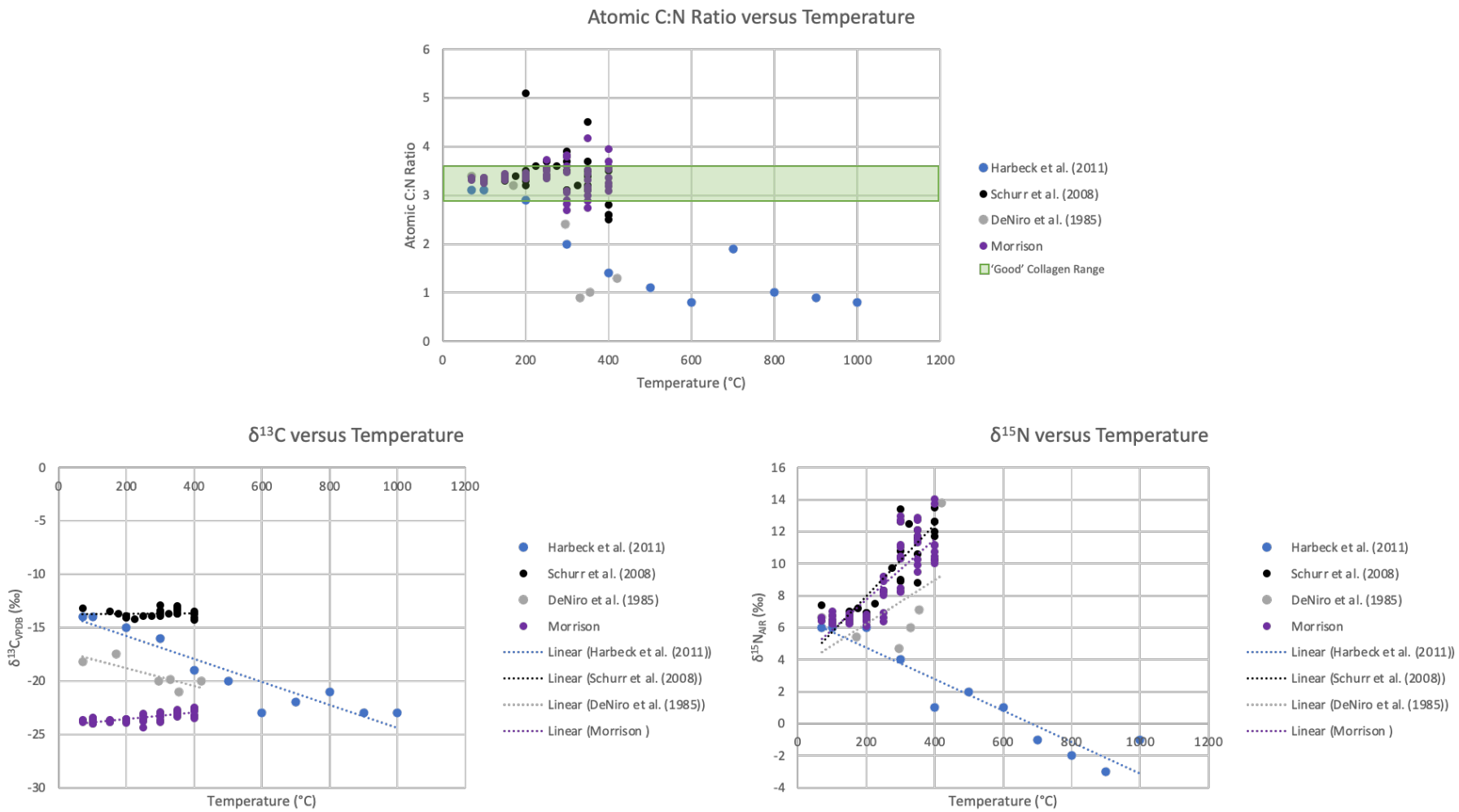


Figure 8.2: Comparison of $\delta^{13}C$ and $\delta^{15}N$ data from this experiment (purple) and previously published data. Above: Atomic C:N ratios from experimentally heated samples, green band indicating the acceptable range 2.9-3.6 as defined by DeNiro and Hastorf (1985). Below left: $\delta^{13}C$ data from experimentally heated samples. Below right: $\delta^{15}N$ data from the same samples.

When observing collagen quality indicators there were some discrepancies. Both DeNiro and colleagues (1985) and Harbeck and colleagues (2011) found that the atomic ratio of carbon to nitrogen (C:N ratio) was sufficient to distinguish unaltered collagen from thermally degraded collagen. However, Schurr and Hayes (2008) and the current research found that in some cases samples with 'good' C:N ratios had thermally altered collagen with $\delta^{13}C$ and $\delta^{15}N$ values that were inconsistent with the control samples. These cases occurred due to carbon and nitrogen being lost at comparable rates, thus the ratio between carbon and nitrogen was maintained; see figure 6.18. If the carbon (%C) and nitrogen (%N) content are compared against those expected for well-preserved bone, these thermally degraded collagen extracts can be eliminated from analysis.

The 200°C threshold was also observed in the $\delta^{34}S$ data observed in this experiment, below 200°C $\delta^{34}S$ values were consistent followed initially by an increase with samples heated to 250°C observed at 3.5‰ higher than the mean $\delta^{34}S$ value of the control samples. At higher temperatures, however, $\delta^{34}S$ values decreased with samples heated to 400°C observed at 3.1‰ below the mean $\delta^{34}S$ value of the control samples. The cause of this pattern is unclear. The variation in $\delta^{34}S$ values in bone samples heated above 250°C is not correlated with sulphur content, which shows progressive loss between unburned samples and those heated up to 250°C but then stabilises with little difference in the sulphur content between samples heated to 250°C (0.18%) and those heated to 400°C (0.16%). A single fractionation process does not explain the observed patten in $\delta^{34}S$ values in these data, instead it appears there are multiple reactions occurring involving sulphur during heating leading to various exchanges and resulting in alterations to the $^{34}S/^{32}S$ ratio of the extractable protein obtained from bone.

One possible explanation may be that the $\delta^{34}S$ values in the controlled heating experiment are not indicating the $\delta^{34}S$ values of bone collagen alone but may be affected by chondroitin sulphate. Chondroitin sulphates are polysaccharides involved in the connection of collagen and the mineral phase of bone and these sugars may survive the collagen extraction procedure (Nehlich and Richards, 2009). These sugars are unlikely to affect carbon or nitrogen analysis due to their minor contribution to the collagen sample; however, as the sulphur content of collagen is so small, sulphur analysis is more susceptible to contamination. The bonds between chondroitin sulphate and collagen are not as robust

as the internal bonds within collagen fibrils; therefore, it is likely that the chondroitin sulphate will be lost at lower temperatures than the methionine contained within the collagen fibrils (Nehlich and Richards, 2009). The relative $\delta^{34}S$ values of methionine versus chondroitin sulphate and the specific temperatures at which these values might change are uncertain but represent an avenue for future research.

Another potential explanation may be a variation in the products of oxidation. While there are several known sulphur oxides, the most common during thermal decomposition are sulphur dioxide (SO_2) and sulphur trioxide (SO_3). At lower temperatures the production of sulphur trioxide occurs more frequently than at higher temperatures, while at higher temperatures minimal sulphur trioxide is produced (Rees and Holt, 1991). Sulphur trioxide is more likely to incorporate the heavier ^{34}S isotope when compared with sulphur dioxide; thus, if proportionally more sulphur trioxide is being produced during the heating experiment the remaining sulphur in the bone samples is likely to become depleted in ^{34}S (Rees and Holt, 1991). However, this reaction is dependent on oxygen availability. As oxygen influx occurred when the bone samples were introduced to the furnace and then at the half hour and one hour intervals, the samples heated for two hours would be most affected by the limitation of oxygen.

Another issue may be contamination arising from the mineral phase of the bone samples. While the initial step in the collagen extraction procedure involves the demineralisation of the bone samples, it is possible that this procedure was not entirely successful. The collagen extracted from the samples was relatively unchanged in appearance up to 200°C, merely acquiring a slight discolouration. However, as temperatures increased the collagen extract lost its 'fluffy' appearance and became increasingly dense; see figure 8.3. This change in consistency may indicate that there were remnants of bone mineral in the extract, particularly among those samples heated to 350°C and 400°C. Thus, the pattern seen in the $\delta^{34}S$ values may reflect the heat-induced fractionation of the sulphur content of collagen up to 200°C. At higher temperatures the collagen $\delta^{34}S$ signature may be swamped by inclusions from the bone mineral. This would

have a more significant effect on sulphur analysis than on either carbon or nitrogen analysis due to the low sulphur content found in bone collagen.

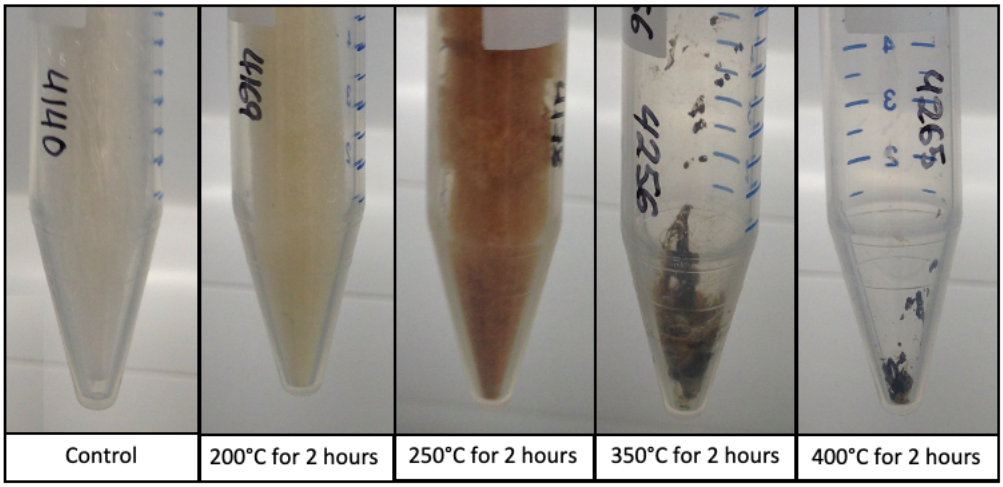


Figure 8.3: Collagen extracts from the controlled heating experiment showing the change in texture of the extracts from bone samples heated to higher temperatures.

These processes are not exclusive. The results found in this experiment, the initial increase in $\delta^{34}S$ values followed by a decrease in these values at higher temperatures, suggest that multiple reactions involving sulphur are occurring. The interaction among these factors is likely complex. Further research is needed to fully explore these reactions to reach an understanding of the expected thermal changes to $\delta^{34}S$ values from bone collagen.

8.2.6 Experiment Design:

While a plethora of experimental research on burned bone has accumulated, particularly since the late twentieth century, consensus in the results has remained elusive. The primary thermal changes that occur in bone have been divided into four stages, but Inconsistencies remain in the temperature ranges at which these stages are expected to occur in bone; see section 3.4.2.a. The temperatures; contributing factors, such as duration or oxygen availability; and even descriptions of secondary changes are not consistent among studies, as outlined in section 3.4.2.b. However, determining whether these results are truly contradictory, or the result of variable experimental conditions remains unclear. The lack of consistency and clarity of methodology used in experimental research on burned bone

continues to obscure any conclusions reached (Sandholzer, 2015). Basic differences among controlled heating experiments include the species used for bone samples; whether the bone samples are fleshed when heated; whether bone samples are sectioned before or after burning; whether samples are heated in a muffle furnace, crematorium, open fire, et cetera; temperature fluctuations during heating period; and cooling protocol. All of these factors may affect the results produced by a controlled heating experiment, but these factors are not always reported within the methodology described by such experiments (Sandholzer, 2015). An illustration of this issue can be seen in table 8.2, which shows the differences in these factors among studies of carbon and nitrogen isotope analyses conducted on experimentally burned bone samples.

Table 8.2: Experiment designs from published research on stable isotope analysis of burned bone compared against this experiment. Temperatures in °C.

	DeNiro et al. (1985)	Schurr and Hayes (2008) Schurr et al. (2008)	Harbeck et al. (2011)	Morrison
Materials	Goat Pig	Cow	Cow	Cow
Overlying Flesh	No	No	No	No
Bone Morphology During Heating	Whole Tali Homogenised Powder	Sections	Sections	Sections
Heat Source	Muffle Furnace	Small Furnace	Muffle Furnace	Muffle Furnace
Oxygen Levels	Not Specified	Not Specified	Maintained Throughout	Periodically Refreshed
Temperature Range	170° to 420° 200°	150° to 600°	100° to 1000°	100° to 400°
Temperature Increments	Irregular	25° to 50°	100°	50°
Duration Evaluated	3 hours Separately, up to 12 hours	0.5 to 3 hours	1.5 hours and 4 hours	0.5 to 2 hours
Pre-heated	No	No	No	Yes
Cooling Protocol	Not Specified	Not Specified	Not Specified	Removed immediately to room temperature

For the experiment in this thesis, the author chose to follow a methodology that limited fluctuations in temperature and variations in exposure times to allow for more exact determinations of the relationships between temperature exposure, duration of temperature exposure and collagen conservation. Thus, the preference for introducing bone samples to the muffle furnace only once the furnace had reached a stable temperature at each selected target temperature. While introducing samples to a room temperature furnace and building to the target temperature may better reflect pyre conditions, this method introduces uncontrolled variables. First, the time period that is

required to reach the target temperature varies and increases at higher temperatures. Second, while heating to a specific temperature muffle furnaces experience significant temperature fluctuations. However, once the entire furnace has reached a stable temperature the introduction or removal of samples causes only small deviations in the internal temperature; see figures 6.1 and 6.2. Thus, the samples analysed in this experiment were heated to discrete temperature ranges, for controlled amounts of time allowing for direct association between these variables and associated changes in bone chemistry. Unfortunately, this methodology is significantly removed from the conditions of an open-air pyre cremation. Potentially, these variables could be added individually to determine which interactions produce the most significant variations from the results obtained using the initial methodology. For instance, a comparison between results obtained from samples introduced at room temperature, then maintained at target temperatures for various times against those obtained using a preheated furnace would be useful in determining whether maximum temperature or sustained temperature is more important in determining collagen conservation. Differences in cooling strategies following heating should also be explored: whether cooling at room temperature or gradual cooling in the muffle furnace has an impact on collagen. The influence of oxygen availability is another significant factor to be investigated. In this experiment samples were heated within a muffle furnace and therefore in an atmosphere with limited oxygen availability; however, the furnace door was opened to remove samples after each allotted time period was reached allowing a periodic introduction of fresh oxygen. The atmosphere within the furnace was not specifically controlled and the influence of oxidising versus reducing conditions during this experiment is therefore unclear. Further experiments comparing a maintained flow of oxygen against a fully closed environment would help to elucidate this influence. Interactions between bone and overlying tissue could also be observed within a muffle furnace under controlled conditions, compared against defleshed results. Whether bone samples are influenced by interaction with a fuel source is another variable; testing the interaction between bone and fuel source while controlling temperature ranges would be ideal. Commercially available grills fuelled by calibrated wood pellets allow for remote, consistent temperature monitoring and would allow a control sample of fuel to be tested in order to observe interactions between fuel source and bone collagen; see figure 8.4 (e.g. Traeger, 2021). Finally, a simulation of open pyre cremation using whole bone or whole

carcasses to approximate past conditions while monitoring temperatures attained at various areas throughout the simulation would highlight interactions with the surrounding environment.

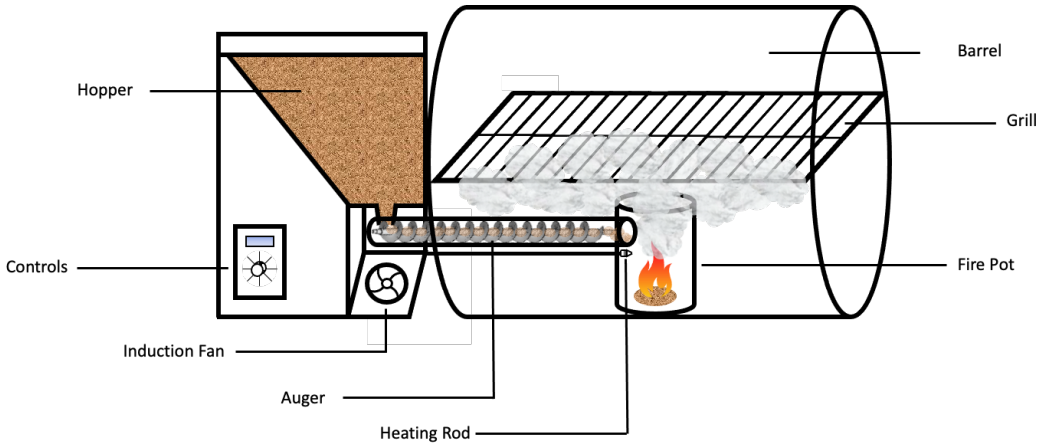


Figure 8.4: Commercially available grill fueled by calibrated wood pellets held within the hopper, released at a controlled rate to maintain or manipulate temperatures, delivered by the auger to a fire pot where the pellets are ignited by a heating rod. An induction fan ensures temperatures remain even and stable throughout the barrel. These grills are designed for cooking and are only capable of reaching temperatures of 260°C; however, a similar design with greater heat insulation would allow for a larger temperature range. Design reproduced from Traeger, 2021.

8.2.7 Summary

The results of the controlled heating experiment conducted here suggest that it should be possible to extract collagen from cremated remains that can be used for carbon and nitrogen isotope analysis. However, the success of this method requires the ability to determine the thermal history of the bone being analysed. Colour analyses suggest that there is a relatively consistent sequence of colour change expected in bone heated to increasing temperatures and that these changes can be used as a broad indicator of past temperature exposures. Some of the colours observed in this experiment are easily distinguished in experimental conditions, but may not be distinct in archaeological samples that have been exposed to soil staining. In particular, the difference between the yellow-brown colouration of samples heated between 250°C and 300°C and the grey-brown seen in samples heated to 400°C may not be evident in archaeological samples. In this case, charred samples expected to have been heated to between 300°C and 400°C may be selected, especially if these samples show a lighter internal colouration indicating the lower end of this spectrum. The charred outer surface should be discarded, and the internal, lighter bone should be used for analysis. From previous research portions of the occipital,

temporals, scapulae, vertebrae, sacrum, illium, and proximal femur are likely to have been exposed to lower temperatures due to tissue shielding and a supine position on the cremation pyre (McKinley, 1994; Squires, 2011; Symes et al., 2015). FTIR analysis provided good separation of bone samples heated at low temperatures. The use of multiple peak ratios allowed for the creation of temperature exposure models that showed distinct separation between samples heated to less than 300°C and those heated to higher temperatures. These models can be used to interpret FTIR data from archaeological samples, allowing more nuanced selection of samples than is possible from colour alone. Finally, collagen quality indicators measured in this experiment were sufficient to prevent thermally altered isotope ratios from being mistaken for biogenic values, but only when %carbon and %nitrogen are considered alongside the atomic C:N ratio. As $\delta^{34}S$ values are conserved up to a similar threshold as $\delta^{15}N$ values, these collagen quality indicators should be sufficient to verify $\delta^{34}S$ data as well.

8.3 Results from the Archaeological Application

8.3.1 Data from Inhumed Individuals

The bone samples taken from inhumed individuals at Elsham and Cleatham cemeteries showed reasonable collagen yields, averaging 6% and 13% respectively. Collagen yields ranged from 3% to 20%; thus, while several bone samples showed compromised collagen preservation, others showed near ideal conservation of collagen (van Klinken, 1999). Collagen preservation was notably lower among the bone samples taken from individuals inhumed at Elsham cemetery and this difference was found to be significant at a level of 0.05, using both the Kolmogorov-Smirnov test and the Mann-Whitney U test. Additionally, while all the collagen extracts obtained from inhumed individuals from these cemeteries produced C:N ratios within acceptable ranges, two samples taken from individuals inhumed at Elsham cemetery had nitrogen contents below the expected range, suggesting questionable collagen preservation (DeNiro, 1985; van Klinken, 1999). The factors identified as having the greatest impact on collagen preservation are moisture, soil pH, microbial attack, temperature, and time (Lee-Thorp, 2008). Both Elsham and Cleatham are located in northern Lincolnshire and would generally have experienced similar temperatures (Leahy, 2007; Squires, 2011). Both cemeteries are dated to the early Anglo-

Saxon period with Elsham dated to the fifth through sixth centuries and Cleatham dated to the fifth through seventh centuries, suggesting the length of time the remains were buried was not a significant factor in collagen conservation between the two sites (Leahy, 2007; Squires, 2011). The soil conditions at both Elsham and Cleatham are described as freely draining and slightly acidic, but Elsham cemetery is on loamy soil while Cleatham is on sandy soil (Soilscapes, 2020). The characteristics of the soil may have affected the amount of moisture, the proliferation of microbes, and the pH which may have resulted in differential collagen preservation between the two sites. The conditions the remains were curated in following excavation may have also had an impact. Currently, both collections are held in the same facility in similar conditions. However, Elsham was excavated in 1975 and 1976, while Cleatham was excavated from 1984 through 1989; as post-excavation handling and curation standards for human remains are continually being improved the remains excavated from Elsham may have been subjected to conditions now considered substandard (Cassman et al., 2007; Roberts, 2009; Squires et al., 2019). Finally, the sample sizes studied from both Elsham and Cleatham cemeteries are small, n=4 and n=16 respectively; therefore, conclusions drawn from these results must be interpreted with caution.

The stable isotope analyses produced expected results for individuals living in early Anglo-Saxon England. A diet based in C_3 plants is indicated by the $\delta^{13}C$ values and contributions from terrestrial herbivores are suggested by the $\delta^{15}N$ values; see figure 7.11 (DeNiro, 1987). The two collagen samples from Elsham with low nitrogen contents plot within the range of $\delta^{13}C$ values. One of the samples, from burial EL76AK, has the lowest $\delta^{15}N$ value in the cohort at 9.40‰, this value is only 1.38‰ below the mean of the combined population of inhumed individuals. As these two data points do not affect the overall diet inferred for either population, they have been accepted as likely biogenic and retained in the data set presented.

Comparing the data from Elsham and Cleatham there was no significant difference in the distribution of the $\delta^{13}C$ values, but a significant difference was found in the $\delta^{15}N$ values at a level of 0.05 when using the Kolmogorov-Smirnov test. Individuals interred at Cleatham showed higher $\delta^{15}N$ values than those interred at Elsham. However, due to the small sample size available from Elsham (n=4) this difference may be spurious. Additionally, when using the Mann-Whitney U test no significant difference was found in the $\delta^{15}N$ values

obtained from the two sites. When viewed as a combined population there was no significant difference found among the $\delta^{13}C$ data when divided by sex or age groups among the inhumed individuals at Elsham and Cleatham. There were also no age-related patterns found among the $\delta^{15}N$ data; however, there was a significant difference found between the females and males in this cohort when using the Kolmogorov-Smirnov test. Females (n=9) were found to have relatively higher $\delta^{15}N$ values than males (n=10) at Elsham and Cleatham. Only one of the females in this data set was securely aged as older than 25 years; thus, potentially the elevated $\delta^{15}N$ values may be related to childbirth – a ^{15}N enrichment indicative of the physiological stresses of pregnancy and lactation (Fuller et al., 2005). Though the period of pregnancy and lactation may not be long enough to alter the chemistry of bone, successive births each followed by several years of breastfeeding may result in elevated $\delta^{15}N$ values. Alternatively, these women may have been provided with higher protein diets or their diets may have incorporated more freshwater contributions than their male contemporaries (Pate, 1994; Grupe et al., 2009). Finally, while the difference in the distribution of the $\delta^{15}N$ values was significant, the range of $\delta^{15}N$ values among the male population overlapped the entire range of female $\delta^{15}N$ values; see figure 7.14. Furthermore, the difference in the distribution of the $\delta^{15}N$ values appears to be driven largely by one male individual (EL76AL) with a low $\delta^{15}N$ value (9.68‰). When the $\delta^{15}N$ data is compared using the Mann-Whitney U test, no statistically significant difference between the sexes was found. This suggests that if there were sex-related dietary patterns among the individuals buried at Elsham and Cleatham, they were neither simple nor inviolate.

The isotope data fall in line with carbon and nitrogen data from dietary studies conducted on Anglo-Saxon populations; see figure 7.21 (Privat et al., 2002; Fuller et al., 2006b; Lucy et al., 2009; Mays and Beavan, 2012; Hannah et al., 2018). Zooarchaeological evidence from early Anglo-Saxon sites supports the inference of subsistence based on terrestrial herbivores with sheep and cattle providing the majority of evidence at most settlement sites (Crabtree, 1989; 1990; O'Connor, 2011; Crabtree and Campana, 2014). Goat remains have been found frequently at Anglo-Saxon sites, but not in high numbers. However, there is an issue in zooarchaeology in determining whether animal remains represent sheep or goats; these ambiguous remains are often reported as 'sheep-goats' or 'ovicaprids'. However, due to the predominance of sheep remains at Anglo-Saxon sites, these remains are typically interpreted as sheep if dated to this period. Thus, the

importance of goats to the Anglo-Saxon economy may be understated (Crabtree, 1990; O'Connor, 2011). Remains from pigs were also found at most sites, but aside from a few exceptions, such as Wicken Bonhunt, the number of identified specimens (NISP) show that pigs were a minor contribution to early Anglo-Saxon diets (Crabtree, 1990; O'Connor, 2011; Crabtree and Campana, 2014). However, in the initial phase of settlement pig bones were proportionally better represented, as evidenced at West Stow; Crabtree (1989) suggests this indicates an economic strategy among settlers – exploiting the faster maturation and multiplication of pigs to ensure meat production during the uncertain period of establishing a settlement. Horses, cats, and dogs were also found at several early Anglo-Saxon settlements. Evidence suggests that while horses were eaten occasionally, neither cats nor dogs were kept for meat (Crabtree, 1989; 1990). Minimal evidence of fish or bird remains has been found, although this may be due to the recovery methods; Crabtree (1989) indicates that at West Stow, and other sites excavated prior to the 1980s, wet sieving was not conducted. Thus, the small bones of fish and fowl are likely to have been missed during excavation. The few bird bones that have been recovered from early Anglo-Saxon sites mainly represent domestic species such as goose, chicken, or duck (Crabtree, 1989; 1990). The main species of fish identified were pike and perch, both freshwater species (Crabtree, 1990). The contribution of wild species to early Anglo-Saxon diets appears to have been minimal, although evidence has been found of deer, bear, badger, hare, wild birds, eels, and fish (Crabtree, 1989; 1990; Sykes, 2010; Hull and O'Connell, 2011; Crabtree and Campana, 2014). Hunting was uncommon, evidently practised at need, when agricultural products were insufficient (Sykes, 2010). Hunting, particularly of deer, became more common from the seventh century, involving public distribution of venison in the middle Anglo-Saxon period, then developing into an elite practice from the ninth century (Sykes, 2010). Later written sources indicate that bread was a staple in the Anglo-Saxon diet and evidence of several cereal crops has been recovered from archaeological sites including emmer wheat, spelt wheat, bread wheat, rye, barley, and oats (Hull and O'Connell, 2011; Moffat, 2011). While cereal crops do appear to have been important in the Anglo-Saxon diet, it is possible their importance is over-stated due to the differential preservation of plant species. The majority of plant species found are preserved through charring; thus, cereals that are primarily baked or roasted survive in the archaeological record more easily than other plant species (Moffat, 2011). Legumes, including peas and beans, have also been found

frequently at Anglo-Saxon sites (Moffat, 2011). Additionally, a wide variety of fruit, vegetable, and nut species have been found; however, most are not found in sufficient abundance to prove cultivation. Instead, wild plants may have been gathered from hedgerows and woodlands (Moffat, 2011).

The $\delta^{13}C$ data from both the Elsham and Cleatham populations, while distinctly indicating a C_3 signature, are depleted in ^{13}C relative to previously published isotope data from early Anglo-Saxon sites. To demonstrate the magnitude of this difference, data from several studies were compiled to create a reference dietary range for the early Anglo-Saxon period. These data were collected from studies at Queenford Farm, Berinsfield, Melbourn, Polhill, Westfield Farm and a multi-site study by Mays and Beavan (2012); these data can be found in figure 7.21 (Privat et al., 2002; Fuller et al., 2006; Lucy et al., 2009; Hannah et al., 2018). This reference population had an average $\delta^{13}C$ value of -20.1‰, ranging from -18.9‰ to -21.3‰, while the data produced from Elsham and Cleatham averaged -22.4‰ and ranged from -23.9‰ to -20.4‰ (Privat et al., 2002; Fuller et al., 2006; Lucy et al., 2009; Mays and Beavan, 2012; Hannah et al., 2018). The geographic distribution of these sites can be found in figure 8.5.

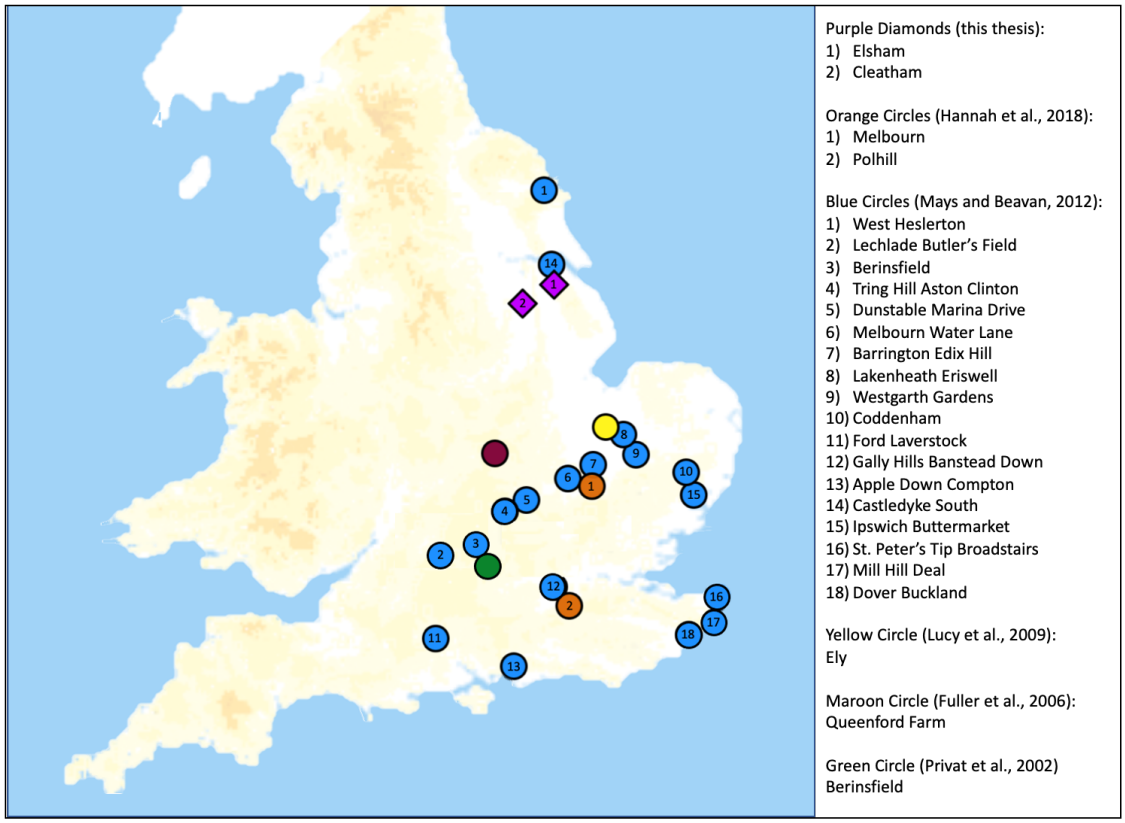


Figure 8.5: Geographic distribution of Anglo-Saxon sites used as a dietary reference population, as well as Elsham and Cleatham cemeteries. The site markers are colour coded to indicate the publications from which their data was drawn, listed to the right.

Several factors can influence the $\delta^{13}C$ value of C_3 plants including elevation, rainfall, temperature, ambient CO_2 composition, soil nutrient content, and light levels (Tieszen, 1991; Bonafini et al., 2013; Goude and Fontugne, 2016; Quinn, 2019). Inter-species variation among C_3 plants has also been shown to be a significant factor in determining $\delta^{13}C$ values among plants grown in controlled environments (Bonafini et al., 2013). Elevation is unlikely to be a factor in the $\delta^{13}C$ variation among these sites as all are located in the south and east of England, areas of relatively low and consistent elevation; see figure 8.6. Similarly, mean annual precipitation, while a good predictor of $\delta^{13}C$ values of C_3 plants in other regions, does not effectively predict $\delta^{13}C$ values among C_3 plants in Europe (Diefendorf et al., 2010; Basu et al., 2019). Tieszen (1991) hypothesised that, while low levels of nitrogen or phosphorus in the soil would result in lower $\delta^{13}C$ values among C_3 plants, these factors would also reduce yields sufficiently that those plants under significant stress would be under-represented in human diets. On a global scale, ambient CO_2 measurements have become depleted in ^{13}C due to the exploitation of fossil fuels, a negative shift of 1-2‰ since the Industrial Revolution (Schoeninger and Moore, 1992). However, on a regional scale ambient CO_2 can be influenced by the recycling of organic material in leaf litter and the respiration gradient of a forest canopy; this 'canopy effect' is entangled with the lower light levels experienced within woodlands (Bonafini et al., 2013). These entwined effects have been shown to cause a $\delta^{13}C$ variation among grass species of approximately 5‰, with a gradient of values between relatively ^{13}C depleted dense woodland, marginal woodland, and relatively ^{13}C enriched open fields (Bonafini et al., 2013). The area of the Lincolnshire Wolds on which both Elsham and Cleatham cemeteries are situated supports woodlands of pine, oak, and birch. Inhabitants of nearby settlements may have incorporated foraged or cultivated vegetables, fruits, or nuts from woodland areas or allowed their livestock to graze in woodland or marginal areas leading to a lower $\delta^{13}C$ values (Leahy, 2007; Bonafini et al., 2013). At the nearby settlement site excavated at West Heslerton analyses of charcoal indicate that woodlands and orchards were being maintained, supporting the possibility of the canopy effect causing the lower $\delta^{13}C$ values found at Elsham and Cleatham. Variation among wheat species has been reported as greater than 3‰ and developmental stages contributed to variations of 9‰ (Tieszen, 1991). Therefore, individuals at Elsham and Cleatham cemeteries may have been eating a higher

proportion of ^{13}C depleted cereals, whether due to a preference in species of cultivars or harvesting cereals at different stages. Finally, caution must be taken in the interpretation of these results as the sample sizes are small (Elsham n=4, Cleatham n=16).

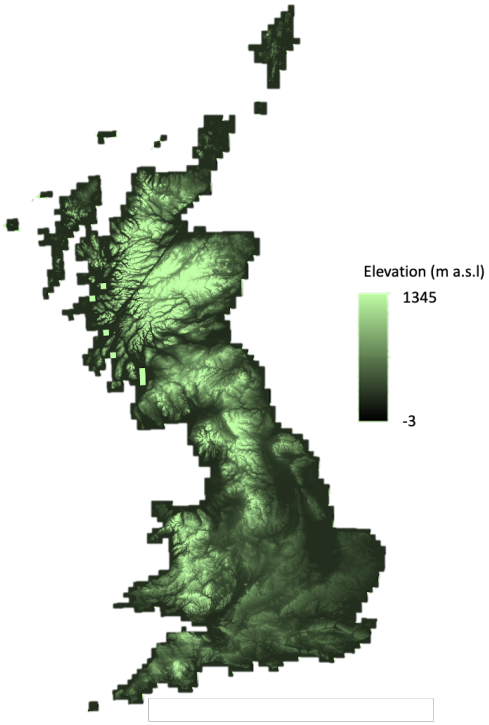


Figure 8.6: Map of England, Wales and Scotland showing elevation data from ordinance survey data, m a.s.l indicating metres above sea level.

The $\delta^{15}N$ data from Elsham and Cleatham were slightly elevated over the reference population of Anglo-Saxon sites. The mean $\delta^{15}N$ value from Elsham and Cleatham individuals was 10.8‰, with a range of 9.4‰ to 11.6‰; in comparison, the reference population had a mean $\delta^{15}N$ value of 9.9‰, with a range of 7.9‰ to 13.2‰ (Privat et al., 2002; Fuller et al., 2006; Lucy et al., 2009; Mays and Beavan, 2012, Hannah et al., 2018). This difference is minor, with the Elsham and Cleatham individuals falling within the expected range of $\delta^{15}N$ values from previous published early Anglo-Saxon sites. Furthermore, when compared against the two geographically closest sites, West Heslerton and Castledyke South, the difference between the mean $\delta^{15}N$ values is reduced to only 0.7‰ (Mays and Beavan, 2012). These sites were investigated in an attempt to determine dietary difference among marine, riverine, and inland populations; however, there was little overall variation in $\delta^{15}N$ values among these groups suggesting that while marine or freshwater resources may have been consumed, these foods were only a minor contribution

to the diet (Mays and Beavan, 2012). Zooarchaeological data from the Anglo-Saxon settlement at West Heslerton suggest that over half of the meat consumed was derived from sheep and approximately a third from cattle (Powlesland, 1998; Rahtz, 2001). Other species found include horse, pig, goat, dog, cat, and geese. Fish bones were scarce, though recovery and preservation may have been a factor in their scarcity (Powlesland, 1998).

The $\delta^{34}S$ values from Elsham and Cleatham ranged from -5.0‰ to 9.2‰. There was no significant difference found in the distributions of the $\delta^{34}S$ values between the two sites therefore they were considered as a single population in further analyses. This range of values represents an expected range for individuals living on substrates of chalk and Jurassic clay with potential contributions from coastal effects, as based on modern data (Evans et al., 2018a). Higher values within the data set may suggest some contribution of marine protein or sea spray affecting terrestrial flora and fauna. The $\delta^{13}C$ and $\delta^{15}N$ values from these individuals, however, are not sufficiently elevated to suggest any significant dietary contribution from marine protein. This leaves a sea spray effect as the more likely explanation for $\delta^{34}S$ values above the 6.3‰ expected for an area dominated by chalk substrates (Evans et al., 2018a). However, the Biosphere Isotope Domains dataset is based on modern data that are likely contaminated by anthropogenic sources of sulphur (Evans et al., 2018a). As discussed in section 4.6, the $\delta^{34}S$ values of fossil fuels are highly varied, recorded at a range from -30‰ to 40‰; as such determining how anthropogenic sulphur contamination has affected the modern samples used for establishing the $\delta^{34}S$ ranges for geological regions is complex (Thode et al., 1991). Long-term agricultural experiments run on the Upper Cretaceous White Chalk subgroup indicate that prior to the 1860s $\delta^{34}S$ values from herbage were much higher than those from modern plants, with a general negative correlation found between SO_2 emissions and $\delta^{34}S$ values (Rothamsted Research, 2006; Jay and Montgomery, 2019). When compared against $\delta^{34}S$ data obtained from Wetwang in Yorkshire, also located on chalk substrates, the $\delta^{34}S$ data from Elsham and Cleatham are surprisingly low; see figure 8.7. Thus, the higher $\delta^{34}S$ values at Cleatham and Elsham should be interpreted as within the normal range for an inland population located over chalk substrates with no evidence for marine contributions to their subsistence strategy. The lower $\delta^{34}S$ values explained by the Jurassic clay, mudstone and ironstone formations underlying the area around both sites. Intra-population comparisons showed an interesting linear pattern in the $\delta^{34}S$ and $\delta^{15}N$ values separating females and males at Elsham and

Cleatham. Females showed lower $\delta^{34}S$ values, higher $\delta^{15}N$ values and lower $\delta^{13}C$ relative to males, perhaps suggesting these female individuals were consuming more freshwater resources. However, this difference was not found to be significant. There was a significant age-related difference in the $\delta^{34}S$ values with older individuals having higher $\delta^{34}S$ values than those in the 19-25 year age group, perhaps suggesting that the consumption of freshwater resources decreased with age. However, the older age group consisted of only four individuals. There were also five individuals for whom precise age estimates were not possible; if these five individuals are included with the 19-25 year age group the correlation is strengthened, but if these five individuals are included with the older age group, the difference between the groups is erased. Therefore, though the difference was statistically significant as shown by both the Kolmogorov-Smirnov test and the Mann-Whitney U test, it must be interpreted with caution. However, it would appear from these data that there is most likely an inter-section between sex and age in determining the diets of these populations. This may relate to status or wealth, with older individuals more likely to have accrued both greater status and wealth over their lifetimes. More valuable foods would then be expected to be consumed predominantly by older individuals. A subtle pattern in the nitrogen data from Berinsfield potentially fits this pattern, with higher status individuals and older males displaying lower $\delta^{15}N$ values than lower status or younger individuals (Privat et al., 2002). Alternatively, there may be a dietary difference related to childbirth and lactation; therefore, most prominent among young women. There may have been food taboos for pregnant or breastfeeding women, or foods that were believed to aid in gestation or lactation (Fuller et al., 2006b). To reach more nuanced interpretations of these $\delta^{34}S$ data further research would be required involving larger sample sizes and contextual data from a range of local faunal samples.

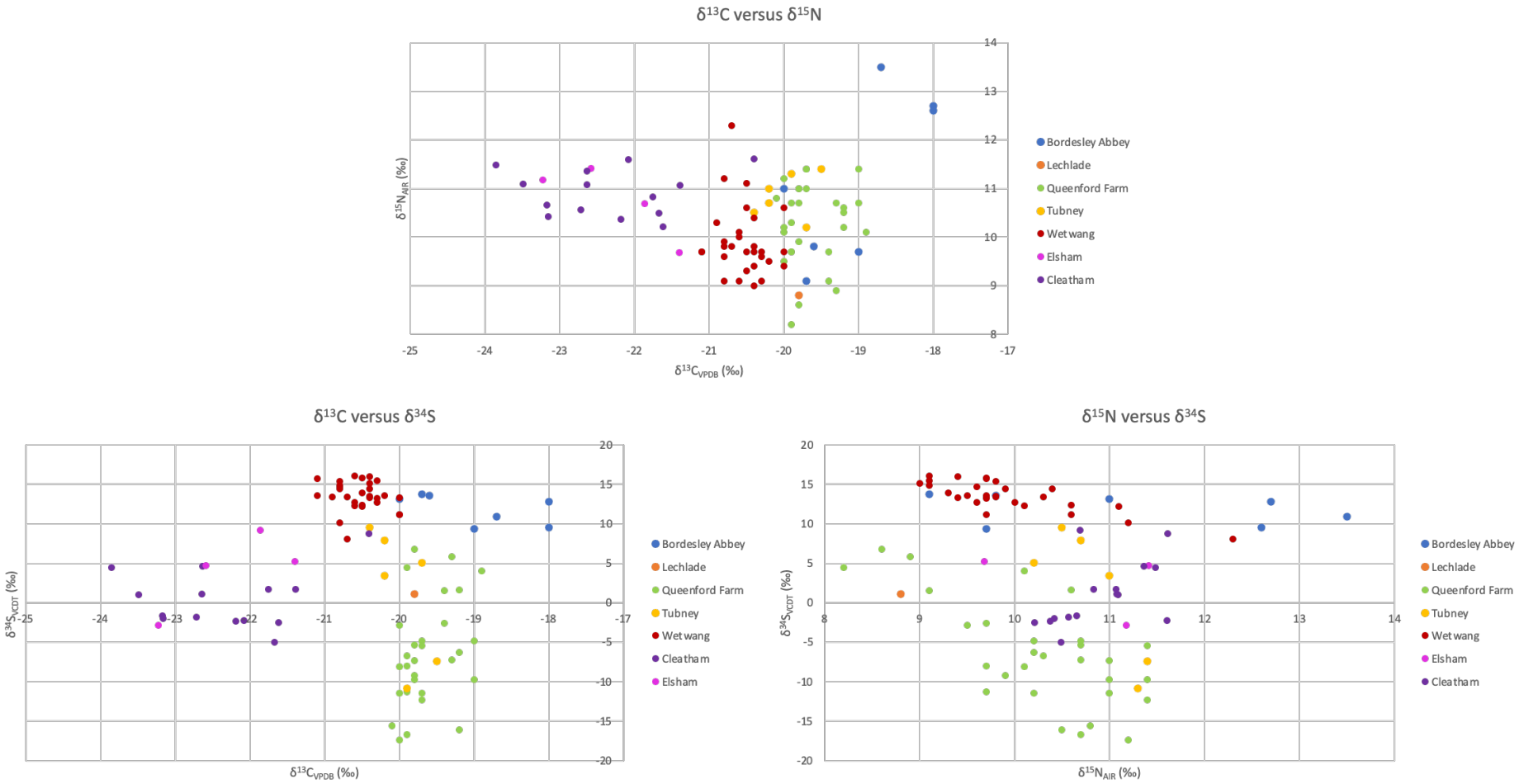


Figure 8.7: Stable isotope data from five previously published English sites: Bordesley Abbey (n=7), Lechlade (n=1), Queenford Farm (n=28), Tubney (n=6) and Wetwang (n=29). Bordesley Abbey and Lechlade data from Richards and colleagues (2001). Queenford Farm and Tubney data from Nehlich and colleagues (2011). Wetwang data from Jay and colleagues (2013). Elsham (n=4) and Cleatham (n=15) data were collected for this thesis. Data included in these plots were obtained from adult individuals.

8.3.2 Data from Cremated Individuals

Colour was used as a screening criterion for samples selected from cremated individuals from Elsham and Cleatham cemeteries; samples were selected that ranged from brown to black suggesting temperature exposures between 200°C and 400°C or with more advanced thermal exposures on their exterior surfaces showing darker coloration on broken surfaces suggesting internal temperatures had remained at 400°C or below; see section 7.2.1. From the experimental data, these samples were expected to yield collagen, while those exposed to temperatures between 200°C and 300°C were expected to provide isotope data not significantly divergent from biogenic values; see section 6.5.1. However, FTIR analysis conducted on these samples indicated that the organic content was minimal and there had been some modification of the bone mineral as well; see section 7.2.2. In controlled heating experiments, FTIR results such as these would indicate temperature exposures in the range of 400°C to 700°C and likely in excess of 500°C (Thompson, 2005; Thompson et al., 2013). However, in archaeological samples these results may also indicate taphonomic changes to bone composition (Surovell and Stiner, 2001). Regardless of the mechanism of change these FTIR results indicate that the bone samples analysed were not likely to contain unmodified collagen. Ideally, these FTIR results would have been collected before collagen extraction began and used to determine whether further testing should continue. As these FTIR results indicated that collagen preservation was unlikely in the bone samples studied, further testing would not have been conducted on these samples. Instead, new bone samples would have been selected and analysed in the hope of recovering collagen during extraction. However, due to COVID-19 restrictions laboratory access was limited. Therefore, FTIR analysis was conducted while collagen extraction was underway. Furthermore, access to additional samples was not possible as a result of the same restrictions. Collagen yields were low from both sites, the mean yield from Elsham was 1.32% and from Cleatham was 1.43%; this marginal conservation of organic material can also be seen in the FTIR data from these samples. However, several of the samples taken from cremated individuals for analysis were composed of trabecular bone. As such, the complete removal of soil inclusions from these bone samples was impossible. This may have resulted in artificially low collagen yields as the collagen weight is compared against a 'before' weight that includes both bone and soil. Nitrogen data from these samples were

unreliable at 0.3 mg; as such, the analysis was repeated with 3 mg of extract, though only ten individuals had sufficient collagen yield for this analysis and produced reliable data. Indications from the collagen quality indicators suggest these samples did not consist of unmodified human bone collagen. The specific combination of high C:N ratios and low $\delta^{13}C$ values found in the samples from cremated individuals is indicative of contamination from plant proteins. These proteins may have been introduced to the bone samples during cremation as carbon and nitrogen were exchanged with the fuel source during the burning process. Alternatively, plant-derived contaminants may have been introduced to the bone samples through the burial environment with organic components of the soil interacting with the bone. Furthermore, these samples may consist of largely human bone collagen that has been modified, through thermal exposure or interaction with the burial environment, such that these samples can no longer be considered representative of *in vivo* isotope ratios. As these data do not represent biogenic $\delta^{13}C$ and $\delta^{15}N$ values, no meaningful comparisons can be made between these data and the data obtained from the inhumed individuals analysed from Elsham and Cleatham cemeteries.

8.4 Comparing the Results of the Controlled Heating Experiment and the Archaeological Application

Experimental data collected here and in previous research suggested that isotope analyses of carbon and nitrogen from cremated samples was a possibility (DeNiro et al., 1985; Schurr and Hayes, 2008; Schurr et al., 2008; Harbeck et al., 2011). However, the sample analysed from archaeologically cremated individuals did not produce biogenic human bone collagen. This may be the result of thermal alteration. If so, the samples selected from cremated individuals were likely exposed to temperatures above 400°C. However, there are several interactions that could alter the chemical composition of these bone samples that were not accounted for by the controlled heating experiment. The methodology used for the controlled heating experiment involved heating bone samples in a muffle furnace for prescribed amounts of time. There was no interaction with an open-air environment that could cause temperature fluctuations, no interaction with a fuel source and the bone samples were analysed immediately after heating without interaction with soil, microbes, or ground water. Any of these interactions could influence the collagen

content – either through degradation or alteration of biogenic chemical composition. In order to move from the theoretical possibility presented by the experimental data into archaeological application of isotopic dietary interpretations from cremated remains these interactions must be investigated.

Firstly, the selection method for samples of cremated bone that may retain sufficient collagen for stable isotope analysis must be refined. Elsham cemetery was comprised of 569 cremation burials, Cleatham cemetery was comprised of 979 – for a combined population of 1548 cremation burials (Squires, 2011). In order to filter this population to a reasonable number for examination within the time available for visual examination, several stages of elimination were undertaken before examining the cremated remains; see section 5.4.4 for full details. The first two stages eliminated accessory vessels, burials not previously analysed, non-adult individuals and individuals without age estimates. Accessory vessels, largely containing animal remains, may be a fruitful source of bone samples for isotope analysis as animals were likely exposed to lower temperatures at the periphery of the pyre (Wahl, 2015). However, this study focused on human remains. Burials without osteological analysis or without age estimates may lack contextual information but may have contained remains exposed to temperatures below 400°C. Non-adult remains were avoided due to the potential complications of weaning and growth on stable isotope ratios. The next stage involved eliminating any cremation burials categorised as showing severe morphological changes related to heat exposure, reducing the combined population to 401 individuals. Although these burials contained elements showing evidence of high temperature exposures, they may also have contained elements exposed to only low temperatures; pyre cremation is not an even process and the assumption that some evidence of severe thermal alteration precludes any collagen conservation is a faulty one (McKinley, 2000). Instead of eliminating cremation burials from analysis based on assumptions of their viability, the full population should ideally be analysed visually for samples of cremated bone showing colouration indicative of low temperature exposures. This exhaustive process would involve a considerable time investment and may not be practical in most cases, but would provide a better picture of the expected colour variation among the cremated population under investigation to the researcher. This experience would likely aid in the appropriate selection of bone samples for further analysis. However, neither this exhaustive approach nor the

experience gained therein would guarantee that appropriate samples, exposed to temperatures lower than 400°C, could be found.

Further experimentation to investigate the influence of an open air-environment and possible interactions with fuel were discussed in section 8.2.6. However, further experiments regarding the effect of diagenesis on experimentally heated bone against unheated controls should also be conducted. The factors affecting collagen conservation in the burial environment (moisture, soil pH, microbial composition, temperature, and time) are unlikely to change; however, the rate at which collagen degrades in heated versus unheated samples is currently unknown (Lee-Thorp, 2008). Calcined bone fragments are relatively inert in the burial environment; this is due to the removal of organic material from the bone matrix, increased size of bioapatite crystals, reduced porosity, and reduced strain as apatite crystals become isotropic (Thompson, 2015; Aplin et al., 2016). However, lower temperature exposures do not eliminate the organic components from bone and do not alter the mineral composition of bone. These conditions are likely to produce bone that is more susceptible to diagenetic processes. This is due to the influence of the surface area to volume ratio on chemical and physical reactions (Nicholson, 1996). On a macroscopic level bone fractures when heated; these smaller fragments of bone with exposed trabeculae will be more readily exposed to soil, microbes, and ground water (Symes et al., 2015). On a microscopic level, collagen fibrils when heated first break into small 'barbell' sections before denaturing; these sections of collagen fibrils will be more susceptible to deterioration than complete fibrils (Koon et al., 2003; 2010). In unheated bone, the mineralised collagen fibrils are so tightly packed that collagenase molecules cannot diffuse through the inter-crystalline spaces, though gradually collagen molecules hydrolyse and are lost from the bone matrix (Von Endt and Ortner, 1984; Child, 1995). However, the porosity of burned bone increases as the organic fraction is compromised, then lost (Thompson et al., 2011). Therefore, we would expect burned bone to be more susceptible to degradation in the burial environment; however, Aplin and colleagues (2016) suggest that, particularly in acidic soils, burned bone survives longer than unburned bone with fully calcined bone persisting the longest. Experiments with cooked animal remains showed little variation in the degradation of bone between cooked and uncooked specimens (Nicholson, 1996). Experiments with calcined bone samples showed that minimal chemical exchange with the burial environment occurred in these samples (Snoeck, 2014). Of these experiments, only Snoeck's (2014)

involved isotope analysis; however, this research involved higher temperature ranges (500°C or above) at which collagen is not expected to survive. Thus, while burned bone clearly survives the burial environment, whether it retains viable collagen and in what conditions should be investigated.

8.5 Wider Research Context

8.5.1 Determining Unknown Burning Conditions

The controlled heating experiment conducted here suggests that stable isotope analysis of carbon isolated from collagen should be possible in bone samples heated to 400°C for up to two hours, while analysis of nitrogen should be possible in bone samples heated to 250°C for up to two hours; see section 6.5.1 for details. However, the bone samples collected from cremated individuals interred at Elsham and Cleatham cemeteries failed to produce biogenic human bone collagen. FTIR results suggest these bone samples were exposed to temperatures of 500°C or higher; see section 7.2.2 for details. Extensive FTIR testing of bone samples from the cremated individuals from these cemeteries may allow for the discovery of samples exposed to lower temperatures; these samples could then be further analysed to determine whether sufficient unaltered collagen remains for stable isotope analysis. FTIR analysis requires only a small sample of ground bone and the sample is not consumed during testing and can be used for further analyses; as such, this method could be applied to large populations. However, FTIR results also reflect taphonomic changes to bone chemistry (Thompson et al., 2009). Both Elsham and Cleatham cemeteries are located on acidic soils that may have dissolved any organic material remaining in the bones sampled for this research; this may also have affected the FTIR results used to estimate temperature exposure (Thompson et al., 2009; Squires, 2011). Taphonomic changes are also known to affect the mineral content of bone from archaeological contexts, altering the FTIR spectra produced (Surovell and Stiner, 2001). Improper storage conditions have also been shown to affect FTIR data (Thompson et al., 2011). Other methods for determining temperature exposure were discussed in section 3.5; however, there are two methods that may be particularly applicable to determining the temperature exposure of archaeologically cremated remains and the potential survival of collagen in bone fragments. First, the application of quantitative petrography to

histomorphometric analysis of burned bone fragments has allowed for relatively narrow temperature estimates in pilot studies; these studies were able to estimate temperature ranges of 100°C – 400°C, 500°C – 600°C, 700°C – 900°C, and 1000°C – 1100°C (Carroll and Squires, 2020a; b). This new quantitative method aims to remove subjective assessment of heat-induced changes from histomorphometric analyses in order to allow for more cross-comparisons within the literature (Carroll and Squires, 2020a; b). This method could allow for more refined temperature estimates and has proven effective on a small sample of archaeologically cremated remains; however, the method is time-consuming requiring five days to analyse a single batch of samples (Carroll and Squires, 2020a; b). Additionally, there are difficulties in preparing slides from friable cremated bone; as such, the method requires considerable expertise to execute properly (Squires, 2011; Carroll and Squires, 2020a).

A method developed to examine collagen fibrils directly involved the extraction of collagen from the bone samples, staining with phosphotungstic acid and uranyl acetate for analysis via Transmission Electron Microscopy (TEM) (Koon et al, 2003; 2010). This methodology was able to show the accumulation of minor damage to the collagen fibril that occurs at low temperatures (Koon et al., 2010). This type of damage may explain the differential susceptibility of bone from low-temperature burning events to the loss of collagen in the burial environment. Furthermore, TEM analysis of the protein extracts from archaeologically cremated bone samples may indicate what these extracts consist of – whether denatured biogenic organic material or contaminants from the burial environment. However, this again is a complex and time-consuming process (Koon et al., 2003). Neither of the two methods discussed could reasonably be applied to a large population, such as that represented by the Anglo-Saxon cremation cemeteries of Elsham or Cleatham. There may, however, be a role for these more labour-intensive processes as an internal calibration for results derived from the more expedient analyses by FTIR or spectrophotometer; a combination of these methods may allow researchers to re-affirm and narrow the results from FTIR and colour analyses without overwhelming investment in these more complicated procedures.

8.5.2 Variation in Cremation Strategies Over Time

There are several other large cremation or mixed rite cemeteries dating to the early Anglo-Saxon period; unfortunately, most are located on acid soils; see table 8.3. While these cemeteries represent a large population of cremated individuals, the issue of soil chemistry influencing the preservation of organic material is likely to be encountered at these sites. However, many cultures cremated their dead. In Britain alone cremation was practised from the Neolithic period through to the 10th century, with considerable variation in the technology employed in the mortuary rite (McKinley, 2015). Cremation burials from these cultures may provide better opportunities for attempting the analyses of carbon and nitrogen isotope ratios; their specific traditions are outlined below.

Table 8.3: Soil data from large Anglo-Saxon cremation cemeteries; only cemeteries with more than 100 cremation burials were included. All soil data from Soilscapes, 2020.

Site	County	Number of Cremation Burials Analysed	Grid Reference	Soil Description			Source
				Moisture Level	Acidity	Soil Type	
Loveden Hill	Lincolnshire	103	SK 908 458	Naturally wet	Very Acidic	Sandy and loamy	Squires, 2012
Cleatham	Lincolnshire	979	SE 932 008	No data	Slightly Acidic	Sandy	Leahy, 2007
Elsham	Lincolnshire	569	TA 046 125	Freely draining	Slightly Acidic	Loamy	Squires, 2011
Spong Hill	Norfolk	2476	TF 981 195	No data	Slightly Acidic	Loamy and clayey	McKinley, 1994
Illington	Norfolk	104	TL 949 898	Freely draining	Not acidic	Sandy Breckland	Davidson et al., 1993
Sancton I	Norfolk	335	SE 889 395	Seasonally wet	Slightly acid	Loamy and clayey	McKinley and Bond, 1993
Rayleigh	Essex	145	TQ 799 923	Seasonally wet	Slightly acid	Loamy and clayey	Ennis, 2008
Mucking II	Essex	403	TQ 673 803	Freely draining	Slightly acid	Loamy	Hirst and Clark, 2010
Millgate	Nottinghamshire	220	SK 792 534	Impeded drainage	Not acidic	Loamy and clayey	Kinsley, 1989

8.5.2.a Neolithic Cremations

The Neolithic cremation rite parallels the Anglo-Saxon rite in that, in several cases, cremated remains were found interred alongside unburned remains (Beckett and Robb, 2009; Fowler, 2010). The majority of Neolithic burials were collective, whether through successive interments or interments of multiple individuals at once. In several cases, these individuals were subject to a variety of mortuary treatments including excarnation, cremation, defleshing, disarticulation, or intact interment (Fowler, 2010). While the most common rite involved primary burial of an intact corpse within a communal burial chamber, variable treatment of the individuals buried at a site or even within a single deposition is a common finding (Beckett and Robb, 2009). Cremated remains are a common find at Neolithic cemetery sites; however, contrary to the inhumation evidence, the majority of cremated remains appear to have been burned collectively (Fowler, 2010). In some cases, these remains were placed in prepared areas, deemed 'crematoria' in the literature, burned *in situ*, then covered by earthen mounds – as at Willerby Wold in North Yorkshire (Fowler,

2010). Another mortuary practise resulting in burned bone, but perhaps not properly considered 'cremation', was the primary interment of human remains in wooden structures that were later burned and replaced by stone chambers, stone cairns, or earthen mounds. Evidence of this type of practise has been found at Humbledon Hill, near Sunderland, and at Street House, North Yorkshire (Fowler, 2010). The potential conservation of organic material in burned human bone from Neolithic contexts is significant. Firstly, collective cremations are unlikely to have produced uniformly calcined material. As with pyres designed for single individuals, the periphery of the fire is naturally cooler than the centre, a gradient likely to be more significant in a larger fire (McKinley, 2000). Secondly, the collective burning of multiple individuals will increase the potential for specific elements to be shielded from the fire throughout the burning period (Symes et al., 2015). Thirdly, an extensive ash load can be expected to be produced by a large fire that could provide protection to any small skeletal elements that are disarticulated early in the combustion process (McKinley, 2015). Finally, the burning of remains *in situ* and protective enclosure of the barrow prevents the loss of skeletal elements during post-cremation collection of remains for burial. Research suggests that mourners preferentially select white, calcined bone from the pyre debris for burial, leaving remains exposed to lower temperatures to be buried with pyre debris (McKinley, 2015). In cases where wooden mortuary structures are burned around the previously interred human remains, there is also reason to be sanguine regarding the conservation of organic material. First, the burning of a superficial structure over the remains will not provide ideal heat transfer to the remains contained within, simply due to thermodynamics (Drysdale, 1999). Secondly, dry and fleshless remains provide no additional fuel for the fire in the form of volatilised lipids; however, these remains have little, if any, overlying flesh or water content protecting them from the fire (DeHaan, 2008). Indeed, in observations of these remains archaeologists have used terms such as 'charred' or 'scorched' rather than cremated, indicating lower temperature exposures; see figure 8.8 for a distribution of burning intensities from Neolithic cremation burials from Guernsey (Fowler, 2010; Cataroche and Gowland, 2015). Finally, as with Anglo-Saxon remains, the juxtaposition of inhumed and cremated remains provides an opportunity for the comparison of the diet of the individuals practicing these two mortuary technologies (Beckett and Robb, 2009; Fowler, 2010). An important caveat to this optimistic interpretation is that skeletal collections from Neolithic contexts are typically comprised of a

small number of individuals whose remains are both fragmentary and commingled (Beckett and Robb, 2009). While stable isotope analysis does not require intact skeletal remains, the appropriate selection of a representative sample would be complicated by the nature of these skeletal collections.

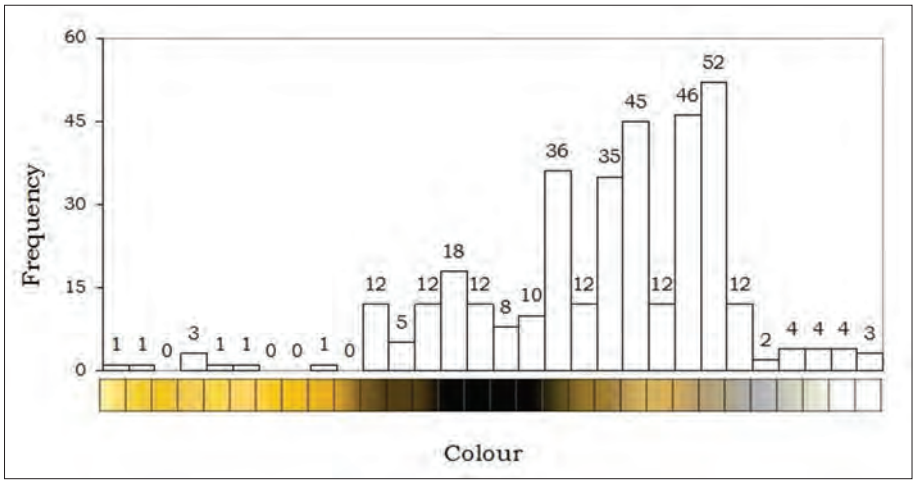


Figure 8.8: Colour variation, indicating burning intensity, from Neolithic cremation burials excavated on Guernsey. Cataroche and Gowland, 2015 (p. 31).

8.5.2.b Bronze Age Cremations

Bronze Age mortuary practises in Britain can be divided into a period between 2500 BC and 1500 BC characterised by the used of barrows and a period from 1500 BC through 1100 BC in which barrow burials are rare and flat cemeteries become more common. There is little evidence of formal burial in the period following 1100 BC (Appleby, 2012). Initially inhumation is the dominant rite practised but circa 1600 BC cremation becomes the predominant rite; however, there is significant overlap between the two practises with cremation burials and inhumation burials often found at the same sites (Appleby, 2012). Indeed, when viewed against the variety of mortuary treatments evidently exercised during the Bronze Age, inhumation and cremation cannot be viewed as binary options but rather part of an extensive spectrum of rites that include: excarnation, removal of flesh or disarticulation, mummification, intact burial or cremation, manipulation of remains after primary interment, retention of remains, and the burial of the pyre and cremated remains *in situ* (Appleby, 2012). The majority of cremated remains recovered from Bronze Age burials appear to have been burned while fleshed; however, cremated bone recovered at Rapness

in Orkney display fracture patterns associated with burning dry bones, suggesting cremation after decomposition (Appleby, 2012). There are also a few examples of cut-marks on cremated remains that may suggest the removal of flesh prior to cremation, including several excavated in Scotland at Eweford West in Lothian, Danure Road in Ayrshire and Seafield West in Inverness-shire and one example recovered in England from Strood Hall, Essex; McKinley (2007), however, cautions that cut-marks of this nature may also represent peri-mortem injuries (Appleby, 2012). Cremated remains from two types of Bronze Age features suggest the potential for stable isotope analysis: 'primary' cremation burials and pyre sites (McKinley, 1997; 2009). The problematic distinction of certain burials as 'primary' indicates either that the burial specified was the first interment at a location or, more subjectively, the most important burial at a site (Peterson, 2014). The term 'primary' is a remnant of the focus on elite, singular burials from the early Bronze Age (Appleby, 2012; Peterson, 2014). However, among Bronze Age cremation burials those that have been designated as 'primary' deposits contain significantly more cremated bone than cremations from other periods or from contemporary deposits not considered 'primary' (McKinley, 1997; 2009; 2013). In a survey of 18 'primary' Bronze Age cremation burials McKinley (1997) found cremation weights ranging from 902 g to 2747 g, with an average weight of 1526 g; the average weight of cremated bone recovered from British cremation burials typically falls between 600 g and 900 g (McKinley 2013). As discussed above, indications suggest that calcined bone is preferred during the collection of cremated remains; as such, cremation weights nearing whole skeletal representation are more likely to include less oxidised elements that may retain organic material (McKinley, 2015). However, the preferential analysis of these burials, likely representing an elite group due to the overt expenditure of labour involved in their collection, would not necessarily provide a representative indication of the diets of Bronze Age individuals (McKinley, 1997; 2000). Pyre sites, or redeposited pyre debris, following the same logic, may also represent a potential source of cremated remains that may retain collagen sufficient for stable isotope analysis. Sites such as Linga Fold on Orkney represent ideal conditions for the conservation of evidence where the pyre site appears to have been buried immediately following cremation preserving cremated bone, charcoal, and ash *in situ* (McKinley, 1997). Bone fragments exposed to temperatures sufficient to char the exterior surface but below the

threshold need for the pyrolysis of carbonates, 300°C to 500°C, are likely to be found among pyre debris (Thompson, 2005).

8.5.2.c Iron Age Cremations

In Britain, relatively few burials dating to the Iron Age have been recovered archaeologically; researchers suggest that the deceased may have been exposed, cremated without subsequent burial, or buried in water rather than interred within formally defined burial grounds (Pearce, 2008). However, evidence of a variety of funerary traditions have been found dating from the Late Iron Age; among them are the cremation burials of the Aylesford-Swarling cultural tradition that emerged in south-eastern England over the course of the first century BC (Whimster, 1979; Stead and Rigby, 1989; Pearce, 2008). The rituals employed share several integral aspects with continental La Tène culture cremations, including pyre technology and the ceramics used as cinerary vessels and grave goods (Whimster, 1979; McKinley, 1997). A minority of these burials were recovered from cemeteries with more than ten graves, with only two of these cemeteries consist of more than one hundred burials: Westhampnett in Sussex with 159 cremation-related features and King Harry Lane in Hertfordshire with 455 cremation burials (Whimster, 1979; Stead and Rigby, 1989; McKinley, 1997). Few Iron Age cremations have been examined by osteologists as many were excavated prior to the 1960s, during a period when archaeologists believed cremated bone held no academic value (McKinley, 1994; 1997). However, a few trends have emerged from the few sites that have been subject to investigation. Late Iron Age cremation burials consist of relatively low weights of cremated bone: the average weight of burials from Westhampnett was 301 g and 49% of burials from King Harry Lane weighed less than 499 g (Stirland, 1989; McKinley, 1997; 2009). Animal remains were found associated with 22% of Late Iron Age cremation burials, though typically only a few grams were included in these burials and only one or two species were represented, most often pig, sheep/goat, or domestic fowl (McKinley, 2009). Pyre technologies were effective resulting in largely calcined skeletal remains and remnants of melted bronze and glass suggesting temperatures in excess of 1000°C (Whimster, 1979; McKinley, 1997). However, at King Harry Lane, 16% of burials (n=74) were characterised as 'badly burnt' suggesting collagen conservation may be possible in these cases. In a multi-period survey of over 1000

cremation burials excavated in Germany dated to the pre-Roman Iron Age typically included skeletal remains that were not fully calcined (Wahl, 2015). As pyre technologies were shared between British and continental cultures during this time, this suggests that Iron Age cremation burials may include less oxidised material that may retain organic material; however, many of these burials are single interments or derive from only very small burial collections (Whimster, 1979). Furthermore, the two large Iron Age cremation cemeteries that have been analysed are unlikely to contain cremated remains from which collagen can be extracted. The cremation burials at Westhampnett are largely calcined with only 3% of cremation-related contexts showing variation in burning conditions and, while there were 74 cremation burials from King Harry Lane that were poorly cremated, at both sites preservation was poor with associated inhumation burials suffering from acid erosion (Stirland, 1989; McKinley, 1997).

8.5.2.d Roman Cremations

Roman cremation follows on from an established rite in late Iron Age Britain, with several cemeteries in southeast England showing continuity from the Late Iron Age (McKinley, 2015). Cremation was the dominant mortuary rite practised in Roman Britain from 43 AD through to circa 150 AD with a gradual shift towards inhumation during the second century; however, cremation did persist throughout Roman Britain, especially in the Northern Frontier zone proximate to Hadrian's Wall (McKinley, 2015). The majority of the cremation related deposits excavated are burials, although pyre sites, redeposited pyre debris, and possible cenotaph deposits are also found (McKinley, 2004; 2015). The majority of cremation burials are urned, with evidence that the unurned cremation burials were likely buried within organic containers that have since decayed (McKinley, 2015). Inclusion of pyre debris within the grave fill of cremation burials was very common; evidence of this was found in 50% of cremation burials at St. Stephan's in Hertfordshire to 100% of burials at Low Borrowbridge in Cumbria (McKinley, 2004). Generally, the Roman cremation rite was efficient and relatively uniform, resulting in the majority of bone fragments interred being fully calcined (McKinley, 2004; 2015; Thompson et al., 2016). However, less oxidised remains are found in a variable proportion of burials and pyre deposits at most sites – only Low Borrowbridge shows no variation in the oxidation of the remains recovered; all

recovered bone was fully calcined (McKinley, 2004). Typically, the less oxidised elements are located on the skull or distal lower limb, peripheral elements likely to experience lower temperature exposures in an open-air cremation (McKinley, 2015; Symes et al., 2015; Thompson et al., 2016). In some cases, discrete patterning of heat-induced changes or pyre goods suggest shielding by clothing or pyre furniture, such as: cushions, hoods, or hats indicated by unilateral pattern of thermal exposure on the skull and hob-nailed boots suggested by low temperature exposures of the feet and iron nails (McKinley, 2015; Thompson et al., 2016). However, in both cases the authors caution against over-interpretation of the evidence (McKinley, 2015; Thompson et al., 2016). Demographically, the adults exhibit more variation in thermal alteration than non-adults and males show more variation than females suggesting that lower body mass was a contributing factor in attaining fully calcined remains during cremation (McKinley, 2015). Geographically, burials excavated from town cemeteries showed more variation than burials excavated from rural sites (McKinley, 2015). Evidence of lower temperature exposures during cremation has been found in 5-66% of burials excavated from Romano-British cremation cemeteries, with the exception of Low Borrowbridge (McKinley, 2004). In some cases, this variation is extensive; see figure 8.9 (Thompson et al., 2016). While fragments of cremated bone exposed to temperatures under 300°C, on which carbon and nitrogen isotope analysis might be successful, are rare from Romano-British cremations, there is reason to be hopeful that in these minority cases collagen may be preserved. The regular incorporation of pyre debris in cremation burials during this period, including large quantities of charcoal, would neutralise acidic soil creating a micro-environment conducive to the preservation of collagen (McKinley, 2004). However, if the selection of bone samples that have been exposed to lower temperatures limits the sample populations to adult males from town cemeteries, the data will be inherently biased. While this data would not be without value, careful consideration of this bias during interpretation would be necessary.

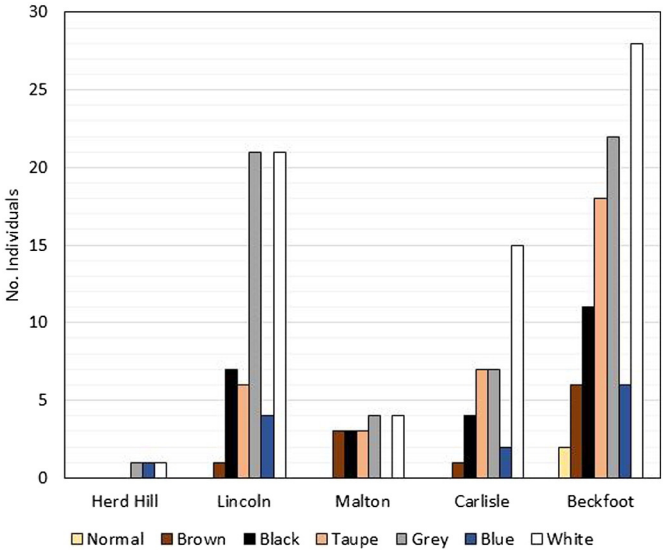


Figure 8.9: Graph showing the variation in heat-induced colour change, indicating burning intensity during cremation, seen at five Romano-British sites. Thompson et al. (2016, p. 6)

8.5.3 Cremated Animal Remains

The animal remains commonly included with human cremation burials constitute another potential area of research. The incorporation of animal remains in Anglo-Saxon cremation burials is discussed in some detail in section 2.5.4 and while Anglo-Saxon cremation burials contain the largest amounts of cremated animal bone and the widest range of species, animal remains are a common occurrence in cremation burials from all periods; see table 8.4. These remains have been investigated in a few cases, largely to determine the species that are represented, their age and whether the elements represent joints of meat, whole carcasses or amuletic inclusions (Davis, 1989; Bond, 1994; 1996; McKinley et al., 1997; Bond and Worley, 2006; Squires, 2013; French, 2017). The bones are often subjected to lower temperatures than the human remains they accompany, whether due to placement on the periphery of the pyre or placement after much of the pyre has burned down (Wahl, 2015). These remains, therefore, may retain extractable collagen even when the human remains they accompany do not. In cases where cemeteries are not associated with related settlement sites these animal remains may be used to establish local, contemporary dietary data for both cremated and inhumed individuals. Furthermore, if collagen can be extracted there is potential for the identification of genus via zooarchaeology by mass spectrometry (ZooMS) (Collins et al., 2010; French, 2017; Brown et

al., 2021). The problem of identifying fragments of cremated animal bone to species or genus is a common one, with fragments often instead referred to by more general terms such as 'small ungulate sized animal' (Bond, 1994; McKinley et al., 1997; Bond and Worley, 2006; Squires, 2013). The problem is especially prevalent in larger species, such as cattle or horses, due to the more extensive fragmentation seen in these remains following cremation and collection for burial (Bond, 1996; Bond and Worley, 2006). As many of these remains are not fully identified, even when examined by a zooarchaeologist, the potential that identification of cremated animal bone fragments by ZooMS would alter current interpretations of funerary rites is significant (Bond and Worley, 2006; Squires, 2013; French, 2017). However, despite the conservation of collagen at temperatures as high as 400°C seen in this experiment, ZooMS requires the conservation of specific peptide markers isolated by trypsin digestion (Collins et al., 2010; Brown et al., 2021). The mass-to-charge ratio of these peptides must be conserved in order to determine species from the produced spectrum, by comparison against a library of identified spectra; if thermal exposures alter the presence of the peptide markers or their mass-to-charge ratios, ZooMS analysis will be ineffective (Collins et al., 2010; French, 2017).

Table 8.4: Showing relative frequency of animal remains recovered from cremation burials across various time periods, reproduced from McKinley, 2009.

Period	Frequency of animal remains	Quantities	Number of Species	Common Species
Neolithic	circa 4%	Few grams	single	Sheep or sheep size
Bronze Age	circa 16%	Few grams	single	Immature pig, sheep and bird
Iron Age	circa 22%	Few grams	1-2	Domestic fowl and pig
Romano-British	circa 10-50%	Few grams	1-2	Pig/sheep and bird
Anglo-Saxon	circa 23-44%	Often >100g	1-5	Horses, sheep, cattle, pig

8.5.4 Forensic Applications

Isotope analyses have become increasingly valuable to forensic science, used to analyse explosives, to evaluate trace evidence from crime scenes, to authenticate food and beverages, and to trace poached wildlife (Bartelink and Chesson, 2019). More recently

isotope analyses have been applied to the provenancing of unidentified human remains and to provide evidence in cases of abuse and neglect (Nardoto et al., 2006; Rauch et al., 2007; Valenzuela et al., 2012; Neuberger et al., 2013; Font et al., 2015; Lehn et al., 2015; Baković et al., 2017; Bartelink and Chesson, 2019).

Stable isotope analyses have been applied to help provenance human remains found in civic jurisdictions, past wars and conflicts, and mass graves from civil wars (Nardoto et al., 2006; Regan, 2006; Rauch et al., 2007; Valenzuela et al., 2012; Bartelink et al., 2014; Font et al., 2014; 2015; Lehn et al., 2015; Someda et al., 2016; Bartelink and Chesson, 2019). To help estimate the likely origins of unidentified human remains world-wide databases of isotope values derived from human tissue samples from different regions around the globe have been created (Lehn et al., 2015). Table 8.5 provides a list of the elements commonly employed in these investigations.

Table 8.5: Elements used in forensic isotope studies to provenance unidentified human remains.

Element	Ratio(s)	Present In	Varies With	Effective for Provenance
Hydrogen	δD	Keratin (hair, nails) Collagen (bone, dentine) Apatite (bone, enamel)	Diet Altitude Latitude Precipitation	Possible Significant overlap
Carbon	$\delta^{13}C$	Keratin (hair, nails) Collagen (bone, dentine) Apatite (bone, enamel)	Diet Latitude	Effective
Nitrogen	$\delta^{15}N$	Keratin (hair, nails) Collagen (bone, dentine)	Diet Stress	Unlikely Significant overlap
Oxygen	$\delta^{18}O$	Keratin (hair, nails) Collagen (bone, dentine) Apatite (bone, enamel)	Precipitation Altitude Latitude Proximity to the ocean	Effective in some cases
Sulphur	$\delta^{34}S$	Keratin (hair, nails) Collagen (bone, dentine)	Diet Geology Proximity to the ocean	Effective
Strontium	$^{87}Sr/^{86}Sr$	Keratin (hair, nails) Apatite (bone, enamel)	Geology Proximity to the ocean	Effective Fewer laboratories offer analysis
Lead	$^{208}Pb/^{204}Pb$ $^{207}Pb/^{204}Pb$ $^{206}Pb/^{204}Pb$ $^{206}Pb/^{207}Pb$ $^{208}Pb/^{207}Pb$ $^{208}Pb/^{206}Pb$	Apatite (bone, enamel)	Largely anthropogenic exposure Geology	Effective in some cases Fewer laboratories offer analysis

Reference data from known individuals have been used to create maps of expected ranges of isotope values expected in various regions, by using multiple isotopes predictive models can narrow down the most likely geographic origins of unknown individuals (Bartelink and Chesson, 2019). Continental scale distinctions can be effectively determined using $\delta^{13}C$ values and $\delta^{34}S$ values. North American, South American, and African $\delta^{13}C$ values tend to be significantly higher than $\delta^{13}C$ values from Europe, Asia, Australia, and New Zealand. In the Americas, corn is an important cultivar utilised directly as a vegetable or as flour, as a sweetener and as silage for domestic livestock (Regan, 2006; Lehn et al., 2015). Additionally, North and South America rely largely on sugarcane, a C_4 plant, for sugar production while sugar beets, C_3 plants, are more commonly exploited in Europe (Valenzuela et al., 2012). The highest $\delta^{34}S$ values are found in Australia and New Zealand, as settlements in these countries are largely focused along the coasts, the lowest $\delta^{34}S$ values found in North America, where marine proteins are rarely exploited. European, Asian, African, and South American $\delta^{34}S$ values are intermediate. Regional determinations within continents as based on similar principles, as shown in figure 8.10 (Lehn et al., 2015). Ratios of hydrogen, and nitrogen are less effective in the provenancing of unknown individuals due to significant overlap between continental and regional ranges (Regan, 2006; Valenzuela et al., 2012; Bartelink et al., 2014; Lehn et al., 2015).

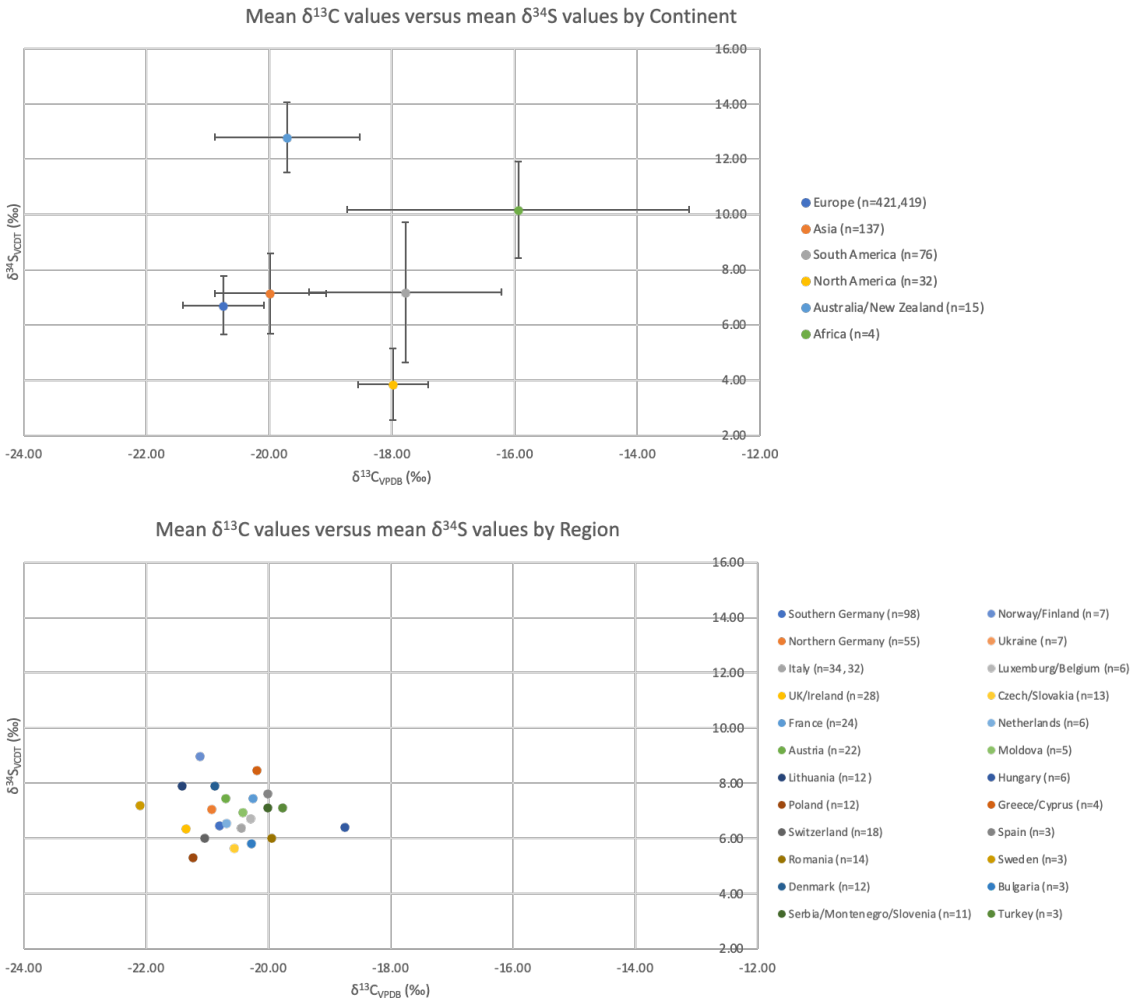


Figure 8.10: Graphs showing the separation of $\delta^{13}C$ values and $\delta^{34}S$ values expected at a continental level (above) and a regional level, within Europe (below). In both graphs data points represent the mean values found for these groups with the number of individuals (n) provided in the legend. In the graph showing continental means error bars represent one standard deviation; in the regional graph these data were omitted for clarity. Data reproduced from Lehn and colleagues (2015).

By using tissues with different formation times: hair, nails, bone, and teeth, reconstructions of life histories can be estimated. For example, a female newborn was found partially skeletonised in Western Germany. Samples taken from distal hair sections, formed six to twelve weeks before death indicated that the infant's mother lived in North America, but the cancellous bone sampled from the femur, mineralising into the last weeks of pregnancy indicated a European diet. This information allowed for the discovery of the infant's mother, an American woman who had recently arrived as a student in Germany (Lehn et al., 2015).

Thus far, investigations of unidentified war dead have focused on bioapatite using carbon, oxygen, strontium, and lead isotopes (Regan, 2006; Font et al., 2014; Someda et al.,

2016). Proposed methods to differentiate East Asian and American soldiers from conflicts in World War II, the Vietnam War, and the Korean War have been successful when applied to individuals of known provenance with $\delta^{13}C$ values again providing the greatest separation among these soldiers (Regan, 2006; Someda et al., 2016). In Europe, $\delta^{18}O$ and $^{87}Sr/^{86}Sr$ values from enamel have been used to determine the most likely origins of recently discovered remains of soldiers who died during World War II (Font et al., 2014). Similar success has been achieved using $\delta^{13}C$ values from bone collagen to differentiate American soldiers from East Asian soldiers and local civilians (Bartelink et al., 2014).

A recently proposed application of isotope anaylsis to forensic cases is to provide evidence in cases of neglect and abuse that lead to malnutrition (Neuberger et al., 2013; Baković et al., 2017). This type of abuse occurs most often among elderly or vulnerable individuals or among children; individuals who are dependent upon family or carers for their nutrition. The production of evidence for these cases is complicated. Medical records are not typically available and the defending caregiver often attempts to misconstrue the duration of the victim's malnutrition (Neuberger et al., 2013). As such, an unbiased reconstruction of the victim's nutritional history is necessary. Observations of patients being treated for severe morning sickness and anorexia nervosa have suggested that nutritional stress leads to an elevation in $\delta^{15}N$ values and a decrease in $\delta^{13}C$ values (Fuller et al., 2005; Mekota et al, 2006).

The increase in $\delta^{15}N$ values occurs via gluconeogenesis (Mekota et al., 2006). This involves the catabolism of proteins, beginning with skeletal muscle, to maintain the synthesis of glucose when the diet is insufficient in protein or energy (Mekota et al., 2006; King et al, 2017). Urea, depleted in ^{15}N, is expelled and the resultant amino acid pool becomes enriched in ^{15}N, essentially creating an internal trophic level enrichment (Neuberger et al., 2013; Baković et al., 2017; King et al., 2017). The decrease in $\delta^{13}C$ values is related to the catabolism of lipids from adipose tissue, ^{13}C depleted relative to other body tissues (Beaumont and Montgomery, 2016; King et al., 2017). In a study of hair samples from individuals known to have suffered from severe undernourishment at time of death showed that 15/16 individuals showed a diagnostic increase in $\delta^{15}N$ values prior to death, the majority also showed either low or decreasing $\delta^{13}C$ values; though there was

considerable inter-individual variability (Neuberger et al., 2013). In a similar case of known malnourishment prior to death, hair samples were taken from an elderly man from Germany. This case showed distinct decreases in $\delta^{13}C$ values in the period leading up to death, but also showed decreasing $\delta^{15}N$ values over this period. The authors suggest that either none of the hair samples reflected the individual's diet prior to malnutrition (all $\delta^{15}N$ values were higher than expected) or the decreasing $\delta^{15}N$ values reflected the impaired function of the liver (the organ was significantly under-weight at time of death) (Baković et al., 2017).

In relation to the current project, these two forensic applications of isotope analysis, both provenancing unidentified individuals and providing evidence in cases of neglect may be applied to burned human remains. Attempts to conceal human remains through burning are rarely successful as human remains do not readily burn (DeHaan, 2015; Symes et al., 2015). Provided the recovered remains include samples of teeth or bone that have not been exposed to temperatures higher than 200°C, $\delta^{13}C$ and $\delta^{15}N$ analyses from dentine or bone collagen should be unaffected. While these tissues will not provide a recent dietary record for geriatric patients, in pediatric cases they can provide these data (Lehn et al., 2015).

8.5.5 Dearth of Archaeological Research on Cremated Remains

Despite the large repository of skeletal remains represented by archaeologically cremated remains, these remains continue to be under-represented in the literature; see table 8.6 (McKinley, 1994a; b; 1997; 2009; Thompson et al., 2009; Squires et al., 2011; Squires, 2013; Thompson, 2015; Thompson et al., 2016; Carroll and Squires, 2020b). This paucity of research continues despite guidelines and recommendations being published in multiple countries for both forensic and archaeological evaluations of cremated bone (Goméz Bellard, 1996; Duday et al., 2000; McKinley 2004; Ubelaker, 2009; Arora et al., 2010; Ellingham et al., 2015; Kurila, 2015; Schmidt and Symes, 2015). However, in the last few decades there has been an increase in the study of cremated remains, with a significant focus on the development of analytical methods (Kujit et al., 2014; Schmidt and Symes, 2015; Thompson, 2015). Methods are being developed to investigate burning intensities

(Piga et al., 2008; Goncalves et al., 2011; Castillo et al., 2013; Thompson et al., 2013; Ellingham et al., 2015; Walker et al., 2015; Carroll and Squires, 2020a;b); radiocarbon dating (Lanting, 2000; Zazzo et al., 2009; 2012; Harbeck et al., 2011; Fredericks et al., 2012); strontium analysis (Sneock et al., 2015; 2016; 2018; de Groot et al., 2021); and carbon and nitrogen analyses (DeNiro et al., 1985; Schurr and Hayes, 2008; Schurr et al., 2008; Harbeck et al., 2011). There has also been a recent focus on the behaviour of dental tissues during burning events (Beach et al., 2015; Mahoney and Miszkiewicz, 2015; Schmidt, 2015; Piga et al., 2016). Yet, despite these myriad advances, the belief among archaeologists that cremated skeletal remains lack research potential persists (Carroll and Squires, 2020b).

Table 8.6: Relative proportion of articles focused on any skeletal remains versus those focused on cremated skeletal remains over the period from 2015 through 2021. This data is the result of a quick search of the two phrases 'cremated skeletal remains' versus 'skeletal remains' from the listed journals; to confirm these results a more nuanced bibliometric study would be required.

Publication	'Cremated skeletal remains'	'Skeletal remains'	Proportion
Journal of Archaeological Science	20	246	8%
American Journal of Physical Anthropology	30	715	4%
International Journal of Osteoarchaeology	30	450	7%
Journal of Forensic Sciences	16	377	4%

One stumbling block for osteologists may be the number of individuals from cremation cemeteries for whom basic demographic data cannot be determined through metric or morphological assessments; McKinley suggests that approximately 39-51% of the population can be assigned a sex estimate with varying degrees of confidence and broad age estimates should be possible for most cremated remains (McKinley, 2004; 2013). It may be possible to bolster these numbers through the use of histological aging methods, applicable in bone fragments heated up to 600°C, although microstructures may be obscured by char in samples heated between 250°C and 400°C (Squires et al., 2011; Absolanová et al., 2012; Carroll and Squires, 2020a). A relatively new method of estimating sex from enamel may allow for sex estimation in previously unsexed cremated individuals;

the method involves minimally destructive acid etches that are obtained from teeth and analysed by mass spectrometry to determine the presence of dimorphic amelogenin peptides, referred to as AMELX and AMELY (Stewart et al., 2017; Gowland et al., 2020). This method allows for the sex estimation of individuals regardless of age and does not share the issue of contamination that plagues ancient DNA analysis as amelogenin peptides are only present in enamel and not other tissues (Stewart et al., 2017; Gowland et al., 2020). However, the method is therefore dependent on the survival of enamel in excavated cremation burials. While the myth of teeth exploding, like 'popcorn', has not been observed in recent burning experiments, enamel does fracture due to dehydration splitting along the cemento-enamel junction and the grooves between cusps (Schmidt, 2015). In remains burned while fleshed the posterior teeth tend to experience less intense burning due to the protection of the overlying flesh, while in defleshed remains the anterior teeth often fall away early in the cremation process experiencing lower burning intensities (Schmidt, 2015). Furthermore, unerupted teeth may be largely protected from heat-induced changes (Schmidt, 2015). However, care must be taken to ensure the recovery of these small, potentially fragile tissues during excavation, including sieving of the surrounding burial medium (Schmidt, 2015). Additionally, there can be no guarantee of recovery as few cremations even approach quantities of bone that represent the entire cremated skeleton (McKinley, 1993; 1994c; 2009).

8.6: Summary

The controlled heating experiment conducted in this research suggests that some extractable collagen remains in bone heated to 400°C. The $\delta^{13}C$ values analysed from these collagen extracts are relatively unaffected by temperatures up to 400°C, while $\delta^{15}N$ values are conserved up to a threshold of approximately 250°C. The atomic ratio of C:N was insufficient to separate thermally-altered samples of collagen when examined alone, as %C and %N were lost in a linear pattern; however, when all three indicators are considered against published standards the thermally-altered samples can be identified and removed from analysis (DeNiro and Hastorf, 1985; van Klinken, 1999). Colour change and FTIR spectra were well-correlated with temperature exposures. Temperature models utilising FTIR peak ratios were especially effective at separating those samples heated to 300°C or

higher from those exposed to lower temperatures. These data suggest that stable isotope analysis of archaeological cremated remains may be possible, given temperature exposures of approximately 250°C or less. However, archaeological samples selected by gross observation to fit this profile did not successfully produce unmodified collagen extracts. FTIR analysis of these samples suggest that organic material was largely absent from these samples indicating either higher temperature exposures, in the region of 500°C or higher, or dissolution of the organic components of bone due to an acidic burial environment. In either case, further attempts at stable isotope analysis from archaeologically cremated remains is encouraged, with adaptations to the sample selection criteria as discussed in section 8.4. In Britain cremation was a dominant funerary rite in the Bronze Age, late Iron Age, early Romano-British period, and early Anglo-Saxon period, resulting in a large and varied population of archaeologically cremated remains with great potential for analysis. In particular, practises of burning remains *in situ* during the Neolithic, the large cremation weights observed in some Bronze Age cremation burials, and the incorporation of pyre debris in the grave fill during the early Romano-British period may allow for greater survival of collagen among thermally-altered bone samples than has been observed among Anglo-Saxon cremated remains. Furthermore, the common practise of cremation throughout time and around the world necessitates greater attention from the bioarchaeological community. Developments in analytical techniques now allow a wealth of information to be determined from these often-ignored remains. Future research should attempt to address the reticence among archaeologists to study burned skeletal remains and to encourage future research.

Chapter 9: Conclusion

9.1 Introduction

The aim underlying this research project was to determine whether isotope analyses of carbon, nitrogen, and sulphur could be applied to archaeologically cremated remains for use in dietary reconstruction. First, the preservation of collagen and biogenic isotope ratios in bone samples heated experimentally were observed, to establish temperature exposures likely to retain viable collagen. Alongside these observations, methods of temperature estimation were evaluated to determine their correspondence with the changing condition of collagen within the thermally-altered bone matrix. These methods were used to select bone samples from individuals cremated during the early Anglo-Saxon period, with the intent of selecting samples exposed to low burning intensities. For comparison, samples were also taken from inhumed individuals buried at the same two early Anglo-Saxon cemeteries, Elsham and Cleatham. These samples were selected with the intent of comparing isotope data from cremated and inhumed individuals interred at mixed rite cemeteries. Isotope ratios of carbon, nitrogen, and sulphur were analysed to determine whether diet was reflected in the choice of funerary ritual, to investigate whether those who cremated their dead ate different foods than those who inhumed their dead. The results of the controlled heating experiment support the potential for isotope analysis from cremated remains: samples heated to 400°C produced extractable collagen, $\delta^{13}C$ values were largely unaffected up to 400°C, $\delta^{15}N$ values were relatively stable up to 250°C, and $\delta^{34}S$ values were relatively stanble up to 200°C. However, the samples selected from individuals cremated during the early Anglo-Saxon period produced minimal collagen (<4 wt.%) with atomic C:N ratios outside of the acceptable range for biogenic human bone collagen. Despite gross observation indicating temperature exposures between 200°C and 500°C more detailed temperature modelling using FTIR data suggested temperature exposures in excess of 500°C for all samples or taphonomic alterations of bone composition. These samples failing to produce unmodified collagen for analysis is, therefore, not unexpected. Further sampling from cremated individuals interred at Elsham and Cleatham, or from other cremation burials recovered from archaeological sites may produce viable collagen for these analyses; pre-screening these samples via FTIR analysis to estimate burning conditions is

recommended. Analyses of carbon, nitrogen, and sulphur isotope ratios were possible for the samples taken from inhumed individuals from the early Anglo-Saxon period and these data fell within expected ranges, based on previously published data from contemporary inhumation burials. The research questions, as set in section 1.5, will be explored individually to address the key conclusions of this project.

9.2 Research Questions

8) Does collagen survive in experimentally heated bone, and if so, to what range of temperatures and exposure times?

In experimental conditions some collagen survived in bone samples heated to 400°C for two hours. However, these samples were heated in controlled conditions – within a preheated muffle furnace, cooled at room temperature, without any interactions with overlying soft tissue, fuel sources, or the outside environment. From the data collected here collagen was minimally affected up to 150°C, then experienced a sharp drop in collagen yields at 200°C, followed by a gradual decrease in yields that still produced an average of 2.4 wt. % at 400°C. Exposure times were also a factor affecting collagen yields with a significant difference found between those samples heated for half an hour and those heated for either one or two hours. However, no significant difference was found between the samples heated for one hour and those heated for two hours. This experiment used small sections of bone; the effect of exposure time on collagen conservation is expected to be more significant in whole bone samples or fully fleshed bodies.

9) Does the collagen from experimentally heated bone retain biogenic values of $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$? To what range of temperatures and exposure times?

During exposures to temperatures ranging from 100°C to 400°C and exposure times of up to two hours, the $\delta^{13}C$ values of the bone samples varied by only 1.9‰. Values of $\delta^{15}N$ were stable in samples heated up to 200°C; however, above this threshold samples became increasingly enriched in ^{15}N. On average the samples heated to 250°C were elevated only 1.4‰ above the average $\delta^{15}N$ value of the unheated control samples. Exposures of 300°C

or higher produce larger effects, sufficient to bias dietary inferences from these samples. When used together collagen quality indicators of %C, %N, and C:N ratio were sufficient to identify thermally-altered collagen, which would allow for these samples to be identified and excluded from a data set derived from samples heated to unknown temperatures. When exposed to temperatures of 200°C or less $\delta^{34}S$ values were stable, reflecting *in vivo* values. Higher temperature exposures initially resulted in elevated $\delta^{34}S$ values at 250°C; however, further increases in temperature exposure resulted in lower $\delta^{34}S$ values.

10) Does colour accurately reflect the chemical changes occurring in bone when heated?

Color changes in the experimentally heated bone followed expected patterns: cream-ivory coloured up to 200°C, yellow to 250°C, brown to 300°C, black through most exposures at 350°C and 400°C. Only those samples heated to 400°C for two hours began to lose the black charred colour for a grey-brown or taupe appearance. While this pattern is well established in research into burned bone from experimental, forensic, and archaeological investigations, what was unknown was whether this pattern would correlate with changes in collagen yields and collagen quality. The initial drop in collagen yields occurred at the same temperature ranges that developed yellow colouration; the shift to a black, charred appearance occurred at the same temperature ranges as the first large increases seen in $\delta^{15}N$ values and the low %C and %N contents that indicate altered collagen. Therefore, the colour changes did reflect the chemical changes affecting bone collagen under the observed conditions. However, the distinction between the yellow-brown appearance seen from 200°C to 250°C and the grey-brown appearance seen at 400°C or higher may be obscured in bone that is also exposed to soil staining in the burial environment. There are soils (for example those with concentrations of organic material or manganese) that can produce black stains in exposed bone (Dupras and Schultz, 2013). Therefore, colour data must be interpreted with caution and cannot be used as sole evidence of burning, or levels of burning intensity.

11) Does FTIR analysis allow for the modelling of temperature exposures in the range of 100°C to 400°C?

FTIR analysis requires only small samples of ground bone and samples are not consumed during testing. The analysis can be done quickly and with minimal preparation, allowing many samples to be tested. Most research has focused on high temperature ranges and the effects experienced by bone mineral, rather than the organic portion of bone. However, the three amide bands at 1660 cm^{-1}, 1550 cm^{-1}, and 1250 cm^{-1}, as well as two absorption bands at 1415 cm^{-1} and 1450 cm^{-1}, related to carbonate mineral (CO_3) and methylene (CH_2), have shown low temperature changes reflecting the loss of organic material from bone samples exposed to temperatures between 300°C and 800°C (Thompson, 2005; Figueredo et al., 2012; Thompson et al., 2013; Ellingham et al., 2015b). Thermal exposure models can be created by comparing ratios between these and other peaks to provide estimates of burning intensities experienced by bone burned in unknown conditions (Thompson et al., 2016). However, whether these models are able to distinguish between bone samples with 'good' collagen remaining and samples with only thermally altered collagen remaining was not known. 'Good' collagen refers to collagen that passes quality indicators such as %C, %N, and C:N ratio and also produces isotope ratios similar to *in vivo* ratios. FTIR modelling from the controlled heating experiment produced clear separation among the samples heated to 300°C, allowing for distinction between those samples heated to 300°C or less and those heated to higher temperatures. These models would potentially include the selection of some samples with thermally-altered collagen, but these samples could be removed from further analysis by examining their collagen quality indicators.

12) Can colour and FTIR analysis be used to select samples of bone from archaeological cremations that have been exposed to low temperatures?

Colour proved an inexact sampling criterion. Separation of low temperature yellow-brown colouration from higher temperature grey-brown, grey, or white colouration was difficult for archaeological samples stained various shades of brown from the burial environment. Several charred samples were selected, which were expected to have been exposed to temperatures of 300°C to 400°C. However, FTIR modelling suggests that all selected samples were exposed to temperatures of 500°C or higher, indicated by changes to the mineral phase of these bone samples. The burial environment in this instance was likely to have been a complicating factor. The samples analysed showed FTIR spectra changes

reflecting a loss of organic material and alterations to the bone mineral; these changes occur as bone is heated but also occur in burial environments, particularly wet or acid environments that are hostile to collagen preservation. Whether these bone samples were altered through heat exposure or through burial conditions, they did not produce unmodified collagen for isotope analysis. Using colour as a broad indicator of chemical change, while problematic, is an effective means by which to screen large quantities of bone without more expensive analysis. This type of screening could be bolstered by a full examination of all cremated remains from the site, where possible, allowing for a site-specific understanding of the colour variation to be expected. FTIR analysis is considered an effective selection method for samples of archaeologically cremated bone; whether collagen is lost to the pyre or to the grave, FTIR analysis provides an indication of the presence or absence of organic material in the bone analysed.

13) Can collagen be extracted from bone samples taken from archaeological cremations, specifically from cremated individuals buried at Elsham and Cleatham cemeteries?

Some organic material was extracted from the samples selected from cremated individuals interred at Elsham and Cleatham cemeteries, though yields were less than 4 wt. %. Further, the collagen quality indicators indicate poor quality collagen: %C were below 5.5, %N were below 0.9, and C:N ratios were between 7.3 and 11.9. These quality indicators suggest that the samples did not consist of unmodified human bone collagen. However, further examinations of bone samples from cremated individuals at other sites may still yield viable results. As suggested in section 8.5.2, preferably further applications of this method should consider sites not located on acidic soils.

14) Are the diets of cremated individuals different than inhumed individuals buried at the same cemetery, when inferred by analyses of $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$?

Unfortunately, this comparison cannot be made at this time due to the lack of biogenic collagen obtained from the samples selected from cremated individuals interred at Elsham and Cleatham. However, $\delta^{13}C$, $\delta^{15}N$ and $\delta^{34}S$ values were obtained and analysed from the samples taken from individuals inhumed at these sites. These data follow previously

published dietary analyses of individuals inhumed during the Anglo-Saxon period. Diets were based on C_3 plants and protein was largely derived from terrestrial animals. The $\delta^{34}S$ data may suggest the consumption of freshwater resources but further contextual information would be needed to determine this.

9.3 Limitations and Points for Consideration

Any study has limitations: some are inherent to the analyses used and cannot be corrected, though they can be mitigated; some arise from constraints in time or funding or from the COVID-19 pandemic and provide direction for further research. All must be acknowledged to allow a nuanced understanding of the data and interpretations provided by the research conducted. This project involved several stages of analysis and, as such, was subject to multiple limitations.

9.3.1 Controlled Heating Experiment Design

The controlled heating experiment was designed to provide evidence of the heat-induced chemical changes experienced by bone collagen at a range of temperatures. In order to produce a direct correlation between the experimental temperature and the chemical changes observed, the experiment design was heavily controlled. Bone sections with the overlying flesh removed were introduced to a pre-heated muffle furnace for a prescribed period of time and then removed to cool at room temperature. There was very little temperature fluctuation within the furnace; see section 6.2. There was no interaction with soft tissues, fuel, or the outside environment. Thus, while the experiment was successful in providing evidence of heat-induced changes in bone collagen, the conditions are far removed from a pyre cremation of a fleshed corpse; this limits the application of these data to archaeological applications. Furthermore, the influence of the burial environment on these samples is unknown. However, these data could be expanded by further testing to determine which additional variables contribute to the alteration of collagen in cremated bone.

9.3.2 Colour Analysis by Spectrophotometer

In a related desire for precision, a spectrophotometer was used to record colour data in the CIEL*a*b* colour space. While the data produced were objective and precise, they are less readily understood. The CIEL*a*b* statistics L* = 77.64, a* = 1.96 and b* = 11.83

provide the same data as the Munsell designation 0.4Y 8/2, that is the colour of fresh bone (as observed on control sample 2c in this experiment). As the Munsell designations refer to named hues (yellow, red, et cetera) they are more readily understood by readers than CIEL*a*b* colours that provide designations as coordinates along three axes. However, this is partially a question of familiarity. Should CIEL*a*b* become a more common colour space utilised in archaeology these coordinates will become more familiar and understandable. As researchers familiar with dietary isotopes recognise a $\delta^{13}C$ value of -23‰ as indicative of C_3-based terrestrial diets, researchers may come to associate an L* value of 77 as towards the white end of the lightness spectrum.

Another issue with the use of the spectrophotometer to record colour data from bone samples was that of precision. As the data produced by the spectrophotometer was highly precise and the colour of the bone samples was variable, twenty measurements were taken to produce a reliable range and average colour for each sample. Section 5.3.3 outlines the determination of the required number of analyses to characterise the colour of a bone sample. This was time-consuming, requiring approximately fifteen minutes per sample. Thus, the method used here would not necessarily be applicable to wide-scale analyses or commercial work. However, by rounding values to a single decimal place, or to an integer, precision would be lost but fewer measurements would be required to establish the colour of a bone sample.

9.3.3 Estimating Burning Conditions via FTIR Analysis

FTIR analyses were used to create models of burning intensity from experimental data in order to estimate the burning conditions experienced by bone samples taken from individuals cremated archaeologically (Thompson, 2005; Munro et al., 2007; Thompson et al., 2009; Squires et al., 2011; Thompson et al., 2011; 2013; Ellingham et al., 2015a; b; Thompson, 2015c; Thompson et al., 2016). This method has proven effective in past research and was useful in this project. However, the method is 'messy'; that is, the data produced are compromised by a significant amount of noise in the spectra produced by FTIR analysis. Corrections such as normalising the data to a known and relatively stable absorption peak help to reduce this noise. Also, ratios between absorption peaks are used to develop the burning intensity models used here and in other research; this removes the noise from the data set used in modeling burning conditions (Thompson et al., 2013;

Ellingham et al., 2015b; Thompson et al., 2016). However, there is potential for the influence of the noise in the data to overwhelm the observations made, particularly when viewed by researchers not familiar with these specific types of analysis. Ambient humidity, differences in instruments, the temperature of the laboratory can all affect the readings produced by FTIR analysis; there are internal calibrations to reduce the influence of these factors, but they may remain evident in the data set. Another factor, introduced in section 5.3.4, is the effect of particle size on FTIR analysis. Bone samples were ground with a mortar and pestle prior to analysis; however, these ground samples were not sieved to ensure an even distribution of particle sizes among the samples. Research suggests that the most reliable FTIR results are obtained on ground bone that consists of particles between circa 20 μm and circa 50-60 μm, isolated by sieving the ground bone (Kontopoulos et al., 2018). When testing organic materials that are inherently variable, the complication of noisy data is problematic. To a certain extent, this limitation has already been addressed in the literature. Early archaeological applications of FTIR use only one ratio, the Crystallinity Index (CI) defined in section 3.5.5.a, for inferences of burning intensity or diagenetic effects (Surovell and Stiner, 2001; Koon et al., 2003; Thompson, 2005). However, more recent research has identified a suite of ratios that have proven useful in modelling burning intensity experienced by bone samples (Thompson et al., 2013; Ellingham et al., 2015b). By using multiple ratios for analysis there is less chance that the noise in the data will significantly impact the results of FTIR analysis. This method provides a quick, quantitative method for analysing samples of burned bone that require only small samples not consumed during testing (Thompson, 2015c).

9.3.4 Method of Collagen Extraction

The collagen extraction method used for this research involved the demineralisation of bone chunks in cold (4°C) hydrochloric acid, followed by denaturing at 70°C in a pH 3 solution, a method adapted from that proposed by Longin in 1971. This method is relatively delicate and produced high yields from both the unheated control samples in the controlled heating experiment and the samples taken from inhumed individuals buried at Elsham and Cleatham cemeteries. However, all collagen extraction procedures are a balance between extracting collagen from bone and dissolving collagen during demineralisation. Thus, while only minimal collagen was recovered from the samples selected from cremated individuals

interred at Elsham and Cleatham cemeteries, there may have been collagen present in these samples that was not recovered during extraction. Similarly, the drop in collagen yields seen in samples heated to 200°C or above may not reflect the actual content of collagen in these bone samples. Partially degraded collagen may be more susceptible to loss during the extraction procedure (Tuross, 2012). Other extraction methods, such as those demineralising bone samples in ethylenediaminetetraacetic acid (EDTA), may have produced better collagen yields (Tuross et al., 1988; Tuross, 2012). Unfortunately, due to time constraints, a comparative analysis of collagen yields from burned bone extracted by various methods could not be conducted during the course of this project.

9.3.5 Selection of Samples from Cremated Individuals

A major limitation to this project was the selection of bone samples from cremated individuals. The methodology involved several filtering steps based on assumptions to reduce the population of cremation burials for analysis from 1548 individuals to a more manageable sub-set that could be evaluated in the time available; this is discussed in section 8.4. Ideally, the selection process would involve the examination of all the cremation burials from the site or sites under investigation. However, this would involve a significant time investment that may not be possible in all instances. Once a sub-set of cremation burials was selected for examination, colour was the main criterion used to select bone samples for further analysis. This proved imprecise. Soil staining obscured the variation between unheated bone, observed among the inhumed individuals, and bone heated beyond the charring stage. During sample preparation for FTIR analysis and collagen extraction the bone samples were cut, exposing surfaces of bone that were not stained by soil. In some cases, this clearly demonstrated that these bone fragments had been exposed to higher temperatures; in others, where soil was embedded within the trabeculae, this was less clear. However, this may represent a simple, if destructive, method to better observe colouration caused by heat exposure; that is, cutting or scratching the bone to observe the unstained surface. If this method is employed, the changes made to the bone must be recorded and photographs of the unstained portion with a colour scale should be retained with the curated remains such that the testing need not be repeated. Surface cleaning may be able to provide similar information, but with friable cremated bone fragments cleaning is likely to lead to substantial fragmentation. Alternatively, by examining the full collection of cremated individuals the

researcher may gain site-specific understanding of the colour variation present among the population; this experience may allow better temperature estimates from gross observation. However, even without the complication of soil, temperature estimates from bone colour are approximate, generally accurate to ±50°C for bone heated to temperatures of 650°C or less (Taylor et al., 1995).

9.3.6 Small Sample Sizes

This project involved only small numbers of samples, a common limitation in archaeological research. Only twenty individuals inhumed during the Anglo-Saxon period were sampled. At Elsham, the four individuals sampled represent 80% of the adult inhumed population; one further individual, not sampled, was represented by only a single parietal fragment. At Cleatham the sixteen individuals sampled constitute only 41% of the adult inhumed population at the site. The cremated populations at each site exceed 500 individuals; the ten individuals sampled at each site represent less than 2% of the population. Thus, for this project the limitation in sample size is not due to the size of the burial populations under study. Instead, the small sample sizes are due largely to time constraints. This project involved two stages of analysis: a controlled heating experiment and an archaeological application. As a result, only half the time could be allocated to archaeological sampling and analysis. Furthermore, the methodology developed involved several stages of analysis and three samples from each cremated individual were analysed; as such, only a small number of individuals could be processed. Initially, the methodology designed for this experiment would have involved FTIR analysis of bone samples to determine whether collagen preservation was likely, followed by selection of new samples to replace those that were deemed unlikely to contain collagen. Unfortunately, due to the COVID-19 pandemic and measures implemented to limit the spread of the SARS-CoV-2 virus the author was unable to return to the Lincolnshire Museum for additional samples from cremated individuals. Further testing to better represent the populations buried at Elsham and Cleatham is warranted. However, for the data set available from this project, small sample sizes impact the interpretations that can be drawn from the data. Particularly, among the inhumed individuals sampled for this project 55% were estimated to be between nineteen and twenty-five years of age and a further 25% could only be defined as 'adult', with more specific age estimation not possible. Thus, any

dietary patterns related to age are not visible in this data set; further testing may allow for this type of comparison.

9.3.7 Methodology Involves Destructive Testing

While further testing could produce valuable data, the methods used in these analyses are destructive. FTIR analysis requires ground samples of bone, although the sample is not consumed during testing and can be used subsequently for other tests. Isotope analyses of carbon, nitrogen, and sulphur from bone collagen first require the isolation of collagen from a bone sample, after which the extracted collagen is combusted during analysis. The destruction of bone for analysis should not be encouraged without a clear research objective that has a reasonable chance of producing quality data (Mays, 2013). At this time, the viability of isotope analyses of carbon, nitrogen, and sulphur from collagen extracted from archaeologically cremated individuals has not been proven, although the experimental data suggests that these analyses should theoretically be possible. Further testing of archaeological bone samples from cremated individuals may prove successful; however, this testing should not be conducted without due consideration. There are further heating experiments that may elucidate the interplay between burned bone and thermal exposures or fluctuations, interactions with fuel sources, interactions with the pyre environment, and interactions with the burial environment. These experiments may be conducted with animal bone proxies or cadaver bone tissues allocated to scientific research rather than archaeological human remains. Once these experiments have been conducted, samples from archaeologically cremated individuals can be selected for isotope analysis with a better understanding of the conditions that allow for preservation of collagen. This will prevent mass destructive testing of human remains that are unlikely to produce viable results; however, ultimately determining whether isotope analyses from bone collagen are possible from archaeologically cremated remains will require further destructive testing. Whether permissions are granted for this type of destructive testing is the purview of those curating collections of cremated individuals.

9.3.8 Interpretation of Isotope Results

Finally, there are limitations in the use of isotope analyses to infer diet. Carbon isotope ratios provide information regarding staple crops, whether diets are based on C_3

plants such as wheat, barley, rice, beans or potatoes or on C_4 plants such as maize, amaranth, sorghum or millet (Pate, 1994). Carbon isotope ratios may also indicate whether marine food sources are being exploited by a population or individual; however, due to overlapping values, distinguishing marine contributions to the diet via $\delta^{13}C$ values is more secure when C_4 plants are not exploited either as a food source or as animal feed (Lee-Thorp, 2008). Nitrogen isotope ratios reflect the trophic level of foods consumed; with consumers showing $\delta^{15}N$ values 2‰ to 4‰ higher than their diets (DeNiro, 1987). A related trophic level effect is seen among infants, those being breastfed will show $\delta^{15}N$ values higher than their mothers (Fuller et al., 2006a). However, $\delta^{15}N$ values may also be influenced by drought stress, nutritional stress or disease; in most cases these acute conditions will not influence $\delta^{15}N$ values obtained from bone collagen due to slow turnover rates but may be a complicating factor in values obtained from dentine (Richards and Montgomery, 2012; Reitsema, 2013; Beaumont et al., 2015). Sulphur isotope ratios reflect the environment from which foodstuffs are obtained; marine $\delta^{34}S$ values are stable at 20.3‰, terrestrial $\delta^{34}S$ values reflect the underlying bedrock and groundwater, coastal $\delta^{34}S$ values will reflect the terrestrial values as influenced by sea spray effects, and freshwater $\delta^{34}S$ values can vary widely (Nehlich, 2015). Sulphur isotope ratios from bone collagen may be able to differentiate the utilisation of terrestrial, marine, and freshwater sources of protein. However, this differentiation is only possible where the underlying geology allows; distinction between freshwater $\delta^{34}S$ signatures and terrestrial $\delta^{34}S$ signatures will be more successful in areas of uniform geology (Privat et al., 2007). Each of these isotopes, when analysed alone, provide only limited, potentially ambiguous information regarding diet; this can be improved by using isotope analyses in concert to provide multiple axes of comparison. Furthermore, dietary inferences based on these analyses are only as accurate as the contextual data on which they are based. There is considerable contextual data available for carbon and nitrogen isotope analysis from the Anglo-Saxon period (Privat et al., 2002; Fuller et al., 2006b; Lucy et al., 2009; Mays and Beavan, 2012; Hannah et al., 2018). However, there is little Anglo-Saxon contextual data available for sulphur isotope analysis; therefore, inferences drawn from these data are more general and less robust. These inferences may be improved when further contextual data becomes available. Still, there are dietary differences that cannot be inferred from isotope analysis, such as the variable exploitation of cattle for meat or dairy products (Hedges and Reynard, 2007).

9.4 Future Research

There are two issues that prevent much of the experimental and forensic research into burned bone from being applied to archaeological cremation burials. The first is the inconsistent protocols used in controlled heating or burning experiments. The other is the difference between controlled burning conditions and the conditions experienced by the bone fragments recovered from archaeological cremation burials. The resolution of these two issues will be an inter-related process. Conducting a series of controlled heating experiments that introduce variables in a step-wise fashion, as discussed in section 8.2.6, will allow researchers to determine which experimental protocols are affecting their results, but will also progressively approach the conditions of an open-air pyre cremation. Once variables such as temperature fluctuation, cooling protocols, influence of overlying flesh, influence of the fuel source, and influence of the open-air environment are explored, the next stage will be to determine the effects of various burial environments on samples of burned bone. The processes by which bone deteriorates in the burial environment are broadly known: hydrolysis of the organic components in bone, dissolution of the mineral components in bone, and microbial actions affecting both organic and mineral components (Collins et al., 2002; Kontopoulos et al., 2016). However, the speed at which these processes occur is influenced by a multitude of inter-related factors including: time, temperature, pH, hydrology, and presence of microbes (Child, 1995; Nicholson, 1996; Collins et al., 2002; Lee-Thorp, 2008). In order to investigate the added influence of heat-induced changes to bone before burial, taphonomic experiments must be conducted. Ideally, these experiments would involve experimentally burned bone subjected to a range of burning conditions, exposed to a range of soil types and drainage conditions both as urned and unurned deposits. The inclusion of pyre or grave goods may also be a factor as copper-alloy goods are a common finding and copper is a known anti-microbial agent (Lucy, 2000; Squires, 2011; Salah et al., 2021). If these experiments are conducted, attempts should be made to examine the bone specimens via multiple techniques to provide data with multiple applications.

For this research, bone samples from archaeological cremation burials were selected with the aim of stable isotope analyses of carbon, nitrogen, and sulphur; these analyses are

reliant on the presence of collagen in the bone samples used. The methodology used to infer collagen survival was two-fold and intended to estimate the burning intensities experienced by the bone samples selected. First, gross observation of bone colour was used as a broad indicator of burning intensity, with the intention of selecting samples that had become yellow, brown, or black as a result of heat-induced changes. However, as discussed in section 9.3.5, this selection criterion was complicated as colour change from soil staining was difficult to separate from colour change due to heat exposure. This challenge can be overcome through greater experience with the site-specific range of colouration expected within a collection. Additionally, cleaning or scoring of the bone samples will allow researchers to determine whether the observed colouration is the result of a superficial staining process or the more pervasive colour changes expected from thermal alterations. The second method used to infer burning intensity from the bone samples selected from archaeological cremation burials was FTIR analysis. More specifically, burning intensity models were created using ratios between absorption peaks related to both organic and mineral compounds from the bone matrix. These models allow for a separation of low, medium, and high intensity burning conditions. As seen in section 7.2.2, the samples selected for this project from archaeological cremation burials showed medium level burning intensities, equivalent to experimental temperature exposures of 400°C to 700°C. Changes to absorption peaks associated with compounds found in bone mineral suggest temperatures in excess of 500°C. The low collagen yields and poor quality collagen indicated by isotope analysis support the inference of temperature exposures in this higher range. FTIR analyses successfully identified the compromised state of the organic content in the bone samples analysed. Ideally, these samples would then have been rejected for further analysis and further bone samples would have been obtained from the archaeological cremation burials at Cleatham and Elsham cemeteries. Unfortunately, due to restricted laboratory access due to the COVID-19 pandemic these tests were run concurrently and access to further bone samples was not possible. However, the method of selecting potential samples through gross observation, then confirmation of burning intensity via FTIR analysis appears to be effective, though the complication of disentangling the effects of heating events from diagenetic changes remains. Future research would involve applying these selection criteria to further cremated remains, whether these remains are obtained from Cleatham and Elsham cemeteries or from other archaeological

contexts. Additional measures, such as sieving the samples of ground bone prior to analysis, designed to increase the reliability of FTIR analysis should also be explored (Kontopoulos et al., 2018). Cremation has been an important mortuary rite in Britain and around the world, practised from the Upper Paleolithic through to modern times providing a wealth of material for analyses of this type (Bowler et al., 2003; Davies, 2005).

Cremation as a funerary tradition dominates the archaeological record; however, archaeological analyses of cremated human remains continues to lag behind analyses of inhumed human remains (McKinley, 1994a; 1994b; 1997; 2009; Thompson et al., 2009; Squires et al., 2011; Squires, 2013; Thompson, 2015a; Thompson et al., 2016; Carroll and Squires, 2020a). There has been an expansion in our understanding of cremated remains from the early 20th century assumption that cremated remains could not be analysed and could, therefore, be safely discarded (McKinley, 2015). From the early pioneering work of Wells (1960), Spence (1968), and Gejvall (1969) the study of cremated remains has grown significantly in recent years. Much of the recent research has been experimental or forensic in nature, investigating the changes that bodies and bones undergo when exposed to heat and what evidence can be recovered from burned human remains (Mayne Correia, 1997; Schmidt and Symes, 2015; Ellingham et al., 2015a; Thompson et al., 2016). However, increasingly this research is being applied to archaeological cremations (McKinley, 1994a; Squires, 2011; McKinley, 2013; Kujit et al., 2014; Wahl, 2015; Thompson, 2015b; Thompson et al., 2016). Techniques have been developed to estimate the pre-burning conditions of human remains (Mayne Correia, 1997; Symes et al., 2015; Ubelaker, 2015), to estimate the burning intensities experienced by human bone (Shipman et al., 1984; Thompson et al., 2013; Ellingham et al., 2015a), to quantify the fragmentation experienced by burned human bone (McKinley, 1994c; Squires, 2011; Gonçalves and Pires, 2016). Isotope analyses have been proposed for the study of archaeologically cremated bone and in the case of strontium analysis have proven successful (Schurr and Hayes, 2008; Harbeck et al., 2011; Sneock et al., 2015; 2016; 2018; de Groot et al., 2021). Osteobiographical information can be determined from burned bone via the same techniques that are applied to unaltered bone (McKinley, 1994a; Mayne Correia, 1997; Squires, 2011). However, in any assemblage of cremated remains there are a substantial proportion for whom age-at-death and/or sex cannot be estimated by the remains recovered from archaeological cremations – largely due to the incomplete recovery of remains that is typical in archaeological cremation burials (McKinley,

2013). Attempts have been made to apply histological aging techniques to cremated remains (Mahoney and Miszkiewicz, 2015; Wolf et al., 2017) and recently developed methods of sex estimation from amelogenin peptides may in future be applied to cremated remains (Stewart et al., 2017; Gowland et al., 2020); these methods may help to bolster the number of cremated individuals for whom age-at-death and sex can be estimated. Pathological indicators have been found among cremated remains including trauma, joint diseases, dental diseases, even calcified lymph nodes; however, demographic analyses of these indicators are not typically possible due to incomplete representation of the individuals within a burial population (Mayne, 1990; McKinley, 1994a; 2000; Ubelaker, 2015; Wahl, 2015). Yet, despite the vast array of techniques available for evaluating cremated remains and the publication of guidance for the study of cremated remains there continues to be a bias against studying cremated remains among osteoarchaeologists (Goméz Bellard, 1996; Duday et al., 2000; McKinley 2004; Ubelaker, 2009; Arora et al., 2010; Ellingham et al., 2015a; Kurila, 2015). The author suspects that one factor preventing osteoarchaeologists from studying cremated remains is a lack of experience. In my personal experience studying osteology and bioarchaeology there have been few instances in which I, or my classmates, received practical instruction regarding burned human bone. Instruction related to burned bone or archaeologically cremated remains was theoretical, without related practical experience. Cremated remains were occasionally presented in laboratory courses as examples, but not included among the material used for instruction in practicing bioarchaeology. While this experience is anecdotal, the author does not believe it was singular. If few osteoarchaeologists have practical experience with cremated remains during their training, it is not surprising that they do not pursue research into cremated remains. To help expand the amount of research conducted on archaeologically cremated remains, there needs to be an emphasis on training osteoarchaeologists to evaluate these thermally altered remains.

9.5 Summary

This project attempted to determine whether it was possible to use stable isotope analyses of carbon, nitrogen, and sulphur to infer the diets of cremated individuals. A controlled heating experiment using animal bone suggested that there was a threshold at

approximately 200°C below which isotope ratios of carbon, nitrogen, and sulphur were conserved and above which delta values of both carbon and nitrogen were increasingly elevated with increasing temperatures. The effect was less pronounced among $\delta^{13}C$ values than among $\delta^{15}N$ values. The pattern of alteration to $\delta^{34}S$ values was more complicated, initially rising and then falling as temperatures increased. However, when isotope analysis was attempted on bone samples selected from archaeologically cremated individuals buried at Elsham and Cleatham Anglo-Saxon cemeteries collagen quality indicators suggested that extracts obtained from these samples were contaminated or modified and no longer represented biogenic collagen composition. There are several possible explanations for the difference between the experimental and archaeological results obtained during this project. First, the controlled heating experiment was designed to limit the number of variables that could affect the $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ values of the heated bone samples; as such, there was no investigation of the influence of heat fluctuations, interactions with an open-air environment, or a fuel source, all of which could have affected the isotope ratios in the bone samples. Secondly, the burning intensities experienced by the bone samples selected from archaeologically cremated individuals were estimated by colour and by FTIR analysis. While observations of bone colour suggested that the bone samples selected had experienced low temperature exposures, FTIR analyses suggested that these bone samples experienced burning intensities equivalent to temperatures of 500°C or higher. If these bone samples were exposed to temperatures in excess of 500°C, collagen would not be expected to remain viable for isotope analysis. Thirdly, the influence of the burial environment on the survival of collagen in burned bone is unknown. This influence was not explored during the controlled heating experiment. There is a chance that the thermal breakdown of collagen fibrils would increase the rate of collagen decay in the burial environment, leading to low collagen yields. Marginal collagen yields may be overwhelmed by proteinaceous contamination from the soil that would explain the poor collagen quality observed in the extracts taken from archaeologically cremated individuals. Both Elsham and Cleatham cemeteries were sited on acidic soils with impeded drainage, conditions that are not ideal for the preservation of collagen. Thus, while the bone samples from archaeologically cremated individuals evaluated in this study did not successfully produce viable collagen for isotope analysis there is potential for this technique to be successful, especially in burial conditions that are conducive to collagen conservation. More widely,

this project has highlighted the dearth of research being conducted on cremated remains in archaeology. While research into burned bone has been growing in the last several decades, much of this research is either experimental or forensic. There has been growing interest among archaeologists regarding cremated remains; however, there continues to be a bias toward inhumed remains in archaeological research despite the abundance of cremated remains available in the archaeological record.

References:

Aaseth, J., Boivin, G., Andersen, O. (2012) Osteoporosis and trace elements – an overview. *Journal of Trace Elements in Medicine and Biology,* 26: 149-152.

Åberg, N. (1926) *The Anglo-Saxons in England,* Almqvist & Wiksells Boktryckeri, Uppsala.

Absolonová, K., Dobisíková, M., Beran, M., Zocová, J., Velemínsky, P. (2012) The temperature of cremation and its effect on the micro-structure of human rib compact bone. *Anthropologischer Anzeiger,* 69(4): 439-460.

Aerssens, J., Boonen, S., Lowet, G., Dequeker, J. (1998) Interspecies differences in bone composition and quality: potential implications for *in vivo* bone research. *Endocrinology,* 139(2): 663-670.

Ambrose, S. H. (1990) Preparation and characterization of bone and tooth collagen for isotopic analysis. *Journal of Archaeological Science,* 17: 431-451.

Ambrose, S. H. (1991) Effects of diet, climate and physiology on nitrogen isotope abundances in terrestrial foodwebs. *Journal of Archaeological Science,* 18: 293-317.

Ambrose, S. H. (2000) Controlled diet and climate experiments on nitrogen isotope ratios of rat bone collagen, hair and muscle. In S. H. Ambrose, M. A. Katzenberg (eds.) *Biogeochemical Approaches to Paleodietary Analysis,* Kluwer Academic, New York. pp. 243-259.

Ambrose, S. H., DeNiro, M. J. (1986) The isotopic ecology of East African mammals. *Oecologia,* 69: 395-406.

Ambrose, S. H., Krigbaum, J. (2003) Bone chemistry and bioarchaeology. *Journal of Anthropological Archaeology,* 22: 193-199.

Amrani, A., Said-Ahmad, W., Shaked, Y., Kiene, R. P. (2013) Sulfur isotope homogeneity of oceanic DMSP and DMS. *Proceedings of the National Academy of Sciences,* 110(46): 18413-18418.

Anusaranasasanakiarti, P.K., Keyes, C.F. (1980) Funerary rites and the Buddhist meaning of death: an interpretive text from northeast Thailand. *Journal of the Siam Society*, 68(1): 1–28.

Aplin, K., Manne, T., Attenbrow, V. (2016) Using a 3-stage burning categorization to assess post-depositional degradation of archaeofaunal assemblages: some observations based on multiple prehistoric sites in Australasia. *Journal of Archaeological Science: Reports,* 7: 700-714.

Appleby, J. (2012) Temporality and the transition to cremation in the late third millennium to mid second millennium BC in Britain. *Cambridge Archaeological Journal,* 23(1): 83-97.

Arce, A. (2007) *Health in Southern and Eastern England: a perspective on the early medieval period,* unpublished PhD thesis, Durham University.

Arneson, L. S., MacAvoy S. E. (2005) Carbon, nitrogen and sulfur diet-tissue discrimination in mouse tissues. *Canadian Journal of Zoology,* 83: 989-995.

Arnold, C. J. (1980) Wealth and social structure: a matter of life and death. In P. Rahtz, T. Dickinson, L. Watts (eds.) *Anglo-Saxon Cemeteries 1979,* British Archaeological Reports, British Series (72), Oxford. pp. 81-142.

Arnold, C. J. (1984) *Roman Britain to Saxon England: An Archaeological Study,* Croom Helm, London.

Arora, A. K., Gupta, P., Kapoor, S. S., Mahajan, S. (2010) An analytic review of burnt bones in medicolegal sciences. *Journal of Punjab Academy of Forensic Medicine and Toxicology,* 10: 31-36.

Attenborough, F. (2015) *The Laws of the Earliest English Kings.* Cambridge University Press, Cambridge.

Aufderheide, A. C., Rodríguez-Martin, C., Langsjoen, O. (1998) *The Cambridge Encyclopedia of Human Paleopathology.* Cambridge University Press, Cambridge.

Baby, R. S. (1954) Hopewell cremation practices. *The Ohio Historical Society Papers in Archaeology*, 1: 1-7.

Baković, M., Vreča, P., Mayer, D. (2017) Case of fatal starvation: can stable isotope analysis serve to support morphological diagnosis and approximate the length of starvation. *Journal of Forensic Sciences,* 62(1): 258-264.

Baldwin Brown, G. (1915) *The Arts in Early England – Saxon Art and Industry in the Pagan Period,* John Murray, London.

Bartelink, E. J., Berg, G. E., Beasley, M. M., Chesson, L. A. (2014) Application of stable isotope forensics for predicting region of origin of human remains from past wars and conflicts. *Annals of Anthropological Practice,* 38(1): 124-136.

Bartelink, E. J., Chesson, L. A. (2019) Recent applications of isotope analysis to forensic anthropology. *Forensic Sciences Research,* 4(1): 29-44.

Barth, A. (2007) Infrared spectroscopy of proteins. *Biochimica et Biophysica Acta (BBA)-Bioenergetics.* 1767(9):1073-1101.

Bassett, S. (1989) Lincoln and the Anglo-Saxon see of Lindsey. *Anglo-Saxon England,* 18: 1-32.

Basu, S., Ghosh, S., Sanyal, P. (2019) Spatial heterogeneity in the relationship between precipitation and carbon isotopic discrimination in C_3 plants: inferences from a global compilation. *Global Planetary Change,* 176: 123-131.

Bayliss, A., McCormac, G., Thompson, M., Hines, J. (2013) Dating methods and their modelling. In J. Hines, A. Bayliss (Eds.) *Anglo-Saxon Graves and Grave Goods of the 6th and 7th Centuries AD: A Chronological Framework,* Society for Medieval Archaeology, Monograph 33, London. pp. 33-87.

Beach, J. J., Passalacqua, N. V., Chapman, E. N. (2015) Heat-related changes in tooth color. In C. W. Schmidt, S. A. Symes, eds. *The Analysis of Burned Human Remains, Second Edition*. London: Elsevier, pp. 139-147.

Beasley, M. M., Bartelink, E. J., Taylor, L., Miller, R. M. (2014) Comparison of transmission FTIR, ATR, and DRIFT spectra: implications for assessment of bone bioapatite diagenesis. *Journal of Archaeological Science,* 46: 16-22.

Beaumont, J., Montgomery, J. (2016) The Great Irish Famine: identifying starvation in the tissues of victims using stable isotope analysis of bone and incremental dentine collagen. *PLOSone,* 11(8): 1-21. e016065. doi:10.1371/journal.pone/0160065

Beaumont, J., Montgomery, J., Buckberry, J., Jay, M. (2015) Infant mortality and isotopic complexity: new approaches to stress, maternal health and weaning. *American Journal of Physical Anthropology,* 157: 441-457.

Beavan, N., Mays, S. (2013) The human skeletons. In J. Hines, A. Bayliss (eds.) *Anglo-Saxon Graves and Grave Goods of the 6th and 7th Centuries AD: A Chronological Framework,* The Society for Medieval Archaeology, Monograph 33, London. pp. 101-131.

Beckett, J., Robb, J. (2009) Neolithic burial taphonomy, ritual, and interpretation in Britain and Ireland: a review. In R. Gowland, C. Knusel (Eds.) *The Social Archaeology of Funerary Remains.* Oxford, Oxbow Books, pp. 57-80.

Bender, M. M., Baerreis, D. A., Steventon, R. L. (1981) Further light on carbon isotopes and Hopewell agriculture. *American Antiquity,* 46(2): 346-353.

Blair, J. (2013) The Tribal Hidage. In M. Lapidge, J. Blair, S. Keynes, D. Scragg (eds.) *The Wiley Blackwell Encyclopedia of Anglo-Saxon England, 2nd Edition,* John Wiley & Sons Ltd., Oxford. pp. 473-475.

Bocherens, H., Billiou, D., Mariotti, A., Patuo-Mathis, M., Otte, M., Bonjean, D., Toussaint, M. (1999) Palaeoenvironmental and palaeodietary implications of isotopic biogeochemistry of last interglacial Neanderthal and mammal bones in Scladina Cave (Belgium). *Journal of Archaeological Science,* 26: 599-607.

Bocherens, H., & Drucker, D. (2003). Trophic level isotopic enrichment of carbon and nitrogen in bone and collagen: case studies from recent and ancient terrestrial ecosystems. *International Journal of Osteoarchaeology*, 13: 46-53.

Bohnert, M., Rost, T., Pollak, S. (1998) The degree of destruction of human bodies in relation to the duration of the fire. *Forensic Science International,* 95:11-21.

Bonafini, M., Pellegrini, M., Ditchfield, P., Pollard, A. M., (2013) Investigation of the 'canopy effect' in isotope ecology of temperate woodlands. *Journal of Archaeological Science,* 40: 3926-3935.

Bond, J. M. (1994) Appendix I: the cremated animal bone. In J. I. McKinley *The Anglo-Saxon Cemetery at Spong Hill, North Elmham. Part VII: the Cremations*. East Anglian Archaeology Report No. 69, Norfolk Museums Service, Dereham: 121-135.

Bond, J. M. (1996) Burnt offerings: animal bone in Anglo-Saxon cremations. *World Archaeology,* 28(1): 76-88.

Bond, J. M., Worley, F. L. (2006) Companions in death: the roles of animals in Anglo-Saxon and Viking cremation rituals in Britain. In R. Gowland, C. Knusel eds. *Social Archaeology of Funerary Remains (Volume One),* Oxbow Books, Oxford: 89-98.

Bowler, J. M., Johnston, H. Oiley, J. M., Prescott, J. R., Roberts, R. G., Shawcross, W., Spooner, N. A. (2003) New ages for human occupation and climatic change at Lake Mungo, Australia. *Nature,* 421(6925): 837-840.

Bowler, J. M., Jones, R., Allen, H., Thorne, A. G. (1970) Pleistocene human remains from Australia: a living site and human cremation from Lake Mungo, Western New South Wales. *World Archaeology,* 2(1): 39-60.

Boyle, L. E. (1997) The Nowell Codex and the poem of Beowulf. In C. Chase ed. *The Dating of Beowulf.* University of Toronto Press, Toronto. Pp. 23-32.

Bradtmiller, B., Buikstra, J. E., (1984) Effects of burning on human bone microstructure: a preliminary study. *Journal of Forensic Science,* 29: 535-540.

British Geological Survey (2021) https://mapapps.bgs.ac.uk/geologyofbritain/home.html?&_ga=2.168700199.722285717.1627651551-1647475128.1593786031 [Accessed 08/06/2021]

Brugmann, B. (2011) Migration and endogenous change. In H. Hamerow, D. A. Hinton, S. Crawford (eds.) *The Oxford Handbook of Anglo-Saxon Archaeology,* Oxford University Press, Oxford. pp. 30-45.

Brush, K. A. (1993) *Adorning the Dead: the Social Significance of Early Anglo-Saxon Funerary Dress in England (Fifth to Sixth Centuries AD),* unpublished PhD thesis, University of Cambridge.

Buckberry, J. (2000) Missing, presumed buried? Bone diagenesis and the under-representation of Anglo-Saxon children. *Assemblage: University of Sheffield Graduate Student Journal of Archaeology,* 5: http://hdl.handle.net/10454/676.

Burris, R. H., Roberts, G. P. (1993) Biological nitrogen fixation. *Annual Review of Nutrition,* 13(1): 317-335.

Calvin, M. (1961) The path of carbon in photosynthesis (Nobel Prize Lecture). Ernest Orlando Lawrence Berkeley National Laboratory, University of California Radiation Laboratory-Berkeley, United States Department of Energy, Berkeley, CA.

Campbell, J. (1982) *The Anglo-Saxons.* Phaidon, Oxford.

Capelli, C., Redhead, N., Abernathy, J. K., Gratrix, F., Wilson, J. F., Moen, T., Hervig, T., Richards, M., Stumpf, M. P. H., Underhill, P. A., Bradshaw, P., Shaha, A., Thomas, M. G., Bradman, N., Goldstein, D. B. (2003) A Y-chromosome census of the British Isles. *Current Biology,* 13: 979-984.

Carroll, E. L., Squires, K. E. (2020a) The application of quantitative petrography and macroscopic colour change in a comparative analysis of Roman and Anglo-Saxon cremation practices. *International Journal of Osteoarchaeology,* 30: 882-890.

Carroll, E. L., Squires, K. E. (2020b) Burning by the numbers: a pilot study using quantitative petrography in the analysis of heat-induced alteration in burned bone. *International Journal of Osteoarchaeology,* 30: 691-699.

Cassman, V., Odegaard, N., Powell, J. (2007) *Human Remains: Guide for Museums and Academic Institutions,* Altamira Press, Plymouth.

Castillo, R. F., Ubelaker, D. H., Acosta, J. A. L., de la Rosta, R. J. E., Garcia, I. G. (2013) Effect of temperature on bone tissue: histological study of the changes in the bone matrix. *Forensic Science International,* 226: 33-37.

Cataroche, J., Gowland, R. (2015) Flesh, fire, and funerary remains from the Neolithic site of La Varde, Guernsey: Investigations past and present. In T. Thompson, ed. *Archaeology of Cremation: burned human remains in funerary studies.* Oxford: Oxbow Books, pp. 19-41.

Chadwick, H. M. (1940) The Sutton Hoo ship-burial. VIII. Who was he? *Antiquity,* 14(53): 76-87.

Child, A. M. (1995) Towards an understanding of the microbial decomposition of archaeological bone in the burial environment. *Journal of Archaeological Science,* 22: 165-174.

Chirachariyavej, T., Amnueypol, C., Sanggarnjanavanich, S., Tiensuwan, M. (2006) The relationship between bone and ash weight to age, body weight and body length of Thai adults after cremation. *Journal of the Medical Association of Thailand* 89(11): 1940-1945.

Chisholm, B. S., Nelson, D. E., Hobson, K. A., Schwarcz, H. P., Knyf, M. (1983) Carbon isotope measurement techniques for bone collagen: notes for the archaeologist. *Journal of Archaeological Science,* 10: 355-360.

Chisholm, B. S., Nelson, D. E., Schwarcz, H. P. (1982) Stable-carbon isotope ratios as a measure of marine versus terrestrial protein in ancient diets. *Science,* 216(4550): 1131-1132.

Cole, G., Waldron, T. (2016) Purple staining of archaeological human bone: an investigation of probable cause and implications for other tissues and artifacts. *Journal of Anthropology.* 2016:1-11.

Collins, M., Buckley, M., Grundy, H. H., Thomas-Oates, J., Wilson, J., van Doorn, N. (2010) ZooMS: the collagen barcode and fingerprints. *Spectroscopy Europe,* 22(2): 6-10.

Collins, M. J., Neilsen-Marsh, C. M., Hiller, J., Smith, C. I., Roberts, J. P., Prigodich, R. V., Wess, T. J., Csapò, J., Millard, A. R., Turner-Walker, G. (2002) The survival of organic matter in bone: a review. *Archaeometry,* 3: 383-394.

Coplan, T. B. (1995) Discontinuance of SMOW and PDB. *Nature,* 375(6529): 285.

Coplan, T. B. (2011) Guidelines and recommended terms for expression of stable-isotope-ratio and gas-ratio measurement results. *Rapid Communications in Mass Spectrometry,* 25(17): 2538-2560.

Crabtree, P. J. (1989) Sheep, horses, swine and kine: a zooarchaeological perspective on the Anglo-Saxon settlement of England. *Journal of Field Archaeology,* 16(2): 205-213.

Crabtree, P. J. (1990) *West Stow: early Anglo-Saxon animal husbandry*. East Anglian Archaeology Report No. 47*,* Suffolk County Planning Department, Ipswich.

Crabtree, P. J., Campana D. V. (2014) Wool production, wealth, and trade in Middle Saxon England. In B. S. Arbuckle, S. A. McCarty (Eds.) *Animals and inequality in the ancient world,* Boulder, University Press Colorado. pp. 335-351.

Craig, O. E., Ross, R., Andersen, S. H., Milner, N., Bailey, G. N. (2006) Focus: sulphur isotope variation in archaeological marine fauna from northern Europe. *Journal of Archaeological Science,* 33: 1642-1646.

Crawford, S. (2000) Children, grave goods and social status in early Anglo-Saxon England. In J. S. Derevenski (ed.) *Children and Material Culture,* Routledge, London. Pp. 169-179.

Crawford, S. (2007) Companions, co-incidences or chattels? Children in the early Anglo-Saxon multiple burial ritual. In S. Crawford, G. Shepherd (eds.) *Children, Childhood and Society,* British Archaeological Reports, International Series (1696), Archaeopress, Oxford. pp. 83-92.

Davies, D. J. (2005) A chronology of cremation. In D. J. Davies and L. H. Mates (Eds.) *Encyclopedia of cremation.* Ashgate Publishing. Credo Reference.

Davies, D. J., Kent, E., Keizer, H. (2005) Introduction. In D. J. Davies and L. H. Mates (Eds.) *Encyclopedia of cremation.* Ashgate Publishing. Credo Reference.

Davison, A., Green, B., Miligan, B. (1993) *Illington: a study of a Breckland Parish and its Anglo-Saxon Cemetery.* East Anglian Archaeology Report 63, Field Archaeology Division Norfolk Museums Service, Dereham.

DeHaan, J. D. (2012) Sustained combustion of bodies: some observations. *Journal of Forensic Sciences,* 57(6) 1578-1584.

DeHaan, J. D. (2015) Fire and Bodies. In C. W. Schmidt, S. A. Symes, eds. *The Analysis of Burned Human Remains.* London: Elsevier, pp. 1-15.

DeHaan, J. D., Campbell, S. J., Nurbakhsh, S. (1999) Combustion of animal fat and its implications for the consumption of human bodies in fires. *Science & Justice*, 39:27-38.

DeNiro, M. J. (1985) Postmortem preservation and alteration of *in vivo* bone collagen isotope ratios in relation to palaeodietary reconstruction. *Nature,* 317: 806-809.

DeNiro, M. J. (1987) Stable isotopy and archaeology. *American Scientist,* 75(2): 182-191.

DeNiro, M. J., Epstein, S. (1978) Influence of diet on the distribution of carbon isotopes in animals. *Geochimica et Cosmochimica Acta,* 42: 495-506.

DeNiro, M. J., Epstein, S. (1981) Influence of diet on the distribution of nitrogen isotopes in animals. *Geochimica et Cosmochimica Acta,* 45: 341-351.

DeNiro, M. J., Hastorf, C. A. (1985) Alteration of $^{15}N/^{14}N$ and $^{13}C/^{12}C$ ratios of plant matter during the early stages of diagenesis: studies utilizing archaeological specimens from Peru. *Geochimica et Cosmochimica Acta*, 49: 97-115.

DeNiro, M. J., Schoeninger, M. J. (1983) Stable carbon and nitrogen isotope ratios of bone collagen: variations within individuals, between sexes, and within populations raised on monotonous diets. *Journal of Archaeological Science,* 10: 199-203.

DeNiro, M. J., Schoeninger, M. J., Hastorf, C. A. (1985) Effect of heating of the stable carbon and nitrogen isotope ratios of bone collagen. *Journal of Archaeological Science,* 12: 1-7.

Devlin, J.B., Herrmann, N. P. (2015) Bone colour. In C. W. Schmidt, S. A. Symes, eds. *The Analysis of Burned Human Remains.* London: Elsevier, pp. 119-138.

DeWald, S., Josiah, S., Erdkamp, B. (2005) NebGuide G1554: *Heating with wood: producing, harvesting and processing firewood*. University of Nebraska-Lincoln, Institute of Agriculture and Natural Resources. Available at: https://outreach.cnr.ncsu.edu/ncwood/documents/NebraskaFirewoodGuide.pdf [accessed 01/04/2021].

Dickinson, T. (1980) The present state of Anglo-Saxon cemetery studies. In P. Rahtz, T. Dickinson, L. Watts (eds.) *Anglo-Saxon Cemeteries 1979,* British Archaeological Reports, British Series (72), Oxford. pp. 39-80.

Dickinson, T. (2011) Overview: mortuary ritual. In H. Hamerow, D. A. Hinton, S. Crawford (eds.) *The Oxford Handbook of Anglo-Saxon Archaeology,* Oxford University Press, Oxford. pp. 221-237.

Dickinson, T., Speake, G. (1992) The seventh-century cremation burial in Asthall Barrow, Oxfordshire: a reassessment. M. O. H. Carver, ed. *The Age of Sutton Hoo,* Boydell and Brewer, Woodbridge: 95-130.

Diefendorf, A. F., Mueller, K. E., Wing, S. L., Koch, P. L., Freeman, K. H. (2010) Global patterns in leaf ^{13}C discrimination and implications for studies of past and future climate. *Proceedings of the National Academy of Sciences of the United States of America,* 107(13): 5738-5743.

Dockray-Miller, M. (2017) Old English has a serious image problem. *JSTOR Daily.* pp. 1-18 [Available from: https://daily.jstor.org/old-english-serious-image-problem/]

Down A., Welch, M. (1990) *Chichester Excavations VII: Apple Down and the Mardens,* Chichester District Council, Chichester.

Downward, K. M. (2007) Francis William Aston: the man behind the mass spectrometer. *European Journal of Mass Spectrometery,* 13: 177-190.

Drinkall, G., Foreman, M. (1998) *The Anglo-Saxon cemetery at Castledyke South, Barton-on-Humber,* Sheffield Excavation Reports (6), Humber Archaeology Partnership, Sheffield.

Drysdale, D. D. (1999) *An Introduction to Fire Dynamics, Third Ed*. John Wiley & Sons, Chichester.

Dubois, J. A., Beauchamp, H.K. (1906) *Hindu Manners, Customs and Ceremonies 3rd Edition,* Clarendon Press, Oxford.

Duday, H., Depierre, G., Janin, T. (2000) Validation des paramètres de quantification, protocols et strategies dans l'étude anthropologique des sépultures secondaires à incineration. L'exemple des nécropoles protohistoriques du midi de la France. In B. Dedet, P.

Gruat, G. Marchand, M. Py, M. Schwaller (Eds.) *Archéologie de La Mort, Archéologie de la tombe au premier Âge du Fer. Actes du XXI colloque Intenational de l'AFEAF, Volume 5: Monographies d'Archéologie Méditerranéenne*, Lattes, Paris. pp. 7-29.

Dumville, D. N. (1975) "Nennius" and the "Historia Brittonum". *Studia Celtica,* 10: 78-95.

Dumville, D. N. (1977) Sub-Roman Britain: History and Legend 1. *History,* 62(205): 173-192.

Dupras, T. L., Schultz, J. J. (2013) Taphonic Bone Staining and Color Changes in Forensic Contexts. *Manual of Forensic Taphonomy,* pp. 315-340.
Eagles, B.N. (1979) *The Anglo-Saxon Settlement of Humberside,* British Archaeological Reports, British Series (68), Oxford.

Eagles, B. (1989) Lindsey. In *The Origins of Anglo-Saxon Kingdoms,* S. Bassett ed. London: Leicester University Press, pp. 202-212.

Ellingham, S. T. D., Thompson, T. J. U., Islam, M., Taylor, G. (2015a) Estimating temperature exposure of burnt bone – A methodological review. *Science and Justice.* 55: 181-188.

Ellingham, S. T. D., Thompson, T. J. U., Islam, M. (2015b) The effect of soft tissue on temperature estimation from burnt bone using Fourier Transform Infrared Spectroscopy. *Journal of Forensic Sciences* 61(1):1-7.

Elliot, A. (2017) A vile love affair: right wing nationalism and the Middle Ages. *The Public Medievalist.* Pp. 1-15. [Available from: https://www.publicmedievalist.com/vile-love-affair/]

Emery, K. M., Williams, H. (2018) A place to rest your (burnt) bones? Mortuary houses in early Anglo-Saxon England. *Archaeological Journal,* 175(1): 55-86.

Ennis, T. (2008) *An Early Saxon Cemetery at Rayleigh, Essex: excavations at the former Park School.* East Anglian Archaeology Reports 127, Essex County Council, Chelmsford.

Ericson, J. E. (1985) Strontium isotope characterisation in the study of prehistoric human ecology. *Journal of Human Evolution,* 14(5): 503-514.

Essential FTIR (2021) Baseline Correction. Available from: https://www.essentialftir.com/baselineCorrection.html [Accessed: 21/02/2022]

Etok, S. E., Valsami-Jones, E., Wess, T. J., Hiller, J. C., Maxwell, C. A., Rogers, K. D., Manning, D. A. C., White, M. L., Lopez-Capel, E., Collins, M. J., Buckley, M., Penkman, K. E. H., Woodgate, S. L. (2007) Structural and chemical changes of thermally treated bone apatite. *Journal of Materials Science* 42(23):9801-9816.

Evans, J. A., Chenery, C. A., Mee, K., Cartwright, C. E., Lee, K. A., Marchant, A. P., Hannaford, L., (2018): Biosphere Isotope Domains GB (V1): Interactive Website. British Geological Survey. (Interactive Resource). https://doi.org/10.5285/3b141dce-76fc-4c54-96fa-c232e98010ea [Accessed 08/06/2021]

Evans, J. A., Chenery, C. A., Montgomery, J. (2012) A summary of strontium and oxygen isotope variation in archaeological human tooth enamel excavated from Britain. *Journal of Analytical Atomic Spectrometry,* 27(5): 754-764.

Evans, J. A., Mee, K., Chenery, C. A., Cartwright, C. E., Lee, K. A., Marchant, A. P. (2018) *User guide for the Biosphere Isotope Domains GB (Version 1) dataset and web portal*. Nottingham, British Geological Survey. pp: 1-21. (OR.18/005)

Evans, J. A., Montgomery, J., Wildman, G., Boulton, N. (2010) Spatial variation in biosphere $^{87}Sr/^{86}Sr$ in Britain. *Journal of Geological Society, London,* 167: 1-4.

Evison, V. E. (1963) Sugar-loaf shield bosses. *Antiquaries Journal,* 43: 38-96.

Evison, V. E. (1987) *Dover: The Buckland Anglo-Saxon cemetery,* Historic Buildings and Monuments Commission Report No. 91, London.

Fahy, G. E., Deter, C., Pitfield, R., Miszkiewicz, J. J., Mahoney, P. (2017) Bone deep: variation in stable isotope ratios and histomorphometric measurements of bone remodelling within adult humans. *Journal of Archaeological Science,* 87: 10-16.

Fairchild, M. D. (2013). *Color Appearance Models*. John Wiley & Sons.

Fassett, B. (1856) *Inventorium Sepulchrale: an account of some antiquities dug up at Gilton, Kington, Sibertswold, Barfriston, Beakebourne, Chartam, and Crundale, the county of Kent from A.D. 1757 to A.D. 1773,* T. Richards, London.

Faull, M. L. (1977) British survival in Anglo-Saxon Northumbria. In L. Laing (ed.) *Studies in Celtic Survival,* British Archaeological Reports, British Series (37), Archaeopress, Oxford. pp. 1-56.

Fengming, L., Jintong, Z., Yongren, Z., Yueling, G., Hongchang, Z., Jian, L. (2005) China. In D. J. Davies and L. H. Mates (Eds.) *Encyclopedia of cremation.* Ashgate Publishing. Credo Reference.

Field, A. (2013) *Discovering Statistics Using IBM SPSS Statistics, 4th Edition.* Sage Publishing, London.

Figueiredo, M. M., Gamelas, J. A. F., Martins, A. G. (2012). Characterization of bone and bone-based graft materials using FTIR spectroscopy. In T. Theophile (Ed.) *Infrared spectroscopy-life and biomedical sciences*, Books on Demand, Norderstedt, Germany. pp. 315-338.

Fischer, A., Olsen, J., Richards, M., Heinemeier, J., Sveinbjörnsdóttir, A. E., Bennike, P. (2007) Coast-inland mobility and diet in the Danish Mesolithic and Neolithic: evidence from stable isotope values of humans and dogs. *Journal of Archaeological Science,* 34: 2125-2150.

Fogel, M., Tuross, N., Owsley, D. (1989) Nitrogen isotope tracers of human lactation in modern and archaeological populations. *Carnegie Institute Yearbook,* 88: 133-134.

Font, L., Jonker, G., van Aalderen, P. A., Schiltmans, E. F., Davies, G. R. (2014) Provenancing of unidentified World War II casualties: application of strontium and oxygen isotope analysis in tooth enamel. *Science and Justice,* 55: 10-17.

Font, L., van der Peijl, G., van Leuwen, C., van Wetten, I., Davies, G. R. (2015) Identification of the geographical place of origin of an unidentified individual by multi-isotope analysis. *Science and Justice,* 55: 34-42.

Foot, S. (1993) The Kingdom of Lindsey. In *Pre-Viking Lindsey,* A. Vince, ed. Lincoln: City of Lincoln Archaeology Unit, pp. 128-140.

Fornander, E., Eriksson, G., Lidén, K. (2008) Wild at heart: Approaching Pitted Ware identity, economy, and cosmology through stable isotopes in skeletal material from the Neolithic site Korsnäs in Eastern Central Sweden. *Journal of Anthropological Archaeology,* 27: 281-297.

Fowler, C. (2010) Pattern and diversity in the Early Neolithic mortuary practices of Britain and Ireland: contextualising the treatment of the dead. *Documenta Praehistorica,* 37: 1-22.

Fredericks, J. D., Bennet, P., Williams, A., Rogers, K. D. (2012) FITR spectroscopy: a new diagnostic tool to aid DNA analysis from heated bone. *Forensic Science International: Genetics,* 6: 375-380.

French, K. M. (2017) *Multispecies Cremations in a Transitional World: evidence from early medieval England,* unpublished PhD Thesis, New York University.

Fuller, B. T., Fuller, J. L., Harris, D. A., Hedges, R. E. M. (2006a) Detection of breastfeeding and weaning in modern human infants with carbon and nitrogen stable isotope ratios. *American Journal of Physical Anthropology,* 129: 279-293.

Fuller, B. T., Fuller, J. L., Sage, N. E., Harris, D. A., O'Connell, T. C., Hedges, R. E. M. (2005) Nitrogen balance and $\delta^{15}N$: why you're not what you eat during nutritional stress. *Rapid Communications in Mass Spectrometry,* 19: 2497-2506.

Fuller, B. T., Molleson, T. I., Harris, D. A., Gilmour, L. T., Hedges, R. E. M. (2006b) Isotopic evidence for breastfeeding and possible adult dietary differences from Late/Sub-Roman Britain. *American Journal of Physical Anthropology,* 129: 45-54.

Fuller, M. (2012) Determination of protein and amino acid digestibility in foods including implications of gut microbial amino acid synthesis. *British Journal of Nutrition,* 108(S2): S238-S246.

Fultz, B., Howe, J. M. (2012). *Transmission electron microscopy and diffractometry of materials*. Springer Science & Business Media.

Gannes, L. Z., Martinez del Rio, C., Koch, P. (1998) Natural abundance variations in stable isotopes and their potential uses in animal physiological ecology. *Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology,* 119(3): 725-737.

Gat, J. R. (1981) Historical Introduction. In *Stable isotope hydrology. Deuterium and oxygen-18 in the water cycle,* J. R. Gat, R. Gonfiantini, eds. International Atomic Energy Agency (IAEA): IAEA, pp. 1-6.

Geake, H. (1997) *The Use of Grave-Goods in Conversion Period England, c. 600-c.850,* British Archaeological Reports, British Series (261), Oxford.

Gejvall, N-G. (1947) Bestämning av brända ben från forntida graver. *Fornvännen: Journal of Swedish Antiquarian Research,* 42:39-47.

Gejvall, N-G. (1969) Cremations. In D. Brothwell, E. Higgs, eds. *Science in Archaeology: Revised and Enlarged Edition.* Praeger Publishers, New York. pp. 468-479.

Geodert, J., Fourel, F., Amiot, R., Simon, L., Lécuyer, C. (2016) High-precision $^{34}S/^{32}S$ measurements in vertebrate bioapatites using purge-and-trap elemental analyser/isotope ratio mass spectrometry technology. *Rapid Communications in Mass Spectrometry,* 30(18): 2002-2008.

Goméz Bellard, F. (1996) El análisis antropológico de las cremaciones. *Complutum Extra,* 6: 55-64.

Gonçalves, D. (2011) The reliability of osteometric techniques for the sex determination of burned human skeletal remains. *HOMO – Journal of Comparative Human Biology,* 62: 351-358.

Gonçalves, D. (2012) The micro-analysis of human burned bones: some remarks. *Cadernos do GEEvH* 1(1): 32-40.

Gonçalves, D., Campanacho, V., Thompson, T., Mataloto, R. (2015) The weight of the matter: examining the potential of skeletal weight for the bioarchaeological analysis of cremation at the Iron Age necropolis of Tera (Portugal). In T. Thompson, eds. *The Archaeology of Cremation*. Oxbow Books, Oxford. pp. 63-96.

Gonçalves, D., Pires, A. E. (2016) Cremation under fire: a review of bioarchaeological approaches from 1995 to 2015. *Archaeological and Anthropological Sciences.* 9(8): 1677-1688.

Gonçalves, D., Thompson, T. J. U., Cunha, E. (2011) Implications of heat-induced changes in bone on the interpretation of funerary behaviour and practice. *Journal of Archaeological Science* 38:1308-1313.

Goude, G., Fontugne, M. (2016) Carbon and nitrogen isotopic variability in bone collagen during the Neolithic period: influence of environmental factors and diet. *Journal of Archaeological Science,* 70: 117-131.

Gowland, R. L. (2002) *Age as an aspect of social identity in fourth-to-sixth-century AD England: the archaeological funerary evidence.* Unpublished PhD thesis, Durham University.

Gowland, R. (2006) Ageing the past: examining age identity from funerary evidence. In R. Gowland, C. Knüsel (eds.) *Social Archaeology of Funerary Remains,* Oxbow, Oxford. pp. 143-154.

Gowland, R. (2007) Beyond ethnicity: symbols of social identity from the fourth and sixth centuries in England. *Anglo-Saxon Studies in Archaeology and History,* 14: 56-65.

Gowland, R., Stewart, N. A., Crowder, K. D., Hodson, C., Shaw, H., Gron, K. J., Montgomery, J. (2020) Sex estimation of teeth at different developmental stages using dimorphic enamel peptide analysis. *American Journal of Physical Anthropology,* 174: 859-869.

Gowland, R. L., Western, A. G. (2012) Morbidity in the marshes: using spatial epidemiology to investigate skeletal evidence for malaria in Anglo-Saxon England (AD 410-1050). *American Journal of Physical Anthropology,* 147: 301-311.

Graham, E. J. (2015) Introduction: embodying death in archaeology. In Z. L. Devlin, E. J. Graham (eds.) *Death Embodied: Archaeological Approaches to the Treatment of the Corpse,* Oxbow Books, Oxford. pp. 1-17

Green, C. (2020) *Britons and Anglo-Saxons: Lincolnshire AD 400-650, Volume 3.* History of Linconshire Committee, Lincoln.

Green, T. (2008) The British Kingdom of Lindsey. *Cambrian Medieval Celtic Studies,* 56: 1-30.

Green, T. (2011) *A Re-evaluation of the evidence of Anglian-British interaction in the Lincoln region,* unpublished PhD thesis, University of Oxford.

Grupe, G., Heinrich, D., Peters, J. (2009) A brackish water aquatic foodweb: trophic levels and salinity gradients in the Schlei fjord, Northern Germany, in Viking and medieval times. *Journal of Archaeological Science,* 36(10): 2125-2144.

Grupe, G., Hummel, S. (1991) Trace element studies on experimentally cremated bone. I. Alteration of the chemical composition at high temperatures. *Journal of Archaeological Science,* 18: 177-186.

Grupe, G., Klaut, D., Mauder, M., Kröger, P., Lang, A., Mayr, C., Söllner, F. (2018) Multi-isotope provenancing of archaeological skeletons including cremations in a reference area of the European Alps. *Rapid Communications in Mass Spectrometry,* 32:1711-1727.

Gustafson, G. (1950) Age determination on teeth. *Journal of the American Dental Association,* 41: 45-54.

Hakenbeck, S. (2013) Seriation and correspondence analysis. In C. Hills, S. Lucy (Eds.) *Spong Hill Part IX: chronology and synthesis.* McDonald Institute for Archaeological Research, Cambridge.

Hamerow, H., Hinton, D. A., Crawford, S. (2011) Preface. In H. Hamerow, D. A. Hinton, S. Crawford (eds.) *The Oxford Handbook of Anglo-Saxon Archaeology,* Oxford University Press, Oxford. pp. xxi-xxv.

Hannah, E. L., McLaughlin, T. R., Keaveney, E. M., Hakenbeck, S. E. (2018) Anglo-Saxon diet in the conversion period: a comparative isotopic study using carbon and nitrogen. *Journal of Archaeological Science: Reports,* 19: 24-34.

Hanson, M., Cain, C. R. (2007) Examining histology to identify burned bone. *Journal of Archaeological Science,* 34: 1902-1913.

Harbeck, M., Schleuder, R., Schneider, J., Weichmann, I., Schmahl, W. W., Grupe, G. (2011) Research potential and limitations of trace analyses of cremated remains. *Forensic Science International,* 204: 191-200.

Hare, P. E., Fogel, M. L., Stafford Jr., T. W., Mitchell, A. D., Hoering, T. C. (1991) The isotopic composition of carbon and nitrogen in individual amino acids isolated from modern and fossil proteins. *Journal of Archaeological Science,* 18: 277-292.

Härke, H. (1990) "Warrior Graves?" The background of the Anglo-Saxon Weapon burial rite. *Past & Present*, 126: 22-43.

Härke, H. (1992) Changing symbols in a changing society: the Anglo-Saxon weapon burial rite in the seventh century. In M. O. H. Carver (ed.) *The Age of Sutton Hoo: the Seventh Century in North-west Europe,* Boydell, Woodbridge. Pp. 149-165.

Härke, H. (2004) The Anglo-Saxon weapon burial rite: an interdisciplinary analysis. *Opus*, 3: 197-207.

Harland, J. (2017) "Race" in the trenches: Anglo-Saxons, ethnicity and the misuse of the medieval past. *The Public Medievalist.* Pp. 1-15. [Available from: https://www.publicmedievalist.com/race-in-the-trenches/]

Harrison, R. G., Katzenberg, M. A. (2003) Paleodiet studies using stable carbon isotopes from bone apatite and collagen: examples from Southern Ontario and San Nicolas Island, California. *Journal of Anthropological Archaeology,* 22: 227-244.

Hartman, G. (2011). Are elevated δ15N values in herbivores in hot and arid environments caused by diet or animal physiology? *Functional Ecology*, 25(1): 122-131. doi:10.1111/j.1365-2435.2010.01782.x

Hatch, M. D., Slack, C. R. (1966) Photosynthesis by sugar cane leaves: a new carboxylation reaction and the pathway of sugar formation. *Biochemical Journal,* 101(1): 103-111.

Hawkes, S. C., Wells, C. (1975) Crime and punishment in an Anglo-Saxon cemetery? *Antiquity,* 49: 118-122.

Heaney, S. (2000) *Beowulf: a new verse translation.* W. W. Norton and Company, New York.

Hedeager, L. (2000) Migration period Europe: the formation of a political mentality. In F. Theuws, J. L. Nelson (eds.) *Rituals and Power: From Late Antiquity to the Early Middle Ages,* Brill, Leiden. Pp. 15-57.

Hedges, R. E. M., Clement, J. G., Thomas, D. L., O'Connell, T. C. (2007) Collagen turnover in the adult femoral mid-shaft: modeled from anthropogenic radiocarbon tracer measurements. *American Journal of Physical Anthropology,* 133: 808-816.

Hedges, R. E. M., Reynard, L. M. (2007) Nitrogen isotopes and the trophic level of humans in archaeology. *Journal of Archaeological Science,* 34: 1240-1251.

Herrmann, B. (1970) Anthropologische Bearbeitung der Leichenbränden von Berlin-Rudow. *Ausgrabungen in Berlin,* 1:61–71.

Herrmann, B. (1973a) Möglichkeiten und Grenzen der Anthropologischen Bearbeitung von Leichen-bränden. *Mitteilungen der Berliner Gesellschaft für Anthropologie, Ethnologie, und Urgeschichte*, 2:53–55.

Herrmann, B. (1973b) Möglichkeiten histologischer Untersuchungen an Leichbränden. *Mitteilungen Berliner der Gesellschaft für Anthropologie, Ethnologie und Urgeshichte*, 2:164-167.

Herrmann, B. (1976) Neuere Ergebnisse zur Beurteilung menschlicher Brandknochen. *Zeitschrift für Rechtsmedizin,* 77:191–200.

Herrmann, B. (1977a) Anthropologische Bearbeitung der Leichenbrände vom Gräberfeld Lengerich-Wechte, Kreis Steinfurt. *Bodenalterümer Wesfalen,* 15:97-118.

Herrmann, B. (1977b) Über die Abhängigkeit der Schrumpfung vom Mineralgehalt bei experimentell verbranten Knochen. Anthropologischer Anzeiger, 36:7-12.

Herrmann, B. (1977c) On Histological Investigations of Cremated Human Remains. *Journal of Human Evolution,* 6:101–103.

Higham, N. J. (1992) *Rome, Britain and the Anglo-Saxons.* B. A. Seaby Ltd., London.

Higham, N. J. (1994) *The English conquest: Gildas and Britain in the fifth century.* Manchester University Press, Manchester.

Hills, C. (1980) Anglo-Saxon cremation cemeteries, with particular reference to Spong Hill, Norfolk. In P. Rahtz, T. Dickinson, L. Watts (eds.) *Anglo-Saxon Cemeteries 1979,* British Archaeological Reports, British Series 82, Oxford. pp. 197-207.

Hills, C., Lucy, S. (2013) *Spong Hill Part IX: Chronology and Synthesis*. McDonald Institute for Archaeological Research, Cambridge.

Hines, J. (1984) *The Scandinavian Character of England in the pre-Viking Period,* British Archaeological Reports, British Series (124), Oxford.

Hines, J., Bayliss, A. (eds.) (2013) *Anglo-Saxon Graves and Grave Goods of the 6th and 7th Centuries AD: A Chronological Framework,* Society for Medieval Archaeology, Monograph 33, London.

Hirst, S. M. (1985) *An Anglo-Saxon cemetery at Sewerby, East Yorkshire*, York University Archaeology Publications, York.

Hirst, S., Clark, D. (2010) *The Mucking Anglo-Saxon cemeteries.* York: Archaeological Data Service, accessed at https://doi.org/10.5284/1000141.

Hobson, K. A., Alisauskas, R. T., Clark, R. G. (1993) Stable-nitrogen isotope enrichment in avian tissues due to fasting and nutritional stress: implications for isotopis analyses of diet. *The Condor,* 95(2): 388-394.

Hodder, I. (1980) Social structure and cemeteries: a critical reappraisal. In P. Rahtz, T. Dickinson, L. Watts (eds.) *Anglo-Saxon Cemeteries 1979,* British Archaeological Reports, British Series (72), Oxford. pp. 161-169.

Hodder, I. (1985) Postprocessual Archaeology. *Advances in Archaeological Method and Theory,* 8: 1-26.

Hoering, T. (1955) Variations of nitrogen-15 abundance in naturally occurring substances. *Science,* 122(3182): 1233-1234.

Høilund Nielsen, K. (2009) Rituals to free the spirit – or what the cremation pyre told. In D. Sayer, H. Williams, eds. *Mortuary Practices and Social Identities in the Middle Ages: Essays in Burial Archaeology in Honour of Heinrich Härke.* University of Exter Press, Exeter. pp. 81-103.

Holck, P. (1986) Cremated bones: a medical-anthropological study of an archaeological material on cremation burials. *Anthropologiske skrifter Nr. 1,* Anatomisk Institutt-Universitetet i Oslo, Oslo.

Holden, J. L., Phakey, P. P., Clement, J. G. (1995) Scanning electron microscope observatuons of heat-treated human bone. *Forensic Science International* 74:29-45.

Hopkins III, J. B., Ferguson, J. M. (2012) Estimating the diets of animals using stable isotopes and a comprehensive Bayesian mixing model. *PloS one* 7(1): e28478.

Hsy, J., Orlemanski, J. (2017) Race and medieval studies: a partial bibliography. *Postmedieval* 8: 500–531. [Available from: https://doi.org/10.1057/s41280-017-0072-0]

Hughes, S. S., Millard, A. R., Chenery, C. A., Nowell, G., Pearson, D. G. (2018) Isotopic analysis of burials from the early Anglo-Saxon cemetery at Eastbourne, Sussex, UK. *Journal of Archaeological Science: Reports,* 19: 513-525.

Hughes, S. S., Millard, A. R., Lucy, S. J., Chenery, C. A., Evans, J. A., Nowell, G., Pearson, D. G. (2014) Anglo-Saxon origins investigated by isotopic analysis of burials from Berinsfield, Oxfordshire, UK. *Journal of Archaeological Science,* 42: 81-92.

Hull, B., O'Connell, T. C. (2011) Diet: recent evidence from analytical techniques. In H. Hamerow, D. A. Hinton, S. Crawford (eds.) *The Oxford Handbook of Anglo-Saxon Archaeology,* Oxford University Press, Oxford. pp. 667-687.

Hüls, C. M., Erlenkeuser, H., Nadeau, M.-J., Grootes, P. M., Andersen, N. (2010) Experimental study on the origin of cremated bone apatite carbon. *Radiocarbon,* 52(2-3): 587-599.

Hummel, S., Schutkowski, H., (1993) Approaches to the histological age determination of cremated human remains. *Histological Ancient Human Bone: Methods Diagnosis,* 1: 111-123.

Hunter, R. S., Harold, R. W. (1987) *The measurement of appearance*. John Wiley & Sons.

Irish, J., Potter, B. A., Reuther, J. D. (2015) An 11,500-year-old human cremation from Eastern Beringia (Central Alaska). In C. W. Schmidt, S. A. Symes, eds. *The Analysis of Burned Human Remains*. London: Elsevier, pp. 295-306.

Jacob, E., Querci, D., Caparros, M., Ruiz, C. B., Higham, T., Devièse, T. (2018) Nitrogen content variation in archaeological bone and its implications for stable isotope analysis and radiocarbon dating. *Journal of Archaeological Science,* 93: 68-73.

Jakob, B. (2004) *Prevalence and patterns of disease in early medieval populations: a comparison of skeletal samples from fifth to eighth century AD Britain and Southwestern Germany,* unpublished PhD thesis, Durham University.

Jim, S., Ambrose, S. H., Evershed, R. P. (2004) Stable carbon isotopic evidence for differences in the dietary origin of bone cholesterol, collagen and apatite: implications for their use in palaeodietary reconstruction. *Geochimica et Cosmochimica Acta,* 68(1): 61-72.

Johnston, L. B., Borzyskowski, M. (1998) Bladder dysfunction and neurological disability at presentation in closed spina bifida. *Archives of Disease in Childhood,* 19: 33-38.

Jørkov, M. L. S., Heinemeier, J., Lynnerup, N. (2007) Evaluating bone collagen extraction methods for stable isotope analysis in dietary studies. *Journal of Archaeological Science,* 34: 1824-1829.

Katzenberg, M. A. (2000) Stable isotope analysis: a tool for studying past diet, demography, and life history. In *Biological Anthropology of the Human Skeleton,* M. A. Katzenberg, S. R. Saunders, eds. New York: Wiley-Liss. pp. 305-327.

Katzenberg, M. A., Lovell, N. C. (1999) Stable isotope variation in pathological bone. *International Journal of Osteoarchaeology,* 9: 316-324.

Kim, D. (2017) Teaching medieval studies in a time of white supremacy. *In the Middle.* pp. 1-4. [Available from: https://www.inthemedievalmiddle.com/2017/08/teaching-medieval-studies-in-time-of.html]

Kim, J. K., Yarish, C., Hwang, E. K., Park, M., Kim, Y. (2017) Seaweed aquaculture: cultivation technologies, challenges and its ecosystem services. *Algae,* 32(1): 1-13.

Kinaston, R., Buckley, H., Valentin, F., Bedford, S., Spriggs, M., Hawkins, S., Herrscher, E. (2014) Lapita diet in remote Oceania: new stable isotope evidence from the 3000-year-old Teouma site, Efate Island, Vanuatu. *PLOS one,* 9(3): 1-18.

King, A. S., Birge, R. T. (1929) An isotope of carbon, mass 13. *Nature,* 124(3117): 127.

King, C. L., Halcrow, S. E., Millard, A. R., Gröcke, D. R., Standen, V. G., Portilla, M., Arriaza, B. T. (2017) Let's talk about stress, baby! Infant-feeding practices and stress in the ancient Atacama desert, Northern Chile. *American Journal of Physical Anthropology,* 166: 139-155.

King, C. L., Millard, A. R., Gröcke, D. R., Standen, V. G., Arriaza, B. T., Halcrow, S. E. (2017) A comparison of using bulk and incremental isotope analyses to establish weaning practices in the past. *Star: Science & Technology of Archaeological Research,* 3(1): 126-134.

King, C. L., Tayles, N., Gordon, K. C. (2011) Re-examining the chemical evaluation of diagenesis in human bone apatite. *Journal of Archaeological Science,* 38: 2222-2230.

King, R., Barber, A., Timby, J. (1996) Excavations at West Lane, Kemble: an Iron-Age, Roman and Saxon burial site and a medieval building. *Transactions of the Bristol and Gloucestershire Archaeological Society,* 114: 15-54.

Kinsley, A. G. (1989) *The Anglo-Saxon cemetery at Millgate, Newark-on-Trent, Nottinghamshire: excavations between 1958-1978.* University of Nottigham, Department of Classics and Archaeological Studies, Nottingham.

Klingle, D. (2012) *The Use of Skeletal Evidence to Understand the Transition from Roman to Anglo-Saxon Cambridgeshire and Bedfordshire.* British Archaeological Reports, British Series 569, Archaeopress, Oxford.

Knüsel, C., Ripley, K. (2000) The *Berdache* or man/woman in Anglo-Saxon England and early medieval Europe. In W. O. Frazer, A. Tyrell (eds.) *Social Identity in Early Medieval Britain,* Leicester University Press, London. Pp. 157-191.

Kontopoulos, I., Nystrom, P., White, L. (2016) Experimental taphonomy: post-mortem microstructural modifications in *Sus scrofa domesticus* bone. *Forensic Science International,* 266: 320-328.

Konotopoulos, I., Presslee, S., Penkman, K., Collins, M. J. (2018) Preparation of bone powder for FTIR-ATR analysis: the particle size effect. *Vibrational Spectroscopy,* 99: 167-177.

Koon, H. E. C., Nicholson, R. A., Collins, M. J. (2003) A practical approach to the identification of low temperature heated bone using TEM. *Journal of Archaeological Science* 30: 1393-1399.

Koon, H. E. C., O'Connor, T. P., Collins, M. J. (2010) Sorting the butchered from the boiled. *Journal of Archaeological Science,* 37: 62-69.

Krogman, W. M. (1943) Role of the physical anthropologist in the identification of human skeletal remains. Part I. *FBI Law Enforcement Bulletin*. 12(4): 17-40.

Krouse, H. R., Coplen, T. B. (1997) Reporting of relative sulfur isotope-ratio data. *Pure and Applied Chemistry,* 69(2): 293-295.

Kujit, I., Quinn, C. P., Cooney, G. (2014) *Transformation by Fire: The Archaeology of Cremation in Cultural Context,* The University of Arizona Press, Tucson.

Kurila, L. (2015) Cremation as limitation? A paleodemographic inquiry into the accuracy of macroscopic analysis of cremated human remains based on an east Lithuanian sample. *Papers on Anthropology,* 14(2): 67-85.

Lange, M., Schutkowski, H., Hummel, S., Herrmann, S. (1987) *A bibliography on cremation*, PACT, 19, Council of Europe, Strasbourg.

Lanting, J. N., Aerts-Bijma, A. T., van der Plicht, J. (2001) Dating of cremated bones. *Radiocarbon,* 43(2A): 249-254.

Lavachery, P. (2001) The Holocene archaeological sequence of Shum Laka Rock Shelter (Grassfields, Western Cameroon). *African Archaeological Review,* 18(4): 213-247.

Leahy, K. (1993) The Anglo-Saxon Settlement of Lindsey. In *Pre-Viking Lindsey,* A. Vince, ed. Lincoln: City of Lincoln Archaeology Unit, pp. 29-44.

Leahy, K. (2007) *'Interupting the Pots': the Excavation of Cleatham Anglo-Saxon Cemetery, North Lincolnshire.* CBA Research Report 155, Council for British Archaeology, York.

Lee, C. (2011) Disease. In H. Hamerow, D. A. Hinton, S. Crawford (eds.) *The Oxford Handbook of Anglo-Saxon Archaeology,* Oxford University Press, Oxford. pp. 704-723.

Leeds, E. T. (1913) *The Archaeology of Anglo-Saxon Settlements,* Clarendon Press, Oxford.

Leeds, E. T. (1923) A Saxon village near Sutton Courtenay, Berks, *Archaeologia,* 73: 147-192.

Lehn, C., Rossmann, A., Graw, M. (2015) Provenancing of unidentified corpses by stable isotope techniques – presentation of case studies. *Science and Justice,* 55:72-88.

Leslie, S., Winney, B., Hellenthal, G., Davison, D., Boumertit, A., Day, T., Hutnik, K., Royrvik, E. C., Cunliffe, B., Lawson, D. J., Falush, D., Freeman, C., Pirinen, M., Myers, S., Robinson, M., Donnelly, P., Bodmer, W. (2015) The fine-scale genetic structure of the British population. *Nature,* 519: 309-314.

Lethbridge, T. C. (1956) The Anglo-Saxon settlement in eastern England: a reassessment. In D. B. Harden (ed.) *Dark Age Britain – Studies presented to E. T. Leeds,* Methuen, London. Pp.112-122.

Lee-Thorp, J. A. (2008) On isotopes and old bones. *Archaeometry,* 50(6): 925-950.

Lee-Thorp, J. A., Sealy, J. C., van der Merwe, N. J. (1989) Stable carbon isotope ratio differences between bone collagen and bone apatite, and their relationship to diet. *Journal of Archaeological Science,* 16: 585-599.

Libby, W. F., Anderson, E. C., Arnold, J. R. (1949) Age determination by radiocarbon content: world-wide assay of natural radiocarbon. *Science,* 109(2827): 227-228.

Liden, K., Takahashi, C., Nelson, D. E. (1995) The effects of lipids in stable carbon isotope analysis and the effects of NaOH treatment on the composition of extracted bone collagen. *Journal of Archaeological Science,* 22: 321-326.

Lilliefors, H. W. (1967) On the Kolmogorov-Smirnov test for normality with mean and variance unknown. *Journal of the American Statistical Association,* 62 (318): 399-402.

Lisowski, F.P. (1955) The cremations from the Culdoich, Leys and Kinchyle sites, *Proceedings of the Society of Antiquaries of Scotland*, 89: 83-90.

Longin, R. (1971) New method of collagen extraction for radiocarbon dating. *Nature,* 230: 241-242.

Loveluck, C., Laing, L. (2011) Britons and Anglo-Saxons. In H. Hamerow, D. A. Hinton, S. Crawford (eds.) *The Oxford Handbook of Anglo-Saxon Archaeology,* Oxford University Press, Oxford. pp. 534-555.

Lucy, S. J. (1997) Housewives, warriors and slaves? Sex and gender in Anglo-Saxon burials. In J. Moore and E. Scott eds. *Invisible People and Processes: Writing Gender and Childhood into European Archaeology.* Leicester University Press, London. pp. 150-168.

Lucy, S. (2000) *The Anglo-Saxon Way of Death.* Sutton, Stroud.

Lucy, S. (2002) Burial practice in early medieval eastern England: constructing local identities, deconstructing ethnicity. In S. Lucy, A. Reynolds (eds.) *Burial in medieval England and Wales,* Society for Medieval Archaeology Monograph 17, Society for Medieval Archaeology, London. pp. 72-87.

Lucy, S. (2005) Ethnic and cultural identities. In M. Díaz-Andreu, S. Lucy, S. Babić, D. N. Edwards eds. *The Archaeology of Identity: approaches to gender, age, status, ethnicity and religion,* Routledge, London. Pp. 86-109.

Lucy, S., Newman, R., Dodwell, N., Hills, C., Dekker, M., O'Connell, T., Riddler, I., Rogers, P. W. (2009) The burial of a princess? The later seventh-century cemetery at Westfield Farm, Ely. *The Antiquaries Journal,* 89: 81-141.

Macko, S. A., Engel, M. H., Andrusevich, V., Lubec, G., O'Connell, T. C., Hedges, R. E. M. (1999) Documenting the diet in ancient human populations through stable isotope analysis of hair. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences,* 354(1379): 65-76.

Mahoney, P., Miszkiewicz, J. (2015) Formation times in thermally altered enamel. In C. W. Schmidt, S. A. Symes, eds. *The Analysis of Burned Human Remains*. London: Elsevier, pp. 355-363.

Marsh, H. (1970) *Dark Age Britain: some sources of history.* David and Charles Publishers Ltd., Newton Abbot.

Martiniano, R., Caffell, A., Holst, M., Hunter-Mann, K., Montgomery, J., Müldner, G., McLaughlin, R. L., Teasdale, M. D., van Rheenan, W., Veldink, J. H., van den Berg, L. H., Hardiman, O., Carroll, M., Roskams, S., Oxley, J., Morgan, C., Thomas, M. G., Barnes, I., McDonnell, C., Collins, M. J., Bradley, D. G. (2016) Genomic signals of migration and continuity in Britain before the Anglo-Saxons. *Nature Communications,* 7(1): 1-8.

Massesy Jr., F. J. (1951) The Kolmogorov-Smirnov test for goodness of fit. *Journal of the American Statistical Association,* 46(253): 68-78.

May, S. (2011) The effects of body mass on cremation weight. *Journal of Forensic Science,* 56(1): 3-9.

Mayne, P. M. (1990) The Identification of Precremation Trauma in Cremated Remains. Unpublished Master's thesis, University of Alberta, Edmonton.

Mayne Correia, P. M. (1997) Fire modification of bone: a review of the literature. In M. H. Sorg, W. D. Haglund, eds. *Forensic Taphonomy: The Postmortem Fate of Human Remains.* CRC Press, pp. 275-293.

Mays, S. A. (1997) Carbon stable isotope ratios in Mediaeval and later human skeletons from northern England. *Journal of Archaeological Science* 24: 561-567.

Mays, S. A. (2010) *Archaeology of Human Bones*, *2nd ed*. Abingdon: Routledge.

Mays, S., Beavan, N. (2012) An investigation of diet in early Anglo-Saxon England using carbon and nitrogen stable isotope analysis of human bone collagen. *Journal of Archaeological Science* 39: 867-874.

Mays, S., Elders, J., Humphrey, L., White, W., Marshall, P. (2013) Science and the dead: A guideline for the destructive sampling of archaeological human remains for scientific analysis. *English Heritage Publishing with the Advisory Panel on the Archaeology of Burials in England.*

McCutcheon, P. (1992) Burned archaeological bone. In J. K. Stein (ed.) *Deciphering a Shell Midden,* Academic Press, San Diego, California. pp. 347-368.

McKinley, J. I. (1989) Cremations: expectations, methodologies and realities. In C. A. Roberts, F. Lee and J. Bintliff, eds. *Burial Archaeology: Current Research, Methods and Developments.* Oxford: British Archaeological Reports (211), pp. 65-76.

McKinley, J. I. (1993a) Cremated Bone, In J. Timby, Sancton I Anglo-Saxon Cemetery Excavations Carried Out Between 1976 and 1980*, Archaeological Journal,* 150: 287-316.

McKinley, J. I. (1993b) Bone fragment size and weights of bone from modern British cremations and the implications for the interpretation of archaeological cremations. *International Journal of Osteoarchaeology,* 3: 283-287.

McKinley, J. I. (1994a) *The Anglo-Saxon Cemetery at Spong Hill, North Elmham. Part VII: the Cremations*. East Anglian Archaeology Report No. 69, Norfolk Museums Service, Dereham.

McKinley, J. I. (1994b) A pyre and grave goods in British cremation burials; have we missed something? *Antiquity,* 68(258): 132-134.

McKinley, J. I. (1994c) Bone fragment size in British cremation burials and its implications for pyre technology and ritual. *Journal of Archaeological Science,* 21: 339-342.

McKinley, J. I. (1997) Bronze Age 'barrows' and funerary rites and rituals of cremation. *Proceedings of the Prehistoric Society,* 63: 129-145.

McKinley, J. I. (2000) The analysis of cremated bone. In M. Cox, S. Mays, eds. *Human Osteology*. Cambridge University Press, Cambridge. pp. 403-421.

McKinley, J. I. (2004) The human remains and aspects of pyre technology and cremation rituals. In H. E. M. Cool (ed.) *The Roman Cemetery at Brougham Cumbria: Excavations 1966-1967,* Britannia Monograph 21, Society for the Promotion of Roman Studies, London. pp. 283-309.

McKinley, J. I. (2007) Human bone. In J. Timby, R. Brown, E. Biddulph, A. Hardy, A. Powell (eds.) *A Larger Slice of Rural Essex,* Oxford Wessex Archaeology, Oxford/Salisbury. pp. 343-360.

McKinley, J. I. (2009) Cremation ... the cheap option. In R. Gowland, C. Knusel (eds.) *Social Archaeology of Funerary Remains (Volume One),* Oxbow Books, Oxford: 81-88.

McKinley, J. I. (2013) Cremation. In L. N. Stutz, S. Tarlow (eds.) *The Oxford Handbook of the Archaeology of Death and Burial,* Oxford University Press, Oxford. pp. 1-29.

McKinley, J. I. (2015) In the heat of the pyre. In C. W. Schmidt, S. A. Symes, eds. *The Analysis of Burned Human Remains*. London: Elsevier, pp. 181-202.

McKinley, J. I., Bond, J. (1993) Summary Discussion. In J. Timby, Sancton I Anglo-Saxon Cemetery Excavations Carried Out Between 1976 and 1980*, Archaeological Journal,* 150: 308-309.

McKinley, J. I., Bond, J. M. (2001) Cremated bone. In D. R. Brothwell, A. M. Pollard, eds. *Handbook of Archaeological Sciences.* Chichester: John Wiley and Sons Ltd. pp. 281-292.

Meaney, A. (1964) *A Gazetteer of Early Anglo-Saxon Burial Sites,* Allen & Unwin, London.

Mekota, A-M., Grupe, G., Ufer, S., Cuntz, U. (2006) Serial analysis of stable nitrogen and carbon isotopes in hair: monitoring starvation and recovery phases of patients suffering from anorexia nervosa. *Rapid Communications in Mass Spectrometry,* 20:1604-1610.

Merrick, H. V., Monaghan, M. C. (1984) The date of the cremated burials at Njoro River Cave. *Azania: Archaeological Research in Africa,* 19(1): 7-11.

Mkukuma, L. D., Skakle, J. M. S., Gibson, I. R., Imrie, C. T., Aspden, R. M., Hukins, D. W. L. (2004) Effect of the proportion of organic material in bone on thermal decomposition of bone mineral: an investigation of a variety of bones from different species using thermogravimetric analysis coupled to mass spectrometry, high-temperature X-ray diffraction, and Fourier Transform Infrared Spectroscopy. *Calcified Tissue International* 75(4): 321-328.

Moffat, L. (2011) Food plants on archaeological sites: the nature of the archaeological record. In H. Hamerow, D. A. Hinton, S. Crawford (eds.) *The Oxford Handbook of Anglo-Saxon Archaeology,* Oxford University Press, Oxford. pp. 346-360.

Montgomery, J. (2002) *Lead and Strontium Isotope Compositions of Human Dental Tissues as an Indicator of Ancient Exposure and Population Dynamics,* unpublished PhD thesis, University of Bradford.

Montgomery, J., Budd, P., Evans, J. (2000) Reconstructing the lifetime movements of ancient people: a Neolithic case study from southern England. *European Journal of Archaeology,* 3(3): 370-385.

Montgomery, J., Evans, J. A. (2006) Immigrants on the Isle of Lewis: combining traditional funerary and modern isotope evidence to investigate social differentiation, migration and dietary change in the Outer Hebrides of Scotland. In R. Gowland and C. Knusel, eds. *The Social Archaeology of Funerary Remains.* Oxford: Oxbow Books, pp. 122-142.

Montgomery, J., Evans, J., Chenery, C. (2006) Strontium and Oxygen Analysis of burials from Wasperton, Warwickshire. In M. Carver, ed. *Wasperton Anglo-Saxon Cemetery,* Archaeology Data Service. Pp. 1-22. Available from: https://archaeologydataservice.ac.uk/archiveDS/archiveDownload?t=arch-810-1/dissemination/pdf/Archive_Montgomery_isotopes_of_O_and_Sr.pdf

Montgomery, J., Evans, J. A., Powlesland, D. Roberts, C. A. (2005) Continuity or colonization in Anglo-Saxon England? Isotope evidence for mobility, subsistence practice and status at West Heslerton, *American Journal of Physical Anthropology,* 126: 123-138.

Moore, K. M., Murray, M. L., Schoeninger, M. J. (1989) Dietary reconstruction from bones treated with preservatives. *Journal of Archaeological Science,* 16: 437-446.

Morris, M. D., Finney, W. F. (2004) Recent developments in Raman and infrared spectroscopy and imaging of bone tissue. *Spectroscopy,* 18: 155-159.

Mughal, M. R. (1990) The decline of the Indus civilization and the Late Harappan period in the Indus Valley. *Lahore Museum Bulletin,* 3(2): 1-25.

Mui, S. (2018) *Dead Body Language: Deciphering Corpse Positions in Early Anglo-Saxon England,* unpublished PhD thesis, Durham University.

Müldner, G., Richards, M. P. (2005) Fast or feast: reconstructing diet in later medieval England by stable isotope analysis. *Journal of Archaeological Science,* 32: 39-48.

Müldner, G., Richards, M. P. (2007) Stable isotope evidence for 1500 years of human diet at the city of York, UK. *American Journal of Physical Anthropology,* 133: 682-697.

Munro, L. E., Longstaffe, F. J., White, C. D. (2007) Burning and boiling of modern deer bone: effects on crystallinity and oxygen isotope composition of bioapatite phosphate. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 249: 90-102.

Munsell Soil Colour Charts (1994) Macbeth Division of Kollmorgen Instruments Corporation, New Windsor, New York.

Murphy, B. P., Bowman, D. M. J. S. (2006) Kangaroo metabolism does not cause the relationship between bone collagen $\delta^{15}N$ and water availability. *Functional Ecology,* 20(6): 1062-1069.

Myers, J. N. L. (1969) *Anglo-Saxon Pottery and the Settlement of England,* Clarendon Press, London.

Myers, J. N. L. (1977) *A Corpus of Pagan Anglo-Saxon Pottery,* Clarendon Press, London.

Nachim, N. (2008) The Mann-Whitney U: a tests for assessing whether two independent samples come from the same distribution. *Tutorials in Quantitative Methods for Psychology,* 4(1): 13-20.

Nardoto, G. B., Silva, S., Kendall, C., Ehleringer, J. R., Chesson, L. A., Ferraz, E. S. B., Moreira, M. Z., Ometto, J. P. H. B., Martinelli, L. A. (2006) Geographical patterns in human diet derived from stable isotope analysis of fingernails. *American Journal of Physical Anthropology*, 131: 137-146.

Natural England (2015) National Character Area Profile: 43. Lincolnshire Wolds. *Natural England,* [Available at: http://publications.naturalengland.org.uk/publication/9965009] [Accessed: 12/07/2020]

Naudé, S. M. (1929) An isotope of nitrogen, mass 15. *Physical Review,* 34(11): 1498.

Nehlich, O. (2015) The application of sulphur isotope analyses in archaeological research: a review. *Earth-Science Reviews.* 142: 1-17.

Nehlich, O., Barrett, J. H., Richards, M. P. (2013) Spatial variability in sulphur isotope values of archaeological and modern cod (*Gadus morhua*). *Rapid Communications in Mass Spectrometry,* 27: 2255-2262.

Nehlich, O., Borić, D., Stefanović, S., Richards, M. P. (2010) Sulphur isotope evidence for freshwater fish consumption: a case study from the Danube Gorges, SE Europe. *Journal of Archaeological Science,* 37: 1131-1139.

Nehlich, O., Fuller, B. T., Jay, M., Mora, A., Nicholson, R. A., Smith C. I., Richards, M. P. (2011) Application of sulphur isotope ratios to examine weaning patterns and freshwater fish consumption in Roman Oxfordshire, UK. *Geochimica et Cosmochimica Acta,* 75: 4963-4977.

Nehlich, O., Fuller, B. T., Márquez-Grant, N., Richards, M. P. (2012) Investigation of Diachronic dietary patterns on the islands of Ibiza and Formentera, Spain: evidence from sulphur stable isotope ratio analysis. *American Journal of Physical Anthropology,* 149: 115-124.

Nehlich, O., Oelze, V. M., Jay, M., Conrad, M., Stäuble, H., Wolf-Rüdiger, T., Richards, M. P. (2014) Sulphur isotope ratios of multi-period archaeological skeletal remains from central Germany: a dietary and mobility study. *Anthropologie (1962-),* 52(1): 15-34.

Nehlich, O., Richards, M. P. (2009) Establishing collagen quality criteria for sulphur isotope analysis of archaeological bone collagen. *Archaeological and Anthropological Sciences,* 1(1): 59-75.

Nelson, B. K., DeNiro, M. J., Schoeninger, M. J., De Paolo, D. J. (1986) Effects of diagenesis on strontium, carbon, nitrogen and oxygen concentration and isotopic composition of bone. *Geochimica et Cosmochimica Acta,* 50: 1941-1949.

Nelson, R. (1992) A microscopic comparison of fresh and burned bone. *Journal of Forensic Science,* 37: 1055-1060.

Neuberger, F. M., Jopp, E., Graw, M., Püschel, K., Grupe, G. (2013) Signs of malnutrition and starvation – Reconstruction of nutritional life histories by serial isotopic analyses of hair. *Forensic Science International,* 226: 22-32.

Nicholson, R. A. (1993) A morphological investigation of burnt animal bone and an evaluation of its utility in archaeology. *Journal of Archaeological Science,* 20: 411-428.

Nicholson, R. A. (1996) Bone degradation, burial medium and species representation: debunking the myths, an experiment-based approach. *Journal of Archaeological Science,* 23: 513-533.

Nier, A. O. (1938) The isotopic constitution of calcium, titanium, sulphur and argon. *Physical Review,* 53(4): 282.

Nier, A. O., Gulbransen, E. A. (1939) Variations in the relative abundance of the carbon isotopes. *Journal of the American Chemical Society,* 61(3): 697-698.

O'Connor, T. (2011) Animal Husbandry. In H. Hamerow, D. A. Hinton, S. Crawford (eds.) *The Oxford Handbook of Anglo-Saxon Archaeology,* Oxford University Press, Oxford. pp. 361-376.

O'Connell, T. C., Hedges, R. E. M. (1999) Investigations into the effect of diet on modern human hair isotopic values. *American Journal of Physical Anthropology,* 108: 409-425.

O'Connell, T. C., Kneale, C. J., Tasevska, N., Kuhnle, G. G. C. (2012). The diet-body offset in human nitrogen isotopic values: A controlled dietary study. *American Journal of Physical Anthropology,* 149(3): 426-434. doi:10.1002/ajpa.22140

Ohio History Central (2021a) Adena Culture.
https://ohiohistorycentral.org/w/Adena_Culture
[Accessed: 16/08/2021]

Ohio History Central (2021b) Hopewell Culture. https://ohiohistorycentral.org/w/Hopewell_Culture?rec=1283 [Accessed: 16/08/2021]

Olsen, J., Heinemeier, J., Bennike, P., Krause, C., Hornstrup, K. M., Thrane, H. (2008) Characterisation and blind testing of radiocarbon dating of cremated bone. *Journal of Archeological Science,* 35: 791-800.

Pader, E. J. (1980) Material symbolism and social relations in mortuary studies. In P. Rahtz, T. Dickinson, L. Watts (eds.) *Anglo-Saxon Cemeteries 1979: The Fourth Anglo-Saxon Symposium at Oxford,* British Archaeological Reports, British Series (82), Archaeopress, Oxford. pp. 143-159.

Parker, P. L. (1963) The biogeochemistry of the stable isotopes of carbon in a marine bay. *Geochimica et Cosmochimica Acta,* 28: 1155-1164.

Paschalis, E. P., Verdelis, K., Doty, S. B., Boskey, A. L., Mendelsohn, R. Yamauchi, M. (2001) Spectroscopic characterization of collagen cross-links in bone. *Journal of Bone and Mineral Research,* 16(10):1821-1828.

Pate, F. D. (1994) Bone chemistry and paleodiet. *Journal of Archaeological Method and Theory,* 1(2): 161-209.

Pearce, J. (2008) Burial evidence from Roman Britain: the un-numbered dead. In J Scheid (ed.) *Pour une archéologie due rite. Nouvelles perspectives de l'archéologie funéraire,* Rome, L'Ecole Francaise de Rome. pp. 1000-1014.

Pejović-Milić, A., Stronach, I. M., Gyorffy, J., Webber, C. E., Chettle, D. R. (2004) Quantification of bone strontium levels in humans by *in vivo* x-ray fluorescence. *Medical Physics,* 31(3): 528-538.

Perry, G. J. (2013) *United in Death: the Pre-Burial Origins of Anglo-Saxon Cremation Urns,* unpublished PhD thesis, University of Sheffield.

Pestell, T. (2001) Catalogue of inhumations, cremations and other features. In W. Filmer-Sankey, T. Pestell eds. *Snape Anglo-Saxon Cemetery: Excavations and Surveys 1824-1992.* East Anglian Archaeology Report No. 95, Environment and Transport Suffolk County Council, Ipswich.

Petersen, F. (1972) Traditions of multiple burial in Neolithic and Bronze Age England. *Archaeological Journal,* 129: 22-55.

Peterson, B. J., Fry, B. (1987) Stable isotopes in ecosystem studies. *Annual Review of Ecology and Systematics,* 18(1): 293-320.

Peterson, B. J., Howarth, R. W., Garritt, R. H. (1985) Multiple stable isotopes used to trace the flow of organic matter in estuarine food webs. *Science,* 227(4692): 1361-1363.

Petzke, K. J., Feist, T., Fleig, W. E., Metges, C. C. (2006) Nitrogen isotopic composition in hair protein is different in liver cirrhotic patients. *Rapid Communications in Mass Spectrometry,* 20: 2973-2978.

Piga, G., Gonçalves, D., Thompson, T. J. U., Brunetti, A., Malgosa, A., Enzo, S. (2016) Understanding the crystallinity indices behaviour of burned bones and teeth by ATR-IR and XRD in the presence of bioapatite mixed with other phosphate and carbonate phases. *International Journal of Spectroscopy,* 2016(4810149): 1-9.

Piga, G., Malgosa, A., Thompson, T. J. U. (2008) A new calibration of the XRD technique for the study of archaeological burned human remains. *Journal of Archaeological Science,* 35: 2171-2178.

Pijoan, C., Mansilla, J., Leboreiro, I., Lara, V. H., Bosch, P. (2007) Thermal alterations in archaeological bones. *Archaeometry,* 4: 713-727.

Powlesland, D. (1998) The West Heslerton assessment. *Internet Archaeology,* 5. http://doi.org/10.11141/ia.5.4

Privat, K., O'Connell, T. C., Hedges, R. E. M., (2007) The distinction between freshwater- and terrestrial-based diets: methodological concerns and archaeological applications of sulphur stable isotope analysis. *Journal of Archaeological Science* 34:1197-1204.

Privat, K. L., O'Connell, T. C., Richards, M. P. (2002) Stable isotope analysis of human and faunal remains from the Anglo-Saxon Cemetery at Berinsfield, Oxfordshire: dietary and social implications. *Journal of Archaeological Science,* 29: 779-790.

Quinn, C. P., Kujit, I., Cooney, G. (2014) Introduction: contextualising cremations. In I. Kujit, C. P. Quinn, G. Cooney (Eds.) *Transformation by Fire: The Archaeology of Cremation in Cultural Context,* The University of Arizona Press, Tucson. pp. 3-21.

Quinn, R. L. (2019) Isotopic equifinality and rethinking the diet of *Australopithecus anamensis*. *American Journal of Physical Anthropology,* 169: 403-421.

Quintiere (1998) *Principles of Fire Behavior*. International Publishing Company, Albany.

Rahtz, P.(2001) West Heslerton Seminar. *Antiquity,* 75: 305-308.

Rauch, E., Rummel, S., Lehn, C., Büttner, A. (2007) Origin assignment of unidentified corpses by use of stable isotope ratios of light (bio-) and heavy (geo-) elements – a case report. *Forensic Science International,* 168: 215-218.

Ravn, M. (2000) The use of symbols in burials in Migration Age Europe. A theoretical and methodological approach. In D. Olausson, H. Vankilde eds. *Form-Function-Context: Material culture studies in Scandinavian archaeology,* Acta Archaeologica Lundensia, Series 8(31), Lund. Pp. 275-296.

Redfern, R., Roberts, C. A. (2005) Health in Romano-British urban communities: reflections from the cemeteries. In *Fertile Ground: Papers in Honour of Susan Limbrey,* Oxbow Books, Oxford. pp. 115-129.

Rees, C. E., Holt, B. D. (1991) The isotopic analysis of sulphur and oxygen. In H.R. Krouse, V. A. Grinenko (Eds.) *Stable isotopes: Natural and Anthropogenic sulphur in the environment*. John Wiley and Sons, Chichester. pp. 43-64.

Regan, L. A. (2006) *Isotopic Determination of Region of Origin in Modern Peoples: Applications for Identification of U.S. War-Dead from the Vietnam Conflict,* Unpublished PhD Thesis, University of Florida.

Reissland, N., Millard, A. R., Wood, R., Ustun, B., McFaul, C., Froggatt, S., Einbeck, J. (2020) Prenatal effects of maternal nutritional stress and mental health on the fetal movement profile. *Archives of Gynecology and Obstetrics,* 302(1):65-75. doi:10.1007/s00404-020-05571-w

Reitsema, L. J. (2013) Beyond diet reconstruction: stable isotope applications to human physiology, health and nutrition. *American Journal of Human Biology,* 25: 445-456.

Rey, C., Combes, C., Drouet, C. Glimcher, M. J. (2009) Bone mineral: update on chemical composition and structure. *Osteoporosis International,* 20(6): 1013-1021.

Reynard, L. M., Hedges, R. E. M. (2008) Stable hydrogen isotopes of bone collagen in palaeodietary and palaeoenvironmental reconstruction. *Journal of Archaeological Science,* 35: 1934-1942.

Richards, J. D. (1987) *The Significance and Form of Anglo-Saxon Cremation Urns.* British Archaeological Reports, British Series (116), Archaeopress, Oxford

Richards, J. D. (1995) An archaeology of Anglo-Saxon England. In G. Ausenda (ed.) *After Empire: Towards an Ethnology of Europe's Barbarians*, Boydell Press, New York. pp. 51-66.

Richards, M., Capelli, C., Wilson, J. F. (2008) Genetics and the origins of the British population. In *Encyclopedia of Life Sciences,* John Wiley & Sons, Chichester.

Richards, M. P., Fuller, B. T., Hedges, R. E. M. (2001) Sulphur isotopic variation in ancient bone collagen from Europe: implications for human palaeodiet, residence mobility, and modern pollutant studies. *Earth and Planetary Science Letters,* 191: 185-190.

Richards, M. P., Fuller, B. T., Sponheimer, M., Robinson, T., Ayliffe, L. (2003) Sulphur isotopes in palaeodietary studies: a review and results from a controlled feeding experiment. *International Journal of Osteoarchaeology,* 13: 37-45.

Richards, M. P., Montgomery, J. (2012) Isotope analysis and paleopathology: a short review and future developments. In *The Global History of Paleopathology: Pioneers and Prospects,* J. Buikstra, C., Roberts, eds. Oxford: Oxford University Press, pp. 718-731.

Richter, J. (1986) Experimental study of heat induced morphological changes in fish bone collagen. *Journal of Archaeological Science,* 13: 477-481.

Roberts, C. A. (2009) *Human Remains in Archaeology: a handbook,* Council for British Archaeology, York.

Roberts, C. A., Cox, M. (2003) *Health and Disease in Britain: from prehistory to the present day,* Sutton Publishing, Stroud, Gloucestershire.

Roberts, C. A., Manchester, K. (2007) *The Archaeology of Disease,* Cornell University Press, Ithaca, New York.

Rogers, K. D., Daniels, P. (2002) An X-ray diffractions study of the effects of heat treatment on bone mineral microstructure. *Biomaterials*, 23: 2577-2585.

Russell, A. D. (1993) Fabric report on pottery from the Illington cemetery. In A. Davidson, B. Green, B. Milligan *Illington: a study of a Breckland Parish and its Anglo-Saxon cemetery*. East Anglian Archaeology Report No. 63*,* Norfolk Museums Service, Dereham: 107-111.

Salah, I., Parkin, I. P., Allan, E. (2021) Copper as an antimicrobial agent: recent advances. *Royal Society of Chemistry Advances,* 11(30): 18179-18186.

Sandholzer, M. (2015) Influence of heating regimes on dimensions and colorimetric changes of teeth. In C. W. Schmidt, S. A. Symes, eds. *The Analysis of Burned Human Remains, Second Edition*. London: Elsevier, pp.365-379.

Sawyer, P. H. (1998) *Anglo-Saxon Lincolnshire.* Lincoln: History of Lincolnshire Committee.

Sayer, D. (2010) Death and the family: developing generational chronologies. *Journal of Social Archaeology,* 10(1): 59-91.

Sayer, D., Weinhold,M. (2013) A GIS-investigation of four early Anglo-Saxon cemeteries: Ripley's *K*-function analysis of spatial groupings amongst graves. *Social Science Computer Review,* 31(1): 71-89.

Schafer, A. (2001) The colour of the human skull. *Forensic Science International,* 117: 53-56.

Schiffels, S., Haak, W., Paajanen, P., Llamas, B., Popescu, E., Loe, L., Clarke, R., Lyons, A., Mortimer, R., Sayer, D., Tyler-Smith, C., Cooper, A., Durbin, R. (2016) Iron Age and Anglo-Saxon genomes from East England reveal British migration history. *Nature Communications,* 7(10408): 1-9. doi: 10.1038/ncomms10408.

Schmidt, C. W. (2015) Burned human teeth. In C. W. Schmidt, S. A. Symes, eds. *The Analysis of Burned Human Remains*. London: Elsevier, pp. 61-81.

Schmidt, C. W., Oakley, E., D'Anastasio, R., Brower, R., Remy, A., Viciano, J. (2015) Herculaneum. In C. W. Schmidt, S. A. Symes, eds. *The Analysis of Burned Human Remains*, Second Edition. London: Elsevier, pp. 149-161.

Schmidt, C. W., Symes, S. A. (2015) *The Analysis of Burned Human Remains, 2nd edition.* London: Elsevier.

Schoeninger, M. J., DeNiro, M. J. (1984) Nitrogen and carbon isotopic composition of bone collagen from marine and terrestrial animals. *Geochimica et Cosmochimica Acta,* 48: 625-639.

Schoeninger, M. J., DeNiro, M. J., Tauber, H. (1983) Stable nitrogen isotope ratios of bone collagen reflect marine and terrestrial components of prehistoric human diet. *Science,* 220(4604): 1381-1383.

Schoeninger, M. J., Moore, K. (1992) Bone stable isotope studies in archaeology. *Journal of World Prehistory,* 6(2): 247-296.

Schurr, M. R., Hayes, R. G. (2008) Stable carbon- and nitrogen-isotope ratios and electron spin resonance (ESR) *g*-s of charred bones: changes with heating and a critical evaluation of the utility of *g*-values for reconstructing thermal history and original isotope ratios. *Journal of Archaeological Science,* 35: 2017-2031.

Schurr, M. R., Hayes, R. G., Cook, D. C. (2008) Thermally induced changes in the stable carbon and nitrogen isotope ratios of charred bones. In *The Analysis of Burned Human Remains,* C. W. Schmidt, S. A. Symes, eds. London: Elsevier, pp. 95-108.

Schwarcz, H. P. (1991) Some theoretical aspects of isotopic paleodiet studies. *Journal of Archaeological Science,* 18: 261-275.

Scull, C., Bayliss, A. (1999) Radiocarbon dating and Anglo-Saxon graves. In U. von Freeden, U. Kock, A. Wieczorek (eds.) *Wölker an Nord- und Ostsee und die Franken,* Rudolf Habelt, Bonn. Pp. 39-50.

Sealy, J. (2001) Body tissue chemistry and paleodiet. In *Handbook of Archaeological Sciences,* D. R. Brothwell, A. M. Pollard, eds. Chichester: John Wiley and Sons Ltd., pp. 269-280.

Sealy, J. C., van der Merwe, N. J., Lee-Thorp, J. A., Lanham, J. L. (1987) Nitrogen isotopic ecology in southern Africa: implications for environmental and dietary tracing. *Geochimica et Cosmochimica Acta,* 51: 2707-2717.

Seller, A. M. (1907) *Bede's Ecclesiastical History of England.* London: George Bell and Sons.

Sellstedt, H., Engstrand, L., Gejvall, N. G. (1966) New application of radiocarbon dating to collagen residue in bones. *Nature,* 212(5062): 572-574.

Shephard, J. (1979) The social identity of the individual in isolated barrows and barrow cemeteries in Anglo-Saxon England. In B. C. Burnham, J. Kingsbury (eds.) *Space, Hierarchy and Society. Interdisciplinary Studies in Social Area Analysis,* British Archaeological Reports, International Series (59), Oxford. pp. 47-79.

Shipman, P., Foster, G., Schoeninger, M. (1984) Burnt bones and teeth: an experimental study of color, morphology, crystal structure and shrinkage. *Journal of Archaeological Science* 11:307-325.

Silva, A. M., Crubézy, E., Cunha, E. (2009) Bone weight: new reference values based on a modern Portuguese identified skeletal collection. *International Journal of Osteoarchaeology,* 19: 628-641.

Smith, E., Dent, G. (2005) *Modern Raman Spectroscopy: A Practical Approach.* Chichester: John Wiley & Sons, Ltd.

Snoeck, C. (2014) *A Burning Question: Structural and Isotopic Studies of Cremated Bone in Archaeological Contexts*, unpublished PhD thesis, University of Oxford.

Snoeck, C., Lee-Thorp, J. A., Schulting, R. J. (2014) From bone to ash: compositional and structural changes in modern and archaeological bone. *Palaeogeography, palaeoclimatology, palaeoecology,* 416: 55-68.

Snoeck, C., Lee-Thorp, J., Schulting, R., de Jong, J., Debouge, W., Mattielli, N. (2015) Calcined bone provides a reliable substrate for strontium isotope ratios as shown by an enrichment experiment. *Rapid Communications in Mass Spectrometry,* 29: 107-114.

Snoeck, C., Pouncett, J., Claeys, P., Goderis, S., Mattielli, N., Parker Pearson, M., Willis, C., Zazzo, A., Lee-Thorp, J. A., Schulting, R. J. (2018) Strontium isotope analysis on cremated human remains from Stonehenge support links with west Wales. *Nature: Scientific Reports,* 8(10790): 1-8.

Snoeck, C., Schulting, R. J., Lee-Thorp, J. A., Lebon, M. (2016) Impact of heating conditions on the carbon and oxygen isotope composition of calcined bone. *Journal of Archaeological Science,* 665: 32-43.

Sofaer, J. (1997) Engendering children, engendering archaeology. In T. Insoll (ed.) *The Archaeology of Identities: a reader,* Routledge, New York.

Soilscapes (2020) http://www.landis.org.uk/soilscapes/ [Accessed: 10/07/2020]

Someda, H., Gakuhari, T., Akai, J., Araki, Y., Kodera, T., Tsumatori, G., Kobayashi, Y., Matsunaga, S., Ade, S., Hashimoto, M., Saito, M., Yoneda, M., Ishida, H. (2016) Trial application of oxygen and carbon isotope analysis in tooth enamel for identification of past-war victims for discriminating between Japanese and US soldiers. *Forensic Science International,* 261: 166e1-166e5.

Spence, T. F. (1968) The anatomical study of cremated fragments from archaeological sites. *Proceedings of the Prehistoric Society,* 33: 70-83.

Squires, K. E. (2011) *An Osteological Analysis and Social Investigation of the Cremation Rite at the Cemeteries of Elsham and Cleatham, North Lincolnshire,* unpublished PhD thesis, University of Sheffield.

Squires, K. E. (2012) Populating the pots: the demography of the early Anglo-Saxon cemeteries at Elsham and Cleatham, North Lincolnshire. *Archaeological Journal,* 169(1): 312-342.

Squires, K. E. (2013) Piecing together identity: a social investigation of early Anglo-Saxon cremation practices. *Archaeological Journal,* 170(1): 154-200.

Squires, K. E. (2015) The integration of microscopic techniques in cremation studies. In T. J. U. Thompson ed. *Archaeology of Cremation: burned human remains in funerary studies.* Oxford: Oxbow Books, pp. 151-172.

Squires, K. E. (2016) Neighbours and networks: funerary trends among cremation practicing groups in early medieval England and north-western Europe. In L. Keys, I. Riddler, J. Soulet eds. *The Evidence of Material Culture: Studies for Professor Vera Evison,* Monique Mergoil, Montagnac: 119-138.

Squires, K. E. (2017) Come rain or shine? The social implications of seasonality and weather on the cremation rite in early Anglo-Saxon England. In J. I. Cerezo-Román, A. Wessman, H. Williams (eds.) *Cremation and the Archaeoelogy of Death,* Oxford University Press, Oxford. pp. 250-265

Squires, K., Errickson, D., Márquez-Grant, N. (2019) *Ethical Approaches to Human Remains: a Global Challenge in Biioarchaeology and Forensic Anthropology.* Springer Nature, Cham, Switzerland.

Squires, K. E., Thompson, T. J. U., Islam, M., Chamberlain, A., (2011) The application of histomorphometry and Fourier Transform Infrared Spectroscopy to the analysis of early Anglo-Saxon burned bone. *Journal of Archaeological Science,* 38: 2399-2409.

Stead, I. M., Rigby, V. (1989) Verulamium: the King Harry Lane site. *English Heritage: Archaeological Report number 12,* Swindon, English Heritage.

Stenton, F. (1970) *Anglo-Saxon England 3rd Edition.* Oxford University Press, Oxford.

Stewart, N. A., Gerlach, R. F., Gowland, R. L., Gron, K. J., Montgomery, J. (2017) Sex determination of human remains from peptides in tooth enamel. *Proceedings of the National of Sciences of the United States of America,* 114: 13649-13654. http://doi.org/10.1073/pnas.1714926115

Stirland, A. (1989) Paget's disease (osteitis deformans): a classic case? *International Journal of Osteoarchaeology,* 1: 173-177.

Stoodley, N. (1999) *The spindle and the spear: a critical enquiry into the construction and meaning of the Anglo-Saxon burial rite.* British Archaeological Reports: British Series 288, Oxford.

Stoodley, N. (2000) From the cradle to the grave: age organization and the early Anglo-Saxon burial rite. *World Archaeology,* 31(3): 456-472.

Stoodley, N. (2011) Childhood to Old Age. In H. Hamerow, D. A. Hinton, S. Crawford (eds.) *The Oxford Handbook of Anglo-Saxon Archaeology,* Oxford University Press, Oxford. pp. 641-666.

Surovell, T. A., Stiner, M. C. (2001) Standardizing infra-red measures of bone mineral crystallinity: an experimental approach. *Journal of Archaeological Science.* 28: 633-642.

Sutherland, R. S., Mevorach, R. A., Baskin, L. S., Kogan, B. A. (1995) Spinal dysraphism in children: an overview and an approach to prevent complications. *Urology,* 46(3): 294-304.

Swanton, M. J. (1973) *The Spearheads of the Anglo-Saxon Settlements,* Royal Archaeological Institute, London.

Sykes, N. (2010) Deer, land, knives and halls: social change in early medieval England. *The Antiquaries Journal,* 90: 175-193.

Symes, S. A., Rainwater, C. W., Chapman, E. N., Gipson, D. R., Piper, A. L. (2015) Patterned thermal destruction in a forensic setting. In C. W. Schmidt, S. A. Symes, eds. *The Analysis of Burned Human Remains.* London: Elsevier, pp. 17-59.

Tafuri, M. A., Craig, O. E., Canci, A. (2009) Stable isotope evidence for the consumption of millet and other plants in Bronze Age Italy. *American Journal of Physical Anthropology,* 139: 146-153.

Taylor, R. E., Hare, P. E., White, T. D. (1995) Geochemical criteria for thermal alteration of bone. *Journal of Archaeological Science,* 22: 115-119.

Termine, J. D., Posner, A. S. (1966) Infra-red determination of the percentage of crystallinity in apatitic calcium phosphates. *Nature,* 211: 268-270.

Theuws, F. (2000) Introduction: rituals in transforming societies. In F. Theuws, J. L. Nelson (eds.) *Rituals and Power: From Late Antiquity to the Early Middle Ages,* Brill, Leiden. pp. 1-14.

Thode, H. G. (1991) Sulphur Isotopes in Nature and the Environment: an Overview. In *Stable Isotopes in the Assessment of Natural and Anthropogenic Sulphur in the Environment,* H. R. Krouse, V. A. Grinenko, eds. John Wiley & Sons, Ltd. p. 1-26.

Thode, H. G., Monster, J., Dunford, H. B. (1961) Sulphur isotope geochemistry. *Geochimica et Cosmochimica Acta,* 25: 150-174.

Thomas, M. G., Stumpf, M. P. H., Härke, H. (2006) Evidence for an apartheid-like social structure in early Anglo-Saxon England. *Proceedings of the Royal Society B: Biological Sciences,* 273(1601): 2651-2657.

Thompson, E. A. (1979) Gildas and the History of Britain, *Britannia,* 10: 203-226.

Thompson, T. J. U. (2004) Recent advances in the study of burned bone and their implications for forensic anthropology. *Forensic Science International.* 146S: S203-S205.

Thompson, T. J. U. (2005) Heat-induced dimensional changes in bone and their consequences for forensic anthropology. *Journal of Forensic Sciences.* 50(5): 1-8.

Thompson, T. J. U. (2015a) Fire and the body: fire and the people. In T. Thompson, ed. *Archaeology of Cremation: burned human remains in funerary studies.* Oxford: Oxbow Books, pp. 1-18.

Thompson, T. J. U. (ed.) (2015b) *Archaeology of Cremation: burned human remains in funerary studies.* Oxford: Oxbow Books.

Thompson, T. J. U. (2015c) The analysis of heat-induced crystallinity change in bone. In C. W. Schmidt, S. A. Symes, eds. *The Analysis of Burned Human Remains, 2nd edition.* London: Elsevier, pp. 323-337.

Thompson, T. J. U., Gauthier, M., Islam, M. (2009) The application of a new method of Fourier Transform Infrared Spectroscopy to the analysis of burned bone. *Journal of Archaeological Science.* 36: 910-914.

Thompson, T. J. U., Islam, M., Bonniere, M. (2013) A new statistical approach for determining the crystallinity of heat-altered bone mineral from FTIR spectra. *Journal of Archaeological Science.* 40: 416-422.

Thompson, T. J. U., Islam, M., Piduru, K. Marcel, A. (2011) An investigation into the internal and external variables acting on crystallinity index using Fourier Transform Infrared Spectroscopy on unaltered and burned bone. *Palaeogeography, Palaeoclimatology, Palaeoecology.* 299: 168-174.

Thompson, T. J. U., Szigeti, J., Gowland, R. L., Witcher, R. E. (2016) Death on the frontier: military cremation practices in the north of Roman Britain. *Journal of Archaeological Science: Reports,* 10: 826-836.

Tieszen, L. L. (1991) Natural variation in the carbon isotope values of plants: implications for archaeology, ecology, and paleoecology. *Journal of Archaeological Science,* 18: 227-248.

Timby, J. (1995) *The Anglo-Saxon Cemetery at Empingham II, Rutland,* Oxbow Monograph 70, Oxford.

Toncala, A., Söllner, F., Mayr, C., Hölzl, S., Heck, K., Wycisk, D., Grupe, G. (2017) Isotopic map of the Inn-Eisack-Adige-Brenner Passage and its Application to Prehistoric Cremations. In G. Grupe, A. Grigat, G. C. McGlynn (Eds.) *Across the Alps in Prehistory: Isotopic Mapping of the Brenner Passage by Bioarchaeology,* Springer International Publishing, München, Germany.

Traeger (2021) Traeger Wood Fire Grills: Owner's Manual. https://traeger-web-public-prod.s3-us-west-2.amazonaws.com/manuals/grills/timberline-d2/en/Timberline+OM+-+English+-+USA.pdf [Accessed: 30/03/2021].

Tuross, N. (2012) Comparative decalcification methods, radiocarbon dates, and stable isotopes of the VIRI bones. *Radiocarbon,* 54(3-4): 837-844.

Tuross, N., Fogel, M. L., Hare, P. E. (1988) Variability in the preservation of the isotopic composition of collagen from fossil bone. *Geochimica et Cosmochimica Acta,* 52: 929-935.

Twiss, K. (2012) The archaeology of food and social diversity, *Journal of Archaeological Research,* 20(4): 357-395.

Ubelaker, D. H. (2009) The forensic evaluation of burned skeletal remains: a synthesis. *Forensic Science International* 183:1-9.

Ubelaker, D. H. (2015) Case applications of recent research on thermal effects on the skeleton. In T. Thompson, ed. *Archaeology of Cremation: burned human remains in funerary studies.* Oxford: Oxbow Books, pp. 213-226.

Ucko, P. J. (1969) Ethnography and the interpretation of funerary remains, *World Archaeology,* 1(2): 262-280.

Ulgium, P. F. (2015) Analysing cremated human remains from the southern Brazilian highlands: interpreting archaeological evidence of funerary practice at mound and enclosure complexes in the Pelotas River Valley. In T. J. U. Thompson (Ed.) *The Archaeology of Cremation,* Oxbow Books, Oxford. pp. 173-212.

Valenzuela, L. O., Chesson, L. A., Bowen, G. J., Cerling, T. E., Ehleringer, J. R. (2012) Dietary heterogeneity among Western industrialized countries reflected in the stable isotope ratios of human hair. *PLOSone,* 7(3): 1-8. e34234. Doi:10.1371/journal/pone.0034234

van der Merwe, N. J. (1982) Carbon isotopes, photosynthesis, and archaeology: different pathways of photosynthesis cause characteristic changes in carbon isotope ratios that make possible the study of prehistoric human diets. *American Scientist,* 70(6): 596-606.

van Klinken, G. J. (1999) Bone collagen quality indicators for palaeodietary and radiocarbon measurements. *Journal of Archaeological Science,* 26: 687-695.

Van Vark, G. N. (1974) The investigation of human cremated skeletal material by multivariate statistical methods, I methodology. *Ossa* 1:63-95.

Veselka, B., Locher, H., de Groot, J. C. M. J., Davies, G. R., Snoeck, C., Kootker, L. M. (2021) Strontium isotope ratios related to childhood mobility: revisiting sampling strategies of the calcined human pars petrosa ossis temporalis. *Rapid Communications in Mass Spectrometry,* 35: 1-9. E9038.

Vidal, B. C., Mello, M. L. S., (2011) Collagen type I amide I band infrared spectroscopy. *Micron.* 42: 283-289.

Vika, E. (2009) Strangers in the grave? Investigating local provenance in a Greek Bronze Age mass burial using $\delta^{34}S$ analysis. *Journal of Archaeological Science,* 36: 2024-2028.

Vogel, J. C., van der Merwe, N. J. (1977) Isotopic evidence for early maize cultivation in New York State. *American Antiquity,* 42(2): 238-242.

von Endt, D. W., Ortner, D. J. (1984) Experimental effects of bone size and temperature on bone diagenesis. *Journal of Archaeological Science,* 11: 247-253.

Von Euw, S., Wang, Y., Laurent, G., Drouet, C., Babonneau, F., Nassif, N., Azaïs, T. (2019) Bone mineral: new insights into its chemical composition. *Nature: Scientific Reports,* 9(1): 1-11.

Wahl, J. (2015) Investigations on Pre-Roman and Roman Cremation Remains from Southwestern Germany: Results, Potentialities, and Limits. In C. W. Schmidt, S. A. Symes, eds. *The Analysis of Burned Human Remains*. London: Elsevier, pp. 163-179.

Walker, P. L., Bathurst, R. R., Richman, R., Gjerdrum, T., Andrushko, V. A. (2009) The causes of porotic hyperostosis and cribra orbitalia: a reappraisal of the iron-deficiency-anemia hypothesis. *American Journal of Physical Anthropology,* 139: 109-125.

Walker, P. L., Miller, K. W. P., Richman, R. (2008) Time, temperature, and oxygen availability: an experimental study of the effects of environmental conditions on the organic content of cremated bone. In C. W. Schmidt, S. A. Symes, eds. *The Analysis of Burned Human Remains.* London: Elsevier, pp. 129-136.

Walther, L. J. (2017) *All Out of Proportion? Stature and Body Proportions in Roman and Early Medieval England,* unpublished PhD thesis, Durham University.

Ward, S. M., Tayles, N. (2015) The use of ethnographic information in cremation studies: a Southeast Asian example. In C. W. Schmidt, S. A. Symes, eds. *The Analysis of Burned Human Remains, Second Edition*. London: Elsevier, pp. 381-402.

Watson, J. T., Cerezo-Román, J. I., Maldonado, S. I. N., Guzmán, C. C., Villalpando, M. E. (2015) Death and community identity in the Trincheras cremation cemetery, Sonora,

Mexico. In C. W. Schmidt, S. A. Symes, eds. *The Analysis of Burned Human Remains.* London: Elsevier, pp. 339-353.

Weale, M. E., Weiss, D. A., Jager, R. F., Bradman, N., Thomas, M. G. (2002) Y-chromosome evidence for Anglo-Saxon mass migration. *Molecular Biology and Evolution,* 19(7): 1008-1021.

Webb, W., Snow, C. E. (1945) The Adena People. *Publications of the Department of Anthropology* (6) University of Kentucky, Lexington, pp. 166-199.

Webster, J. E., Cherry, J. (1977) Medieval Britain in 1976. *Medieval Archaeology,* 21: 204-262.

Weiner, S., Bar-Yosek, O. (1990) States of preservation of bones from prehistoric sites in the Near East: a survey. *Journal of Archaeological Science,* 17: 187-196.

Weiner, S., Wagner, H. D. (1998) The material bone: structure-mechanical function relations. *Annual Review of Materials Science* 28(1): 271-298.

Welch, M. (1983) *Early Anglo-Saxon Sussex,* British Archaeological Reports, British Series (112), Oxford.

Welch, M. (2011) The Mid Saxon 'Final Phase'. In H. Hamerow, D. A. Hinton, S. Crawford (eds.) *The Oxford Handbook of Anglo-Saxon Archaeology,* Oxford University Press, Oxford. pp. 266-287.

Wells, C. (1960) A study of cremation. *Antiquity* 34: 29-37.

Wells, C. (1993) Human remains. In A. Davidson, B. Green, B. Milligan *Illington: a study of a Breckland Parish and its Anglo-Saxon cemetery*. East Anglian Archaeology Report No. 63*,* Norfolk Museums Service, Dereham: 100-107.

Werner, J. (1964) Frankish royal tombs in the cathedrals of Cologne and Saint-Denis. *Antiquity,* 38: 201-216.

Wessman, A., Williams, H. (2017) Building for the cremated dead: ephemeral and cumulative constructions. In J. I. Cerezo-Román, A. Wessman, H. Williams (eds.) *Cremation and the Archaeology of Death 1st edition,* Oxford University Press, Oxford.

Whimster, R. P. (1979) *Burial practices in Iron Age Britain,* unpublished PhD thesis, University of Durham.

White, C. D., Armelagos, G. J. (1997) Osteopenia and stable isotope analysis ratios in bone collagen of Nubian female mummies. *American Journal of Physical Anthropology,* 103(2): 185-199.

White, T. D., Black, M. T., Folkens, P. A. (2012) *Human Osteology, 3rd Edition,* Academic Press, Massachusetts.

White, T. D., Folkens, P. A. (2005) *The Human Bone Manual.* Elsevier Academic Press, London.

Wilkinson, L. (1980) Problems of analysis and interpretation of skeletal remains. In P. Rahtz, T. Dickinson, L. Watts (eds.) *Anglo-Saxon Cemeteries 1979,* British Archaeological Reports, British Series (82), Oxford. pp. 221-231.

Willey, G. R., Phillips, P. (1958) *Method and Theory in Archaeology,* University of Chicago Press, Chicago.

Williams, H. (2003) Material culture as memory: combs and cremation in early medieval Britain. *Early Medieval Europe,* 12(2): 89-128.

Williams, H. (2004) Death warmed up: the agency of bodies and bones in early Anglo-Saxon cremation rites. *Journal of Material Culture,* 9(3): 263-291.

Williams, H. (2011) Mortuary practices in early Anglo-Saxon England. In H. Hamerow, D. A. Hinton, S. Crawford (eds.) *The Oxford Handbook of Anglo-Saxon Archaeology,* Oxford University Press, Oxford. pp. 238-265.

Williams, H. (2013) Death, memory and material culture: catalytic commemoration and the cremated dead. In S. Tarlow, L. Nilsson Stutz (Eds.) *The Oxford Handbook of the Archaeology of Death and Burial,* Oxford University Press, Oxford. pp. 195-208.

Williams, H. (2014) A well-urned rest: cremation and inhumation in early Anglo-Saxon England. In I. Kuijt, C. P. Quinn, G. Cooney eds. *Transformation by Fire: the Archaeology of Cremation in Cultural Context,* University of Arizona Press, Tucson: 93-118.

Williams, H. (2015) Death, hair and memory: cremation's heterogeneity in early Anglo-Saxon England. *Analecta Archaeologica Ressoviensia,* 10: 29-57.

Wilson, D. F., Massey, W. (1987) Scanning electron microscopy of incinerated teeth. *The American Journal of Forensic Medicine and Pathology,* 8(1): 32-38.

Wolf, M., Streit, B., Dokládal, M., Schultz, M. (2017) Determining human age at death using cremated bone microstructure. *Biomedical Journal of Scientific and Technical Research,* 1(3): 785-791.

Wopenka, B., Pasteris, J. D. (2005) A mineralogical perspective on the apatite in bone. *Materials Science and Engineering: C,* 25(2): 131-143.

World Wildlife Fund (2021) UK Rivers Map. https://www.wwf.org.uk/uk-rivers-map [Accessed 08/06/2021]

Worley, F. L. (2008) *Taken to the Grave. An archaeozoological approach to assessing the role of animals as crematory offerings in first millennium AD Britain,* unpublished PhD thesis, University of Bradford.

Wright, R. P (1996) Introduction: gendered ways of knowing in archaeology. In R. P. Wright ed. *Gender and Archaeology,* University of Pennsylvania Press, Philidelphia. Pp. 1-19.

Wylie, A. (2007) Doing archaeology as a feminist: introduction. *Journal of Archaeological Method and Theory,* 14:209-216.

Yorke, B. (1990) *Kings and Kingdoms of Early Anglo-Saxon England.* Routlegde, London.

Yorke, B. (1993) Lindsey: The Lost Kingdom Found? In *Pre-Viking Lindsey,* Vince, A. ed. Lincoln: City of Lincoln Archaeology Unit, pp. 141-150.

Zazzo, A., Saliège, J-F., Lebon, M., Lepetz, S., Moreau, C. (2012) Radiocarbon dating of calcined bones: insights from combustion experiments under natural conditions. *Radiocarbon,* 54(3-4), 855-866.

Zazzo, A., Saliège, J-F., Person, A., Boucher, H. (2009) Radiocarbon dating of calcined bones: where does the carbon come from? *Radiocarbon,* 51(2): 601-611.

Zhao, F. J., Spiro, B., Poulton, P. R., McGrath, S. P. (1998) Use of sulphur isotope ratios to determine anthropogenic sulphur signals in a grassland ecosystem. *Environmental Science & Technology,* 32(15): 2288-2291.

Zieler, M., Sebald, S., Grupe, G. (2017) Die Berge rufen! Archäologisch-anthropologische Studie zur Migration in die Eisenzeitliche Montanlandschaft Siegerland (Nordhein-Westfalen) anhand von Brandbestattungen. *Archäologisches Korresponenzblatt,* 47: 173-199.

Appendix 1: Written Sources for the Early Anglo-Saxon Period

In 410 AD Emperor Honorius of Rome informed the British that they would need to see to their own defenses; this marked the end of Roman Britain and the beginning of a poorly understood period. The death knells of the Roman occupation are outlined in considerable detail by a sixth century Greek historian named Zosimus; however, following his account we have only four written sources relating the next three centuries of British history (Campbell, 1982; Higham, 1992). The nearest to a contemporary account is "*De Excidio Britanniae*" written by a monk under the name Gildas. The most complete account is provided by Bede in the "*Ecclesiastical History of the English people*". One further account is ascribed to Nennius, the "*Historia Brittonum*". Finally, there is the Anglo-Saxon Chronicle. The Chronicles are not attributed to one specific author, rather the original document was distributed, recopied, and updated by various scribes (Stenton, 1970). These four sources represent the most complete accounts of the early Anglo-Saxon period; however, there are a few additional documents that provide context for this period. Legal codes written by the kings of Kent and Wessex have survived to the present day, shedding light on the governance of the Anglo-Saxon kingdoms (Attneborough, 2015). Some fragments of poetic epics have also survived, providing insight into the mundane, as well as the exceptional, experiences of the Anglo-Saxon elite (Stenton, 1970). None of these sources can be truly considered a primary source; even Gildas was not writing about his own experiences but about the past. While no history is truly written without bias, due to the dearth of comparative material for the Anglo-Saxon period, it is especially difficult to account for the distortions of these authors. The most significant extant sources for the early Anglo-Saxon period are discussed in further detail below.

A1.1 Gildas and the Fall of Roman Britain

The first historical record of the Anglo-Saxon period is an account titled "*De excidio et conquestu Britanniae*" or "*On the Fall of Britain*" produced circa 550 by a priest referred to as Gildas (Campbell, 1982). The document resembles a sermon more than an historical treatise (Higham, 1992; 1994). In the preface to this work, Gildas lays out his intentions – first, to summarize the geography and history of Britain as context for the second section, a

chastising epistle to the Britons. Gildas states outright that his intention is to admonish his countrymen, to reprimand them for their sinful ways. He hopes to foster repentance among his people and thus deliver them, through God's grace, from Anglo-Saxon subjugation.



Figure A.1: Gildas the wise by William Marshall, line engraving, probable date 17th century. National Portait Gallery, 2021.

His account begins with the submission of Britain to Rome, which was accomplished more by intimidation than warfare. Rebellions were easily quashed and Britain became a Roman province. As a monk he is particularly concerned with the introduction of Christianity to the island. Though initially conversions were desultory, there was sufficient zeal that persecutions of Christians under Diocletian failed to stifle Christianity in Britain; levelled churches were rebuilt and new churches erected to the martyrs. Gildas, though, considered the revival to be tainted from within by the growth of the Arian heresy, a nontrinitarian doctrine proposed by the presbyter Arius. Gildas' next entry regards the rebellious campaign of Magnus Maximus. Maximus successfully usurped the imperial throne in 383 and ruled until 388 (Higham, 1992). However, in Gildas' narrative Maximus is no hero but a seditious tyrant who robbed Britain of the "flower of her youth". Without her soldiers Britain was left exposed to incursions by the Picts and Scots of the north. The

Britons sought military aid from Rome, which was provided; the invaders were driven out of the province. However, when the legions departed the Picts and Scots attacked again. Roman forces were once again summoned but promised this would be the last military support Britain would receive. Again, the troops departed and again Britain begged for aid; however, Rome no longer had soldiers to spare. The Picts and Scots renewed their onslaught against feeble British resistance. Scarcity precipitated by the unrest bred civil disputes.

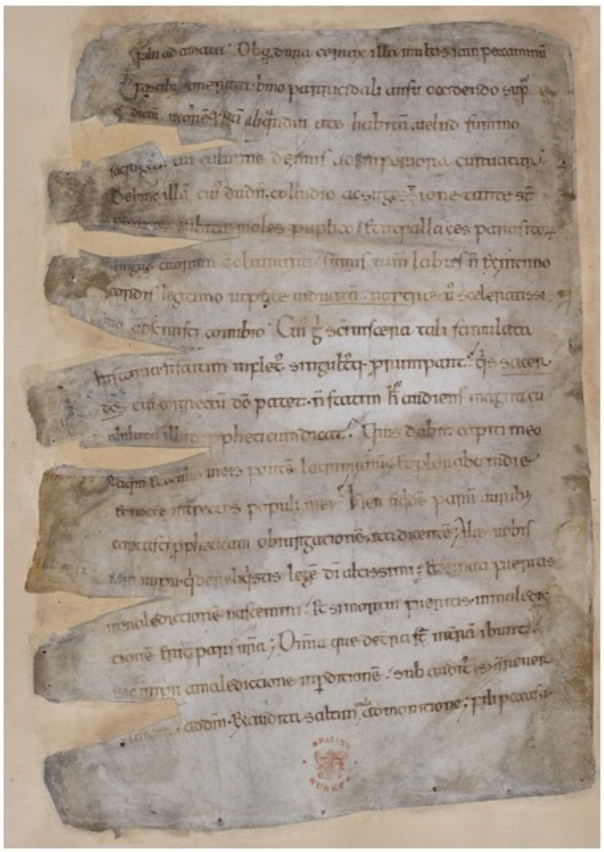


Figure A.2: De excidio Britanniae, Cotton MS Vitellius A VI (British Library (2021a).

The Britons were in a pitiable state. There were factions who surrendered to the invaders in hope of provisions. Yet, some vestige rallied to overthrow their enemies. The invaders were expelled and held to raiding the borders, after years of occupation. Free from invasion for a time, Britain experienced a period of prosperity. Gildas considered prosperity a greater danger than warfare or starvation, as with luxury came temptation. Peace did not last and as rumors of gathering hostile forces spread, a council was called to consider the defense of the nation. In order to protect their borders, the council decided to

invite Saxon warriors to occupy the eastern side of the island in exchange for defense against peoples from the north. The initial Saxon force filled three warships but was soon reinforced by a larger force. The warriors were settled in the east and provisioned by the Britons. However, the Saxons found their allotted supplies insufficient and refused to be confined to the east; they broke the treaty and began to plunder the surrounding lands, spreading to reach the west coast. Britons under Saxon control were killed or enslaved. Those who escaped were not safe: some emigrated to the continent, some found slavery preferable to famine and surrendered, but some managed to remain in Britain while eluding enemy forces. The surviving free-Britons rallied and built their resistance around Ambrosius Aurelianus. Their leader, a Roman who chose to remain in Britain, had lost his family to the Saxons. Most battles were indecisive, the Britons and Saxons trading victories – until the siege of "*Mons Badonicus*", the last victory of the British forces against the Saxons. The culmination of this resistance was not the ejection of the Saxon menace but rather an uneasy peace. The wreckage of the island served to deter both sides from warfare, but civil unrest continued. The generation that survived the war lived in humble peace, acutely aware the recovery of the island was fragile. The lessons faded quickly in Gildas' view; the subsequent generation was ignorant and lived without virtue. This amoral generation was Gildas' audience; his epistle, in truth the entire text of *"De excidio Britanniae*", is addressed to them. He records a litany of offences: plunder, rape, polygamy, fornication, adultery, perjury, betrayal of oaths, unjust war, and murder. Despite lip-service to the Church, the Britons have abandoned God. His invective against the priests and secular leaders of Britain contains contemporary examples of sin bolstered by examples from scripture to demonstrate the repercussions of straying from Christ.

Gildas' "*De excidio Britanniae*" as an historical source is problematic at best. He never intended to write history as a reference for later generations and therefore he is reticent with specifics – there are no dates in his treatise, few names, and fewer identifiable locations (Campbell, 1982). Further, he takes license with the facts in order to fit events to his rhetoric. During the Roman period of his history Gildas largely adheres to the verifiable history of the period. From this we can tie Gildas' account to a few securely dated events. The conquest of Britain is presumably that of Claudius in 43 AD. The "unclean lioness" who rebelled against the Roman conquest is identified as Boudicca whose uprising can be dated to 60 or 61 AD, though Thompson instead considers the lioness a metaphor for the nation of

Britain (1979). Diocletian was Emperor from 284 to 305, his persecution of Christians began in 302 (Higham, 1992). The Edict of Milan, which recognized Christianity as a legal religion, put an end to this onslaught in 313 (Higham, 1992). Arius and his followers questioned the homoousion of the trinity, a position that from 325, the first council of Nicaea, was deemed heretical (Higham, 1992). Magnus Maximus, an Iberian serving in Britain with the Roman army, led a successful military revolt into Rome in 383. He ruled until 388 when he was executed at Aquileia (Higham, 1992).

Further, we can be reasonably assured that Gildas faithfully reported those events within living memory as any obvious deviation would only harm his polemic (Higham, 1992; 1994). Thus, we can accept that there was a Saxon rebellion, that the battle at Mons Badonicus was significant and that the war ended shortly after this to be followed by a generation of relative peace. Unfortunately, as these events were familiar to his audience, Gildas provides us with no details. The only temporal reference is to the passage of 44 years, but it is unclear which events Gildas is separating by this period. Depending on the translator's interpretation this could be 44 years between the arrival of the Saxons and their rebellion, between the battle of Mons Badonicus and the composition of "*De excidio Britanniae*", or between Gildas' birth and the composition of this work. The location of Mons Badonicus, or Badon Hill, is also lost to time (Higham, 1994). The siege that Gildas writes of was a decisive victory for the British, after which there were a number of smaller battles that marked the end of Saxon advancement into British territory.

Finally, in his epistle Gildas gave some indication of the state of Britain during his lifetime. He laments the destruction of the Roman towns and villas, despairing that urban life may never recover. But from this we know that before the Saxon rebellion there was some remnant of Roman-style town life persisting in post-Roman Britain, not critically threatened until the Saxon rebellion. He rails against the unjust courts, but this indictment provides evidence that there were still courts active in areas under British control when "*De excidio Britanniae*" was written (Higham, 1992). The denunciation of the impious clergy proves that organized Christianity was sustained in British areas following the Saxon uprisings. The document itself is proof that Gildas received a traditionally Roman classical education and that there was a sufficient audience with similar education that the treatise was distributed (Campbell, 1982; Higham, 1992). The five kings Gildas distinguishes for their sins provide an indication of the political structure during the composition of "*De excidio*

Britanniae". Constantine, the first king denounced, is recorded as king of Dumnonia, a kingdom comprising the south-west peninsula. The third king mentioned was Vortipor of the Demetae, which would align to modern-day Pembrokeshire. Cuneglas, the fourth king, had his court at Dinarth implying a kingdom centred around Rhos, but likely extending further than this to compare politically with Vortipor and Constantine. Aurelius Caninus cannot be associated with a particular kingdom, though scholars have associated him with an inscription on a memorial stone in Carmarthenshire. Maglocunus ruled over Anglesey, but seemingly also the other four British kings. Gildas addresses Maglocunus as though he has power over all other British kings. However, Gildas does not refer to him as the most powerful dux in Britain, he is only more powerful than most. The language suggests an Anglo-Saxon overlord to whom Maglocunus is subject (Higham, 1992).



Figure A.3: Britain circa 550. Place names in black text, regnal names in purple text as mentioned in Gildas, reproduced from Higham (1992).

Unfortunately, the most questionable chapters of Gildas' work are those regarding the lead up to the arrival of the Saxons, the invitation of these warriors and the rebellion that followed. Gildas is the only clear source we have for these events and he was far from unbiased in his portrayal of them. The rebellion of Magnus Maximus can be securely dated

from continental sources and certainly his campaign depleted British troops. However, there were subsequent rebellions – such as the one lead by Constantine III in 407 – that would have also impacted Britain's defenses and the inclination of the Romans to send aid. Gildas' choice to omit these other rebellions was likely a literary one (Dumville, 1977). However, they too would have contributed to the dearth of military strength in Britain at the close of the fourth century. This curious omission is followed by the outright fabrication regarding Hadrian's and Antonius' Walls. While his ignorance regarding the walls can perhaps be excused, the invented account of their construction proves that Gildas had no qualms substituting theory for fact in his composition. Thus, his account must be dealt with critically. Gildas' tale of Hadrian's Wall ends with the notice from Rome that Britain is to see to her own defenses; this may be verifiable if intended as a reference to the Honorian Rescript of 410 (Campbell, 1982; Higham, 1992; 1994).

The value of Gildas, as a source, is his proximity temporally and geographically. However, the major limitation of "*De excidio Britanniae*" is that Gildas never intended the document as an historical resource – it is deficient in specifics and takes liberties with the facts. The broad outline of historical events can be taken as factual, with the notable exception of the construction of Hadrian's Wall. The Roman history recounted by Gildas can be verified through other sources. The invitation to the Saxons and the bellicose consequences of that invitation can be taken as the accepted oral history of the time; contemporaries of Gildas would have rejected a widely divergent account of events in living memory. Furthermore, Gildas is useful as a cultural resource. His account speaks of an elite Christian Romano-British population facing an apocalyptic change to their culture (Higham, 1992). The wealthy Britons living in a post-Roman world and clinging to an urban, hierarchical hegemony were confronted suddenly, not just with a gradual decline of power but with an aggressive rival society. However, his account argues against a mass-migration of Germanic populations. Even after the initial force had been reinforced, the British were able to provide them with rations while maintaining sufficient luxury that Gildas feared for their souls (Higham, 1992; 1994).

A1.2 Bede and the Conversion of the English

The next document recounting the history of the Anglo-Saxon period was written by Bede, a far more comprehensive document and one that was intended as a relatively unbiased historical account. Bede was born in Northumbria, near the monastery of Monkwearmouth circa 673 (Marsh, 1970). He joined the monastery at age seven and continued to serve until his death at sixty-three years (Stenton, 1970). The libraries at Monkwearmouth and Jarrow, where Bede was taught and where he served, were exceptional and provided Bede with the scholastic base for his extensive works (Stenton, 1970). He wrote translations, biographies, biblical commentaries, and scientific treatises, producing altogether around forty works (Marsh, 1970; Stenton, 1970). In 731, near the end of his life, Bede produced his Ecclesiastical History of the English People (Stenton, 1970).



Figure A.4: Monk working in a scriptorum, possibly Bede, 12th century manuscript (British Library, 2021b)

The scope of Bede's history is impressive: beginning before the invasion of Julius Caesar and continuing into contemporary events and covering events in most of Anglo-

Saxon Britain. The coverage is not consistent and unsurprisingly Northumbrian events are recorded in the most detail (Yorke, 1990). The Celtic areas of the country are all but ignored in Bede's narrative; the native Christian refusal to attempt the conversion of the Germanic migrants fostered antipathy within the Anglo-Saxon church (Yorke, 1990). Unfortunately, scholars have taken Bede's silence as evidence that the Romano-British population was either exterminated or enslaved. However, this interpretation has been challenged since the late 20th century (Yorke, 1990). Bede's record is unbalanced temporally as well as geographically, focused predominantly on the seventh century. The earlier period is clearly drawn from Gildas and provides little additional information. More surprisingly, as the record reaches contemporary events Bede becomes increasingly laconic. Scholars have proposed that this reticence stems from his desire not to offend the potential audience of the piece by recording events that portray the leaders of the time unfavorably (Yorke, 1990). Nevertheless, the Ecclesiastical History is the most influential record of the early Anglo-Saxon period; a record that represents a prodigious effort expended in its compilation of numerous sources – from oral tradition, written documents, the accounts of contemporary scholars, and personal experience (Stenton, 1970; Yorke, 1990). Furthermore, although Bede's history occasionally suffers from allegory or oral tradition, for a monk his history is surprisingly devoid of mysticism (Stenton, 1970; Yorke, 1990). Perhaps the most significant contribution of Bede's scholarship, though not specific to Anglo-Saxon history, was the introduction of a consistent dating system that translated dates from regnal years to anno Domini form (Yorke, 1990).

Bede's account of the coming of the Anglo-Saxons follows Gildas' narrative but provides details lacking in the earlier account. After the withdrawal of Roman forces Britain is repeatedly ravaged by invading Picts and Scots. While Rome provides military support at first, eventually the appeals are refused. The final appeal to Ætius is dated by Bede to the joint reign of Marcian and Valentinian III – 449-456 AD (Stenton, 1970). The British leader who invites mercenaries from northern Europe Bede names Vortigern and the leaders of the initial Germanic force he names Hengist and Horsa. The initial force was soon complemented by further forces of Angles, Saxons, and Jutes. Bede dates the arrival of the mercenaries to 449, with the rebellion occurring six years later. The rallying of the British forces under Ambrosius Aurelianus with the decisive battle at Mons Badonicus Bede records circa 495. Aside from two visits from St. Germanus to suppress the Pelagian heresy, Bede

has nothing more to add until Augustine is sent to attempt the conversion of the English in 596. The source of the additional information provided here is uncertain. Bede clearly lays out his sources and as these events occurred in and around Kent, the information likely came from the Abbot Albinus. However, Albinus was likely relying on oral traditions regarding the leaders relayed in this narrative. Particularly suspicious are the alliterative names of the original leaders – a recognized trope in origin legends throughout Continental Europe (Yorke, 1990). The dates provided by Bede may also be questionable and likely involve interpolation and speculation by later scholars rather than a faithful record of tradition (Stenton, 1970).



Figure A.5: Historia Ecclesiastica gentis Anglorum, Cotton MS Tiberius C II (British Library, 2021c).

The record of the seventh century is focused mainly on the conversion of the English, Bede records the sporadic progression of Christianity through the country and the correspondence between Augustine and Pope Gregory regarding the minutiae of church doctrine. However, alongside that narrative Bede provides a multitude of details regarding the founding of the English kingdoms and the relations between them. The tribal division of Anglo-Saxon England was laid out first by Bede. The Jutes were mainly concentrated in Kent and the Isle of Wight; the Saxons spread through Essex, Wessex, and Sussex; and the Angles gave rise to the kingdoms of East and Middle Anglia, Mercia, and Northumbria. Bede records several of the genealogies of the early kings, most of whom traced their lineage

back to the god Woden, though the East Saxons instead traced their lineage from another god in the pagan Germanic pantheon, Saxnot. The kings of these early nations were little more than warleaders. Their dynasties were not secure, and their titles were not necessarily inherited. However, moving into the sixth century some kings were able to extend their authority and become overlords of the English kingdoms (Yorke, 1990). Bede lists seven kings considered to have 'imperium' over the English nations south of the Humber: Ælle of the South Saxons, Ceawlin of the West Saxons, Æthelbert of Kent, Raedwald of the East Angles, and Edwin, Oswald and Oswiu three kings of Northumbria. The Mercian kings Penda, Wulfhere, Æthelbald, and Offa are described by Bede as having authority over several other kingdoms but are never referred to as holding 'imperium' (Stenton, 1970; Yorke, 1990). Ælle's reign is dated to the later half of the fifth century, during his time and throughout the following century the English position in Britain was not secure (Stenton, 1970). Ælle's imperium, and likely that of several of the others listed by Bede, was a military position, leading a coalition based on dire circumstance and held together by a strong leader (Stenton, 1970). Not until the later seventh century did the position take on a political tilt, becoming a patron rather than a warlord – able to grant safe conduct between kingdoms and transfer provinces between under-kings (Stenton, 1970).

From Bede, and also from literary sources discussed below, we know that the relationship between kings and their warbands was central to the power of a kingdom. Kings would host the warband in their halls and provide them with lavish gifts in return for their loyalty during battle; as such, battles were essential to the maintenance of the kingdom – how else could the king secure the riches needed to secure a contingent of warriors? Further, Bede's central focus of conversion highlights that the legal and cultural landscape of a kingdom rested entirely on the king; kingdoms are considered Christian when the king is converted and, in some cases, revert to paganism when a heathen king succeeds the throne. Additionally, despite his general reticence regarding the Romano-British population, we know that there were British kingdoms thriving into the seventh century – if only because Cadwallon, King of Gwynned attacked Northumbria during the reign of King Edwin, circa 632 (Stenton, 1970). However, despite the remarkable detail provided by Bede, the Ecclesiastical History has in the past been esteemed too highly; nothing in the record can be accepted without question (Dumville, 1977). Bede's history is based heavily on oral traditions and the accounts of his contemporaries – sources that are influenced not only by

the biases of their authors and interests of their patrons, but also by the narrative styles of their times (Dumville, 1977; Yorke, 1990).

A1.3 Nennius, the Romantic British Perspective

After Bede, the next attempt at a comprehensive history of this period is a document produced circa 830 titled the "*Historia Brittonum*". The author of the document is generally referred to as Nennius, though the oldest editions of the manuscript do not include any identification of the author. The *Historia Brittonum* was a popular account in its time and approximately forty medieval copies of the manuscript have survived (Dumville, 1977). However, in only five of these is the author identified as Nennius and then only in a prologue that appears to be a later insertion (Dumville, 1975). The prologue identifies Nennius as the student of the bishop Efoddw who died in 809. An unrelated manuscript attributed to a scholar by the name of Nennius was written in 817; as such, Dumville proposes that rather than an attempt at forgery or misinformation, the prologue represents the educated guess of a 10th or 11th century scholar as to the origins of the *Historia Brittonum* (1975). The unknown author will henceforth be referred to as Nennius for consistency and clarity.

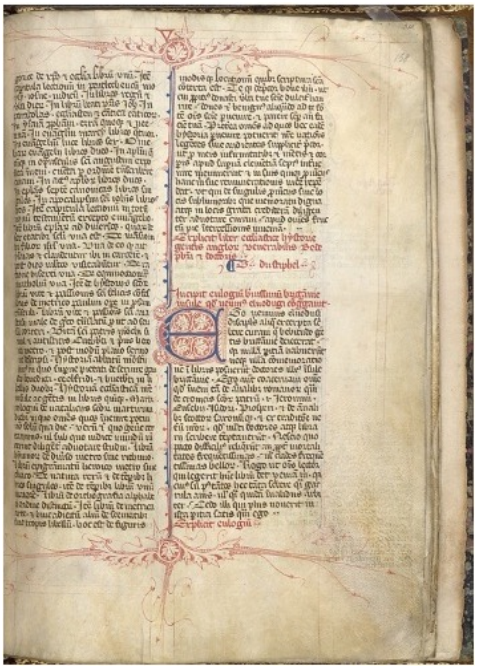


Figure A.6: Historia Brittonum, Harley MS 3859 (British Library, 2021d).

The *Historia Brittonum* is a work of synchronization pulling together continental sources such as Prosper of Acquitaine and Isidore of Seville; British sources such as the accounts of St. Patrick and Gildas' "*De excidio Britanniae*"; Welsh poetry and English legends (Dumville, 1977). However, unlike Bede's restrained account that clearly attempts to report only verifiable information, Nennius fully embraces oral traditions and heroic narratives (Marsh, 1970). From clearly mythic origins of the peoples of Britain, Nennius moves into a quick summary of the era of Roman Britain that is distorted by an adherence to narrative triads rather than historical fact (Marsh, 1970). Nennius then provides a colourful account of Vortigern, or Gwrtheryn, and the arrival of Hengist and Horsa (Dumville, 1977). Hengist and Horsa arrive in Britain as exiles of Germany with three ships of warriors. Vortigern reaches an arrangement with them after their arrival, granting them the Isle of Thanet and supplies of food and clothing in exchange for the defense of Britain from the Picts and Scots. Hengist sends to the Continent for reinforcements, among them his daughter; at a feast Vortigern falls for Hengist's daughter and begs her hand, offering Kent in exchange. However, as the numbers of the Anglo-Saxons grew Vortigern was no longer able to furnish them with supplies and hostilities broke out. Among the battles, Vortigern was lured to a feast and slaughtered treacherously along with 300 of his men. Vortimer, son of Vortigern, was able to defend the island for a time, pushing the Anglo-Saxons back to the Isle of Thanet, but supplied from the Continent, the Anglo-Saxons were not vanquished. The legendary warleader at the Battle of Badon Hill was neither Vortimer nor Ambrosius Aurelianus, but Arthur – whose legend was first recorded by Nennius (Marsh, 1970). Nennius then turns from British kings to English ones, structuring his narrative around the genealogy of the Northumbrian kings (Marsh, 1970).

While entertaining, the *Historia Brittonum* can largely be dismissed as historical fiction – more informative of British literary style than British history; however, there are aspects that deserve attention from the historian as well. Nennius provides a list of thirty-three English cities and the genealogies of the kings of Bernicia, Kent, East Anglia, Deira, and Mercia (Stenton, 1970). These too must be interpreted with caution: they represent evidence that would have been used in legal and political claims and their accuracy would only have been maintained where historical pedigree did not conflict with those claims (Dumville, 1977). There are a few examples from Nennius' record that serve to highlight one of the major faults of Bede – that is, the omission of the Romano-British from his

Ecclesiastical History. Nennius provides an account of Edwin's conquest of the British kingdom of Elmet and also of the British princes who bolstered Penda's forces against Oswiu (Stenton, 1970). These examples serve as a reminder that while Bede was clearly the more measured historian, his account is not without flaws. Another important perspective provided by Nennius is the general dissension among the Britons during the early Anglo-Saxon period (Marsh, 1970). While Bede provided evidence of a series of English overlords, albeit a discontinuous series, Nennius provides only Vortigern and Arthur, warlords of the mid 6th century. There is no further evidence of a united British coalition, instead there is evidence of British leaders allying with English kings (Stenton, 1970).

A1.4 The Anglo-Saxon Chronicle, the West Saxon annals

The final comprehensive historical source for the early Anglo-Saxon period is a collection of annals referred to as the Anglo-Saxon Chronicle. The original text was compiled circa 892 in the kingdom of the West Saxons, under the reign of King Alfred (Campbell, 1982; Yorke, 1990). Seven manuscripts have survived in relatively complete condition, referred to as manuscripts (MS) A through G – though the last is also sometimes referred to as MS W for the editor Abraham Whitlock (Stenton, 1970). All the manuscripts begin with an overview of world history from the invasion of Britain by Julius Caesar to the middle of the fifth century. This is followed by a series of annals that are consistent between the editions up to the year 891; after this the different manuscripts diverge – likely representing when the manuscripts were continued in various churches over time. One edition, MS A, is continued only to 955, but another MS E, continued at Peterborough Abbey, was edited up to 1154 (Stenton, 1970). The document was compiled as part of King Alfred's drive to improve the literacy and education of the West Saxon people and intended to give the reader an outline of history (Stenton, 1970; Yorke, 1990). Despite its simple organization, the Chronicle also involves some subtle propaganda in the telling of contemporary events. Alfred is painted in a favourable light and the tradition of the West Saxons as victorious in battle is emphasised. The reigns of Alfred's brothers are not recorded, neither is the rebellion that prevented Æthelwulf, Alfred's father, from resuming the throne in 856 (Yorke, 1990). Possibly the document was intended to bolster the spirits

of Alfred's people in the face of Viking onslaughts, encouraging them to remain loyal and continue fighting by emphasizing a grand history (Yorke, 1990).

While compiled in the late 9th century the Chronicle shows evidence of the use of earlier sources – oral traditions, genealogies of kings, and earlier annals. The earliest annals reflect a West Saxon set of annals compiled by an unknown ecclesiastical source (Stenton, 1970). Likely written originally in Latin, the entries fit a four-year pattern suggesting the dates were retrospectively entered into tables used to calculate the date of Easter (Stenton, 1970). These entries represent the conjectures of an annalist writing approximately three hundred years after the events he describes (Stenton, 1970). The entries from the 5th and 6th centuries can only be used with caution, representing the accepted foundation legends more than a factual sequence. The Chronicle becomes relatively reliable from circa 648, when scholars believe contemporary annals were being kept, though these may have been revised before inclusion in the final 9th century text (Yorke, 1990). The chronological framework during the conversion period was certainly drawn from Bede. The density of entries between 670 and 750 suggests these annals were copied from an earlier source, a similar pattern is observed in the entries between 800-839. The record from 865 through to 891 would have been completed by a contemporary scholar, some researchers have suggested King Alfred himself, though only based on stylistic comparisons with his translation of Orosius (Stenton, 1970).

The early annals provide a more detailed record of the arrival of Hengist and Horsa and their subsequent battles with Vortigern than is provided by Bede. The Chronicle also records the arrival of Cerdic and Cynric the founders of the West Saxon kingdom, Stuf and Wihtgar founders of the Isle of Wight, and Ælle and his sons who founded the South Saxon kingdom. Their stories of conquest show clear patterns of repetition indicating their origin in heroic poems but emphasising the aggressive expansion of these early kingdoms. As in Bede's Ecclesiastical History, it is clear that a successful Anglo-Saxon king was a strong warleader (Yorke, 1990). The Chronicle also provides a list of Anglo-Saxon kings whose authorities extends beyond their own borders, adding Egbert of the West Saxons to Bede's earlier list, and providing for them the title 'bretwalda' (Yorke, 1990). 'Bretwalda' can be translated as 'Britain ruler' a term not intended as a legal description but one of poetic praise (Stenton, 1970). The Anglo-Saxon Chronicle provides support to Bede's history in the 6th and 7th centuries and serves to extend our understanding into the later 8th and 9th

centuries. However, there are a few points where the Chronicle contradicts Bede in a manner that revises our understanding of the early Anglo-Saxon period. In Bede's history, the kings of Wessex proceed in a singular fashion as suggested by a genealogy; however, in the Anglo-Saxon Chronicle there are several examples of æthelings sharing power within the kingdom. Caewlin shares power with first his brother Cuthwulf and later his son Cuthwine; Ine shares the first years of his reign with his father Cenred (Yorke, 1990). This collective system is absent from Bede's record. Another discrepancy is in the succession of kings following the death of Cenwalh in 672. In the Ecclesiastical History Wessex is divided among under-kings for the subsequent decade; however, in the Chronicle Cenwalh is succeeded first by his widow Seaxburg, then by Æscwine and then Centwine during the same period. Initially scholars rejected the divergent events in the Chronicle; however, a contemporary of Centwine, Aldhelm of Malmesbury, wrote that he was a strong king who drove the Britons to the sea in 682. This contemporary record of Centwine's rule lends credency to the reigns of Seaxburg and Æscwine as well (Stenton, 1970). While this is not the only record of an Anglo-Saxon woman of significant influence, the omission of the reign of a Saxon queen can only serve to reduce the profile of these powerful women in the eyes of later researchers.

A1.5 Law Codes of the Anglo-Saxon Kings

There are three early law codes preserved from the kingdom of Kent: the laws of Æthelberht, the laws of Hlothhere and Eadric, and the laws of Wihtred. The three legislative codes are preserved in a document referred to as the Textus Roffensis (H), dated to the twelfth century. Æthelberht's law code was the first written legislation in any of the Anglo-Saxon kingdoms, composed before his death in 616 (Attenborough, 2015). His laws were enacted after his conversion to Christianity and one of the major objectives of his code was the protection of the Church and the establishment of penalties for offenses against God (Stenton, 1970). However, only the first of the ninety sections laid out by Æthelberht deals specifically with the Church. The remainder of the code is concerned with theft, forced entry, destruction of property, assault, and murder. The code lays out in detail the penalties for each offense: for slaying a freeman, 50 shillings; for the breaking of a jaw, 20 shillings; down to the striking off of a fingernail, 1 shilling. However, the most significant context provided by Æthelberht's law code is that the wergild and other reparations were

dependent on class. An offense against the king required greater compensation than one against his ealdormen. Interestingly, a bishop was ranked on par with a king, followed by ealdormen or nobility, freemen, servants, and finally slaves – whose reparations were typically paid to their owners (Attenborough, 2015). The law code of Hlothhere and Eadric written in the latter half of the 7th century elaborates on Æthelberht's code but is similar in essence. Interesting developments from the earlier code are the mention of 'judges of the Kentish people' as arbiters of the court, distinguished from the ministers of the king. Additionally, there are indications that titles of nobility were hereditary at this time, rather than solely indicating services provided to the king (Stenton, 1970). This law code also provides evidence of age-related status in 7th century Anglo-Saxon society: in the discussion of provisions for widows and orphans, the code states that children should be provided a guardian until they reach ten years of age (Attenborough, 2015). The law code of Wihtred, circe 695, largely addressed ecclesiastical issues. The code focused on the penalties for unlawful marriages, heathen worship, and disregarding of holy days. Wihtred also exempted the church from taxation and placed the oath of a bishop on par with his own, as a king. The only significant secular legislation recorded the means by which an individual accused of an offense might assert their innocence (Stenton, 1970).

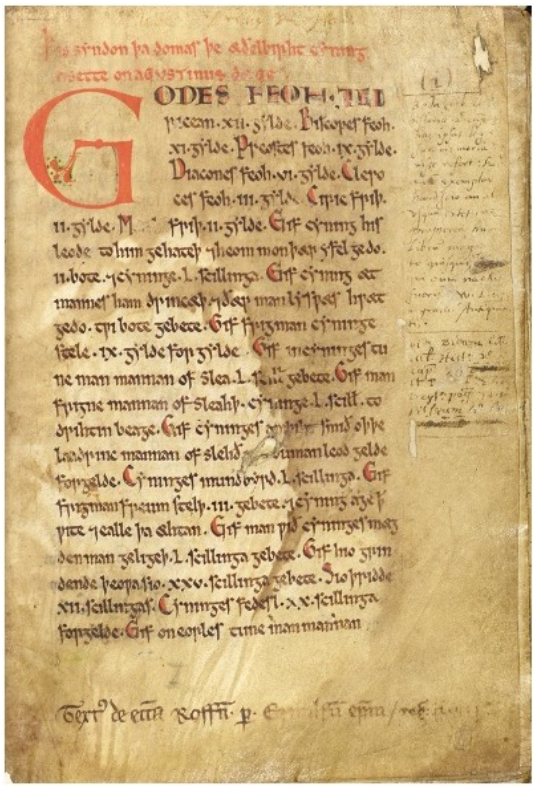


Figure A.7: Law code of Æthelberht of Kent, Textus Roffensis (British Library, 2021e).

Two early law codes of Wessex are preserved together, those of Ine and those of Alfred. Ine's law code, written between 688 and 694, is preserved only because it was appended to Alfred's later code (Attenborough, 2015). Ine's code covers a myriad of relationships and clearly shows the increasing organization of the church in Wessex: requiring servants of god to 'observe their proper rule', children to be baptized shortly after birth, and strict penalties for failing to observe holy days (Attenborough, 2015). However, the most important contextual information provided by Ine's law code is the detailing of food rents – including the provision of honey, bread, ale, cattle or sheep, geese, hens, cheese, butter, salmon, fodder, and eels (Attenborough, 2015). These food rents are mentioned continually in Anglo-Saxon texts but rarely defined in detail (Stenton, 1970). Ine also provides further clues to the domestic life of the 7th century Anglo-Saxon in his sections relating to repayment of pasture or pannage, fines for felling trees on other men's land, the trading of livestock and the maintenance of fences around personal and common land (Attenborough, 2015). In the context of early Anglo-Saxon history, the greatest significance of Alfred's law code is that its manuscript preserved the earlier code written by Ine. Alfred's code shows a changing Anglo-Saxon world – one of greater ecclesiastical organization and a drive towards political union in the face of the Danish invasion – but does not provide further context to the period of the emerging Anglo-Saxon kingdoms relative to the earlier law codes already discussed.

A1.6 Beowulf, early English poetry

The early Germanic poetry that has survived consists of heroic narratives designed to be recited in the courts of powerful men, tales recounted for the entertainment of aristocrats based in their oral history (Stenton, 1970). The technique of alliterative verse preserving an oral tradition was developed among the English poets. While the church was initially suspicious of this heathen tradition, this hostility faded as Christianity became more firmly entrenched in Anglo-Saxon society. The literate clergy became the vehicle of transmission for these oral traditions to modern scholars (Stenton, 1970). Many of these

tales were part of a shared tradition, preserved not only in their places of origin but in several Germanic countries (Stenton, 1970). Thus, the English poetry that remains consists of Beowulf's saga set in Sweden, the tale of Finn of Frisia, Waldhere's story set in Gaul, and Widsith the travelling poet. These fragments of the early English literary tradition preserve aspects of life in the Anglo-Saxon period that are missing from both the histories and the legal record (Stenton, 1970). As these tales were all drawn from a similar tradition of the heroic narrative, only the most complete, Beowulf, will be addressed here.

The English text of Beowulf was written between the seventh and tenth centuries, but likely composed between the birth of Bede and the departure of Alcuin, that is between 672 and 782 (Stenton, 1970; Heaney, 2000). Only one manuscript remains: MS Cotton Vitellius A.XV, held in the British library and known less formally as the Nowell Codex (Boyle, 1997). The manuscript contains, among other copied pieces of prose and verse, a copy of Beowulf transcribed in either the tenth or eleventh centuries (Boyle, 1997). This surviving manuscript has been subject to multiple transcriptions, translations, and interpretations with some scholars focused on its historicity and others on its imaginative and literary merits (Heaney, 2000). However, there is relative consensus regarding the poem's place among a larger tradition of heroic narratives told across several Germanic kingdoms meant to be understood and appreciated by an Anglo-Saxon elite (Stenton, 1970). Furthermore, while the text records a pagan oral tradition it is understood to have been translated to a Christian audience, with clear adjustments to incorporate biblical mythology (Stenton, 1970; Heaney, 2000).

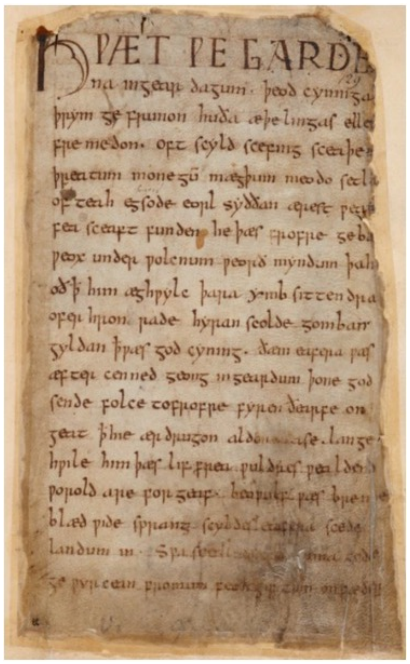


Figure A.8: Beowulf, Cotton MS Vitellius A XV (British Library, 2021f).

Beowulf provides a direct account of the relationship between a king and his thegns (Yorke, 1990). Several times throughout the narrative kings are addressed as 'ring-givers' and the treasures granted for services rendered to the king are recounted in detail. Following Beowulf's death, Wiglaf explains the relationship explicitly. Wiglaf relates how the thegns were selected and honoured above other warriors with 'lavish gifts' and swore to 'make good the gift' by serving Beowulf when needed (Heaney, 2000:179). The gifts themselves were described as treasures of gold torques, rings and bangles; but also, of war-gear: swords, helms, mail, and horses (Heaney, 2000). The poem also provides several descriptions of kings, both flattering and derogatory; thus, we learn, a Germanic king was expected to be strong, bellicose, wealthy, and generous (Yorke, 1990; Heaney, 2000). The king's mead hall was the centre of his kingdom. The hall was where he feasted his thegns, where he bestowed treasures, where his guard slept, and where the community took refuge in emergencies. Additionally, in the heroic narrative there are a number of noble deaths and descriptions of the funerals of important men (Heaney, 2000). These descriptions have been used by archaeologists as analogies for cemetery finds and pyre construction (McKinley, 1994a; Squires, 2011). In Beowulf cremation is the expected funerary rite for kings. The funeral pyres are raised by the community and bedecked with treasures. These

cremations are not a simple, practical solution to the disposal of a corpse, but an emotive, spiritual event attended by a whole community in mourning (Heaney, 2000).

References:

Attenborough, F. (2015) *The Laws of the Earliest English Kings.* Cambridge University Press, Cambridge.

Boyle, L. E. (1997) The Nowell Codex and the poem of Beowulf. In C. Chase ed. *The Dating of Beowulf.* University of Toronto Press, Toronto. Pp. 23-32.

British Library (2021a) https://www.bl.uk/collection-items/gildas-the-ruin-of-britain [Accessed: 23/08/2021]

British Library (2021b) http://www.bl.uk/manuscripts/Viewer.aspx?ref=yates_thompson_ms_26_fs001ar [Accessed: 23/08/2021]

British Library (2021c) https://www.bl.uk/collection-items/bedes-ecclesiastical-history-of-the-english-people [Accessed: 23/08/2021]

British Library (2021d) https://www.bl.uk/catalogues/illuminatedmanuscripts/TourPopupMax.asp?TourID=310 [Accessed: 23/08/2021]

British Library (2021e) https://www.bl.uk/collection-items/the-law-code-of-king-aethelberht-of-kent [Accessed: 23/08/2021]

British Library (2021f) http://www.bl.uk/manuscripts/Viewer.aspx?ref=cotton_ms_vitellius_a_xv_f132r [Accessed: 23/08/2021]

Campbell, J. (1982) *The Anglo-Saxons.* Phaidon, Oxford.

Dumville, D. N. (1975) "Nennius" and the "Historia Brittonum". *Studia Celtica,* 10: 78-95.

Dumville, D. N. (1977) Sub-Roman Britain: History and Legend 1. *History,* 62(205): 173-192.

Heaney, S. (2000) *Beowulf: a new verse translation.* W. W. Norton and Company, New York.

Higham, N. J. (1992) *Rome, Britain and the Anglo-Saxons.* B. A. Seaby Ltd., London.

Higham, N. J. (1994) *The English conquest: Gildas and Britain in the fifth century.* Manchester University Press, Manchester.

Marsh, H. (1970) *Dark Age Britain: some sources of history.* David and Charles Publishers Ltd., Newton Abbot.

McKinley, J. I. (1994a) *The Anglo-Saxon Cemetery at Spong Hill, North Elmham. Part VII: the Cremations*. East Anglian Archaeology Report No. 69, Norfolk Museums Service, Dereham.

National Portrait Gallery (2021) https://www.npg.org.uk/collections/search/portrait/mw124039/St-Gildas [Accessed: 23/08/2021]

Squires, K. E. (2011) *An Osteological Analysis and Social Investigation of the Cremation Rite at the Cemeteries of Elsham and Cleatham, North Lincolnshire,* unpublished PhD thesis, University of Sheffield.

Stenton, F. (1970) *Anglo-Saxon England 3rd Edition.* Oxford University Press, Oxford.

Thompson, E. A. (1979) Gildas and the History of Britain, *Britannia,* 10: 203-226.

Yorke, B. (1990) *Kings and Kingdoms of Early Anglo-Saxon England.* Routlegde, London.

British Library (2021f) http://www.bl.uk/manuscripts/Viewer.aspx?ref=cotton_ms_vitellius_a_xv_f132r [Accessed: 23/08/2021]

National Portrait Gallery (2021) https://www.npg.org.uk/collections/search/portrait/mw124039/St-Gildas [Accessed: 23/08/2021]

Appendix 2 – Temperature Fluctuations during the Controlled Heating Experiment

Target Temperature (°C)	Duration (hours)	Temperature (°C)		
		Low	High	Range
100°	0.5	98°	102°	4°
	1	100°	100°	0°
	2	99°	101°	2°
150°	0.5	146°	153°	7°
	1	149°	151°	2°
	2	149°	150°	1°
200°	0.5	194°	206°	12°
	1	199°	201°	2°
	2	199°	201°	2°
250°	0.5	241°	255°	14°
	1	249°	251°	2°
	2	248°	251°	3°
300°	0.5	289°	308°	19°
	1	299°	301°	2°
	2	298°	301°	3°
350°	0.5	334°	358°	24°
	1	347°	351°	4°
	2	348°	352°	4°
400°	0.5	381°	413°	32°
	1	397°	401°	4°
	2	398°	400°	2°

- Data available as spreadsheet in supplemental materials.

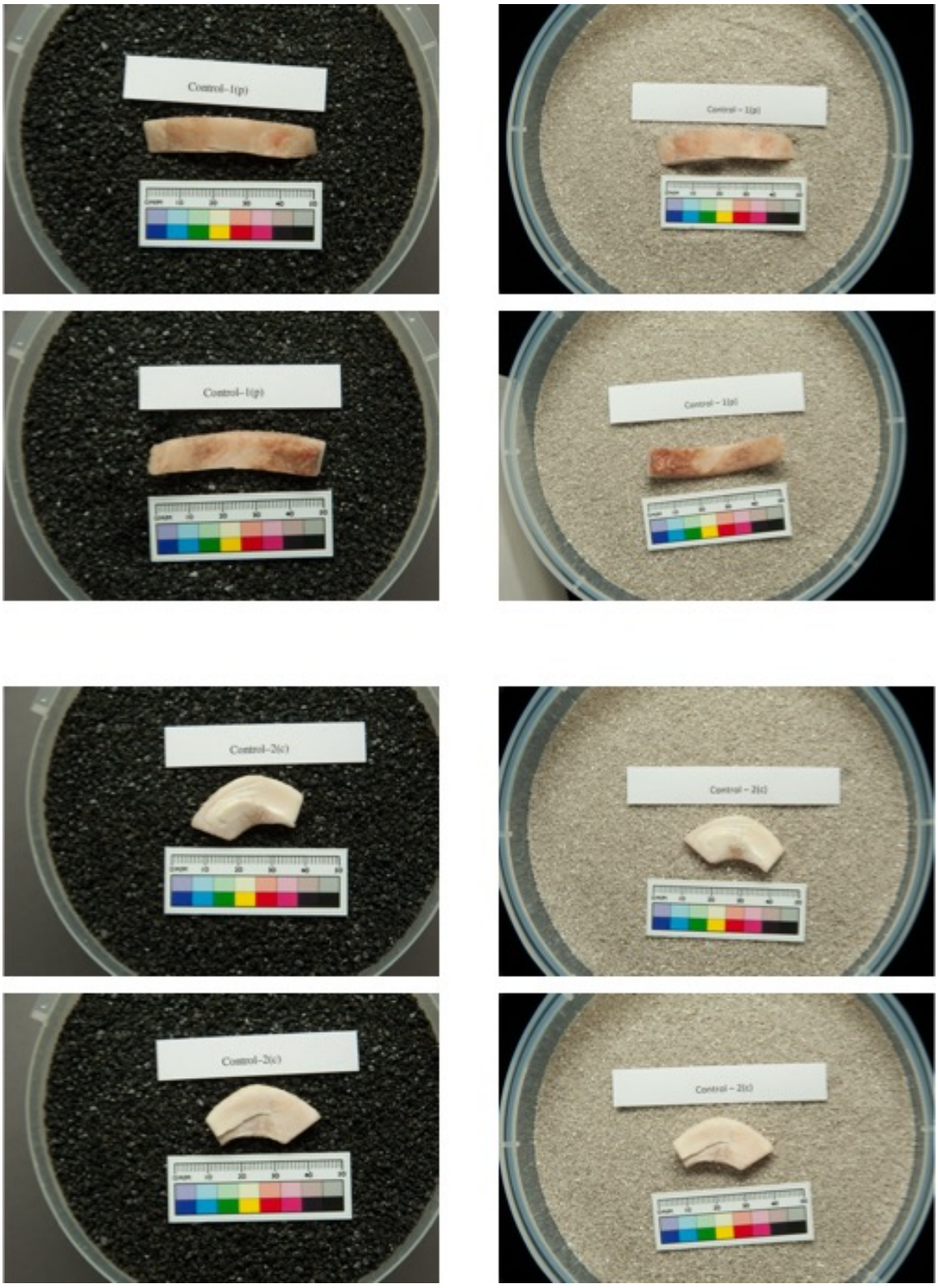
Appendix 3 – Change in Mass During the Controlled Heating Experiment – Raw Data

	Change in Mass			
Sample	**Before (g)**	**After (g)**	**Difference (g)**	**Difference (%)**
Control-1(p)	3.50	3.40	0.10	2.78
Control-2(c)	2.90	2.90	0.00	0.00
Control-3(d)	3.00	3.00	0.00	0.00
100-0.5-1	3.40	3.20	0.20	6.25
100-0.5-2	3.00	2.80	0.20	6.67
100-0.5-3	3.50	3.40	0.10	2.86
100-1-1	3.10	2.80	0.30	9.68
100-1-2	4.00	3.90	0.10	2.44
100-1-3	3.90	3.70	0.20	4.88
100-2-1	4.40	4.00	0.40	8.89
100-2-2	3.70	3.40	0.30	7.69
100-2-3	4.80	4.40	0.40	8.00
150-0.5-1	4.60	4.30	0.30	6.38
150-0.5-2	5.30	4.90	0.40	7.55
150-0.5-3	4.10	3.90	0.20	4.76
150-1-1	4.80	4.20	0.60	12.50
150-1-2	3.70	3.30	0.40	10.53
150-1-3	3.80	3.30	0.50	12.82
150-2-1	3.90	3.40	0.50	12.50
150-2-2	5.80	5.10	0.70	18.92
150-2-3	3.50	3.00	0.50	8.33
200-0.5-1	4.10	3.60	0.50	12.20
200-0.5-2	5.10	4.60	0.50	9.62
200-0.5-3	5.00	4.50	0.50	10.00
200-1-1	4.60	3.90	0.70	14.58
200-1-2	5.60	4.70	0.90	16.98
200-1-3	5.60	4.80	0.80	14.29
200-2-1	4.60	4.00	0.60	12.77
200-2-2	4.80	4.10	0.70	14.29
200-2-3	5.50	4.70	0.80	14.04
250-0.5-1	5.00	4.20	0.80	16.00
250-0.5-2	4.00	3.30	0.70	17.50
250-0.5-3	4.10	3.40	0.70	17.07
250-1-1	4.40	3.40	1.00	22.73
250-1-2	4.90	3.90	1.00	20.41
250-1-3	4.00	3.20	0.80	19.51
250-2-1	5.70	4.50	1.20	20.69
250-2-2	3.90	3.20	0.70	17.50
250-2-3	4.30	3.60	0.70	16.28
300-0.5-1	4.90	4.00	0.90	18.00
300-0.5-2	4.50	3.80	0.70	15.22
300-0.5-3	4.60	3.70	0.90	19.15
300-1-1	4.80	3.70	1.10	22.00
300-1-2	4.30	3.30	1.00	21.74

	Change in Mass			
Sample	**Before (g)**	**After (g)**	**Difference (g)**	**Difference (%)**
300-1-3	3.90	3.00	0.90	22.50
300-2-1	3.30	2.40	0.90	27.27
300-2-2	4.30	3.20	1.10	23.91
300-2-3	4.80	3.40	1.40	28.00
350-0.5-1	6.30	4.50	1.80	26.87
350-0.5-2	3.10	2.30	0.80	25.00
350-0.5-3	5.60	4.20	1.40	24.14
350-1-1	6.30	4.30	2.00	30.77
350-1-2	4.50	3.20	1.30	28.26
350-1-3	4.30	3.10	1.20	27.27
350-2-1	4.60	3.30	1.30	27.08
350-2-2	3.80	2.60	1.20	29.27
350-2-3	4.70	3.30	1.40	29.17
400-0.5-1	4.10	2.90	1.20	28.57
400-0.5-2	4.30	3.10	1.20	28.57
400-0.5-3	4.10	3.00	1.10	26.19
400-1-1	3.70	2.50	1.20	30.77
400-1-2	4.20	2.90	1.30	29.55
400-1-3	5.90	3.80	2.10	35.00
400-2-1	3.70	2.40	1.30	33.33
400-2-2	3.00	1.70	1.30	43.33
400-2-3	3.10	2.00	1.10	35.48

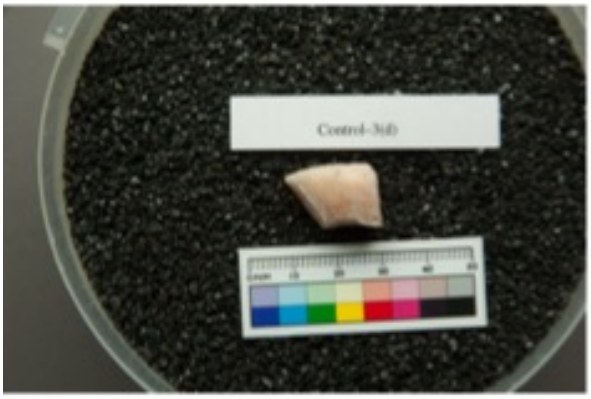
- Conventions used in numbering the samples reflect heating conditions. The first number is the target temperature, the second number is the length of exposure, the final number is an arbitrary designation to separate the three samples exposed to the same conditions. Thus, sample '100-0.5-1' was the first of three samples heated to 100°C for 0.5 hours.
- For the three control samples the letters following the sample number reflect the position along the humeral shaft at which the sample was taken. P = proximal, C = central and D = distal.
- Sample 400-2-2 shows an unexpectedly high loss of mass and is likely erroneous.
- Data available as spreadsheet in supplemental materials.

Appendix 4 – Photographs of Bone Samples from Controlled Heating Experiment



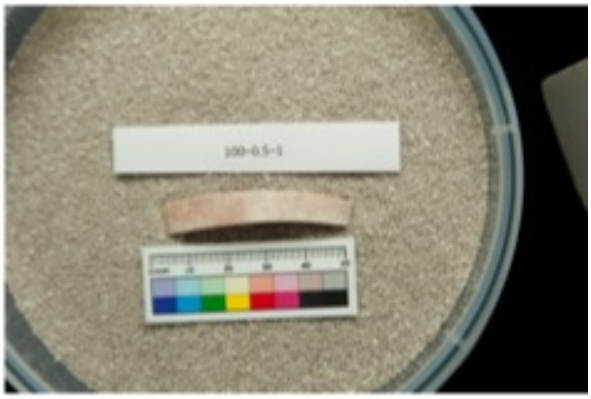

Control-3(d)


Control - 3(d)


Control-3(d)


Control - 3(d)

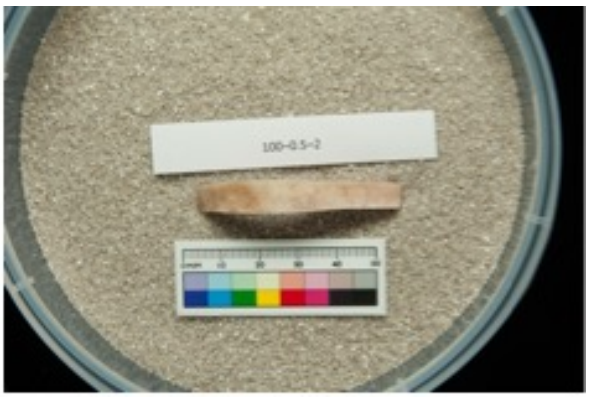

100-0.5-1


100-0.5-1


100-0.5-1

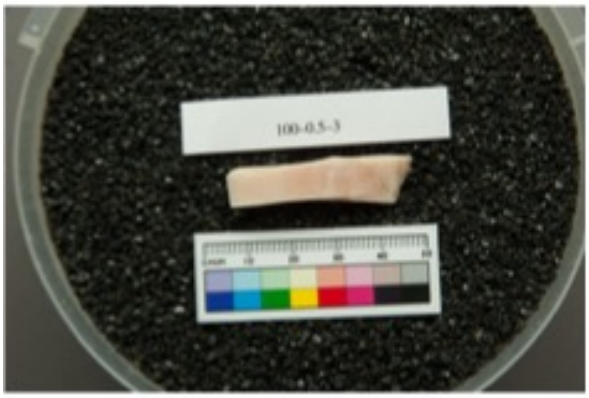

100-0.5-1


100-0.5-2


100-0.5-2

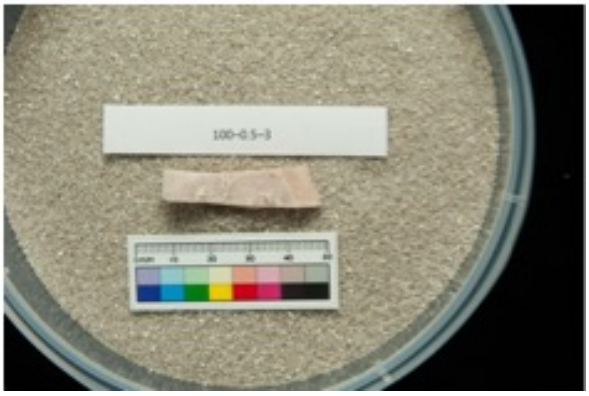

100-0.5-2

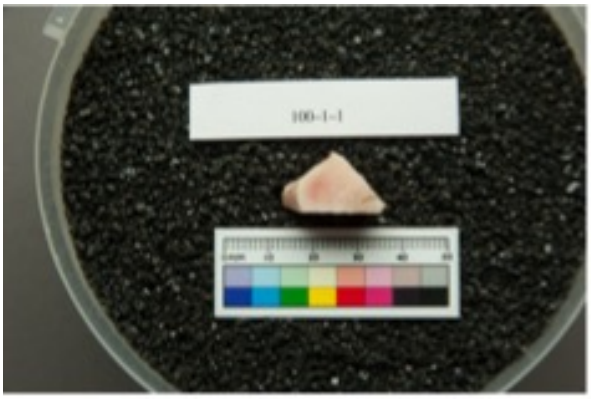
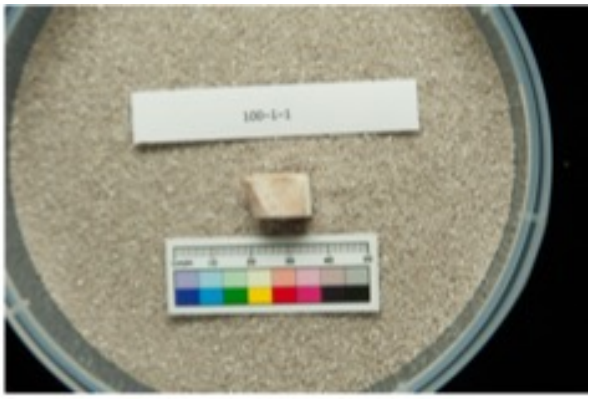
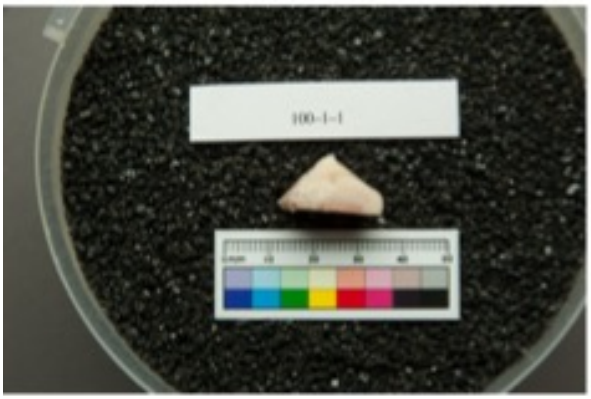
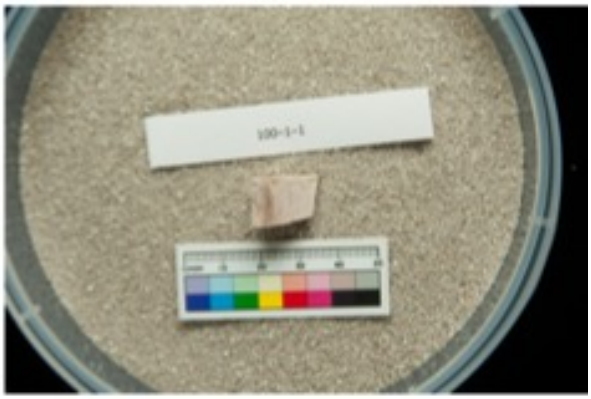
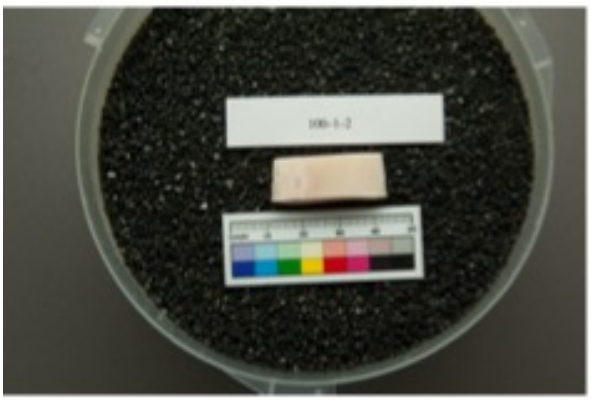

100-0.5-2

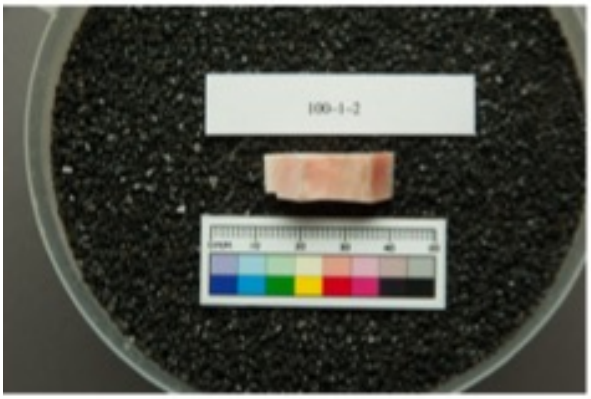

100-0.5-3


100-0.5-3

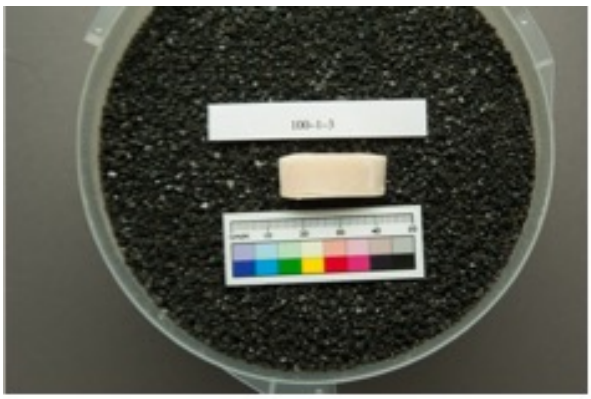

100-0.5-3

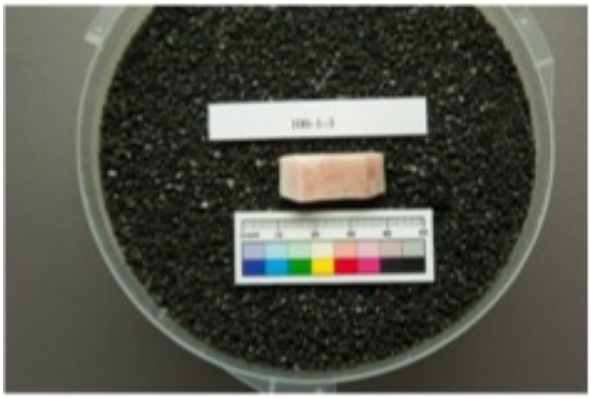

100-0.5-3

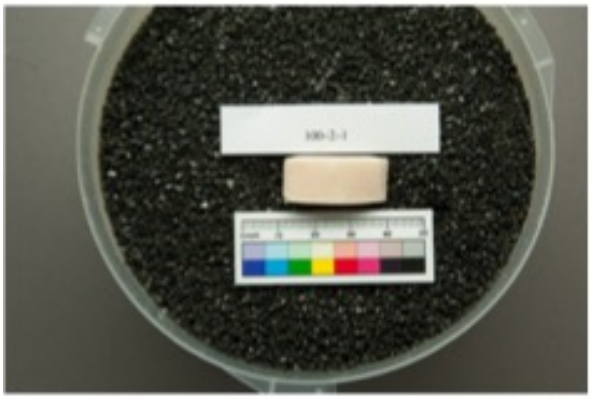
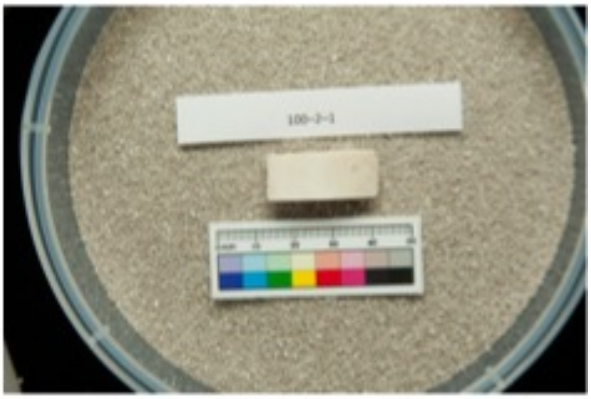
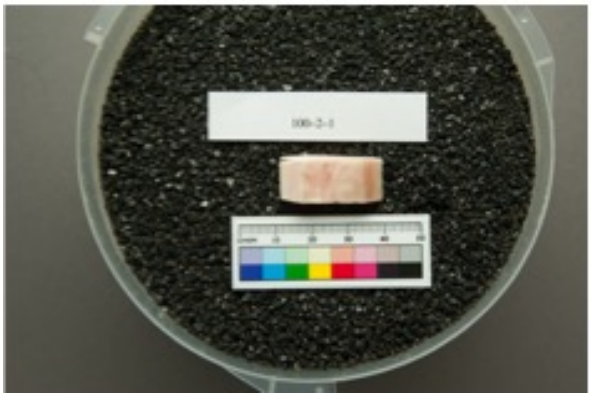

100-1-1

100-1-1

100-1-1

100-1-1

100-1-2

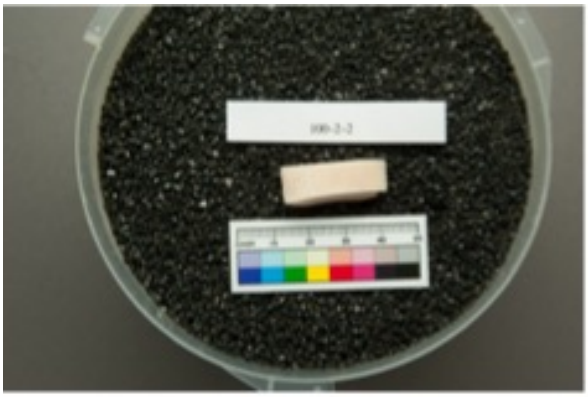
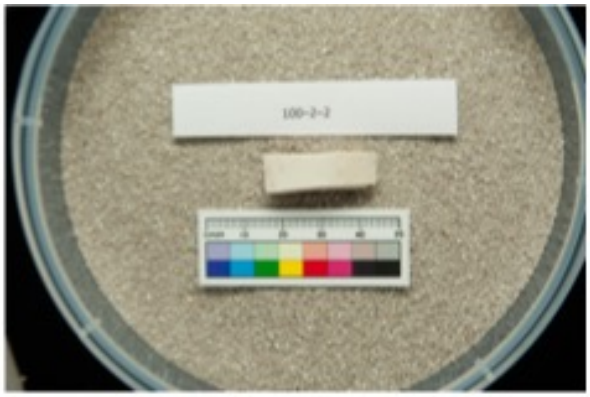
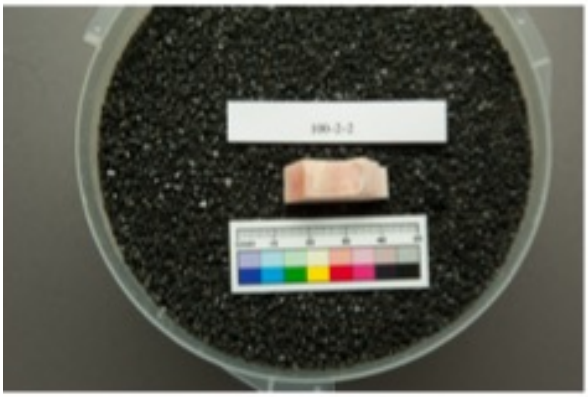
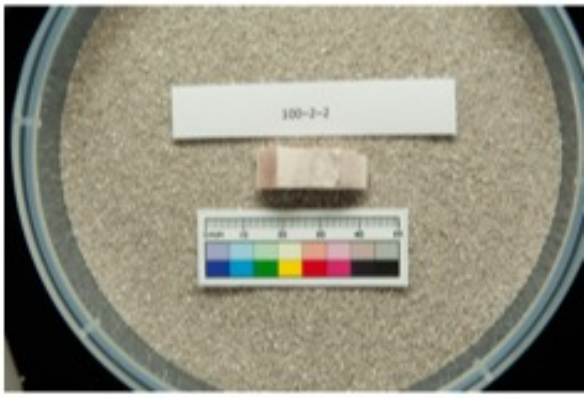
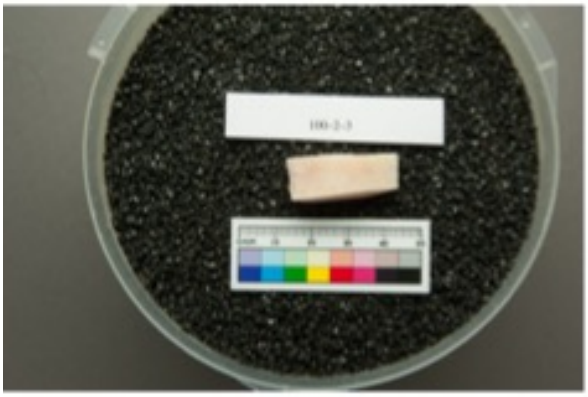
100-1-2

100-1-2

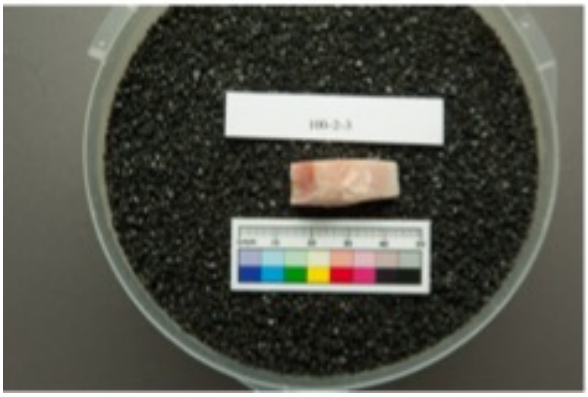
100-1-2





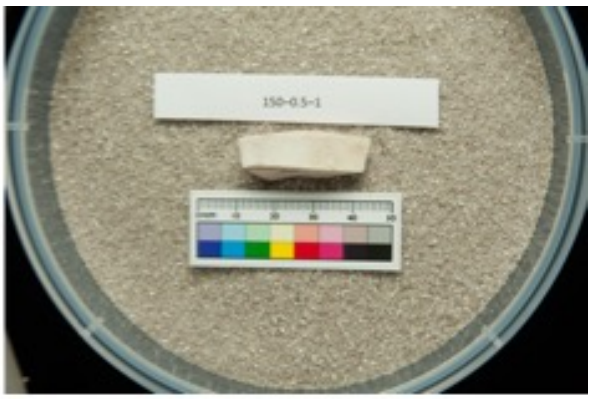




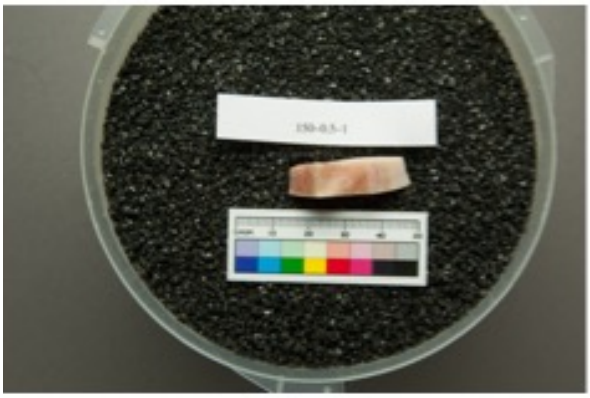







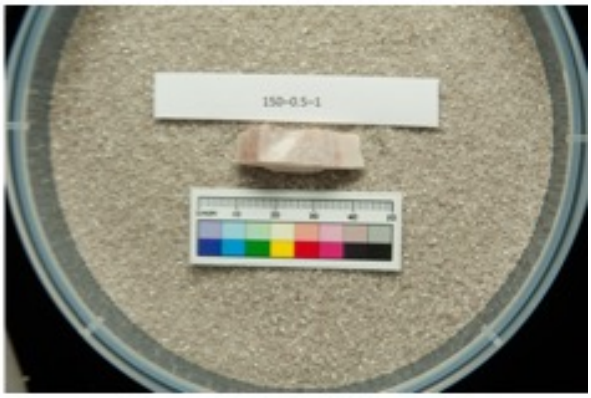


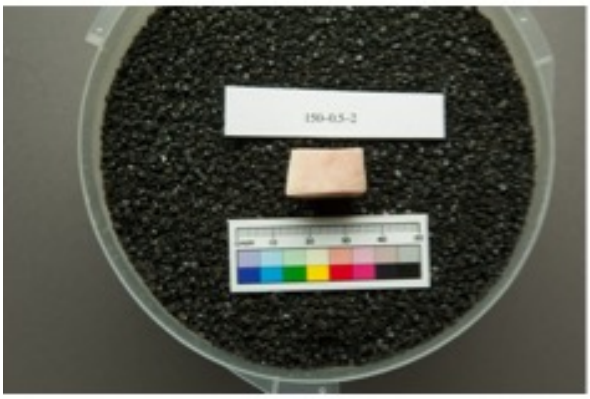


150-0.5-1

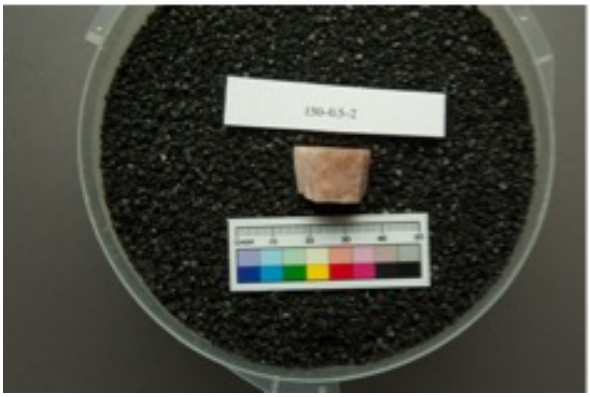

150-0.5-1


150-0.5-1

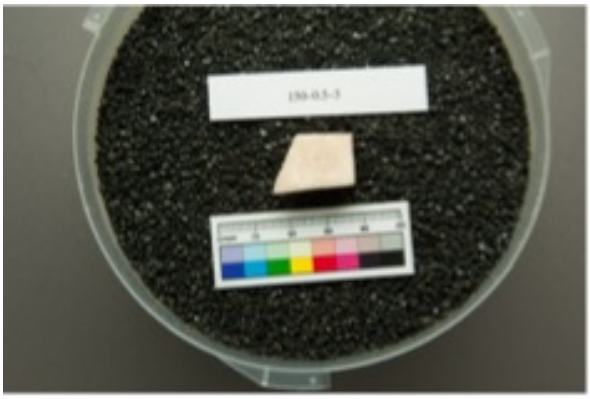
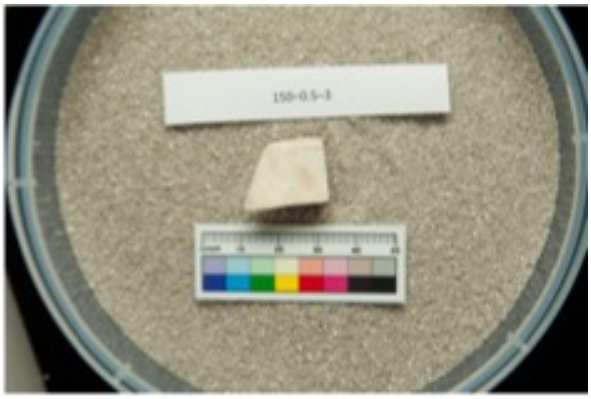
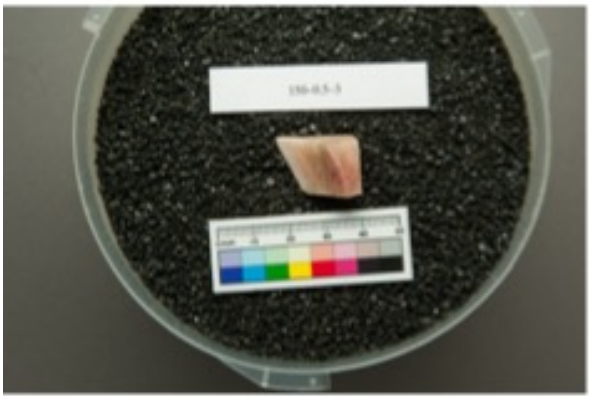

150-0.5-1

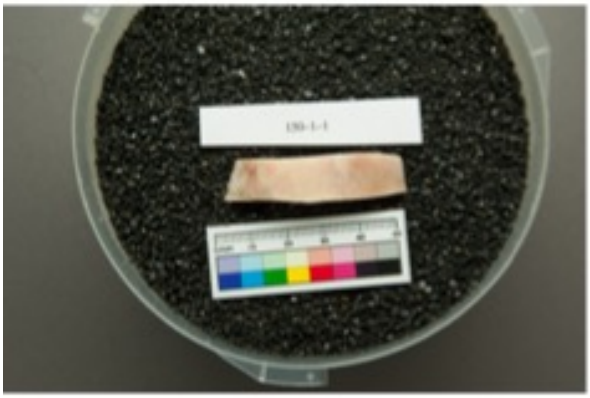

150-0.5-2


150-0.5-2

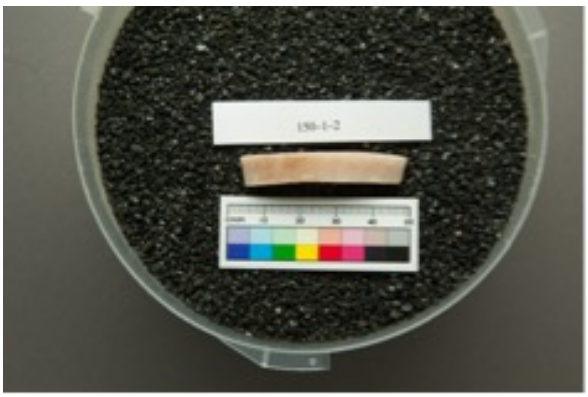
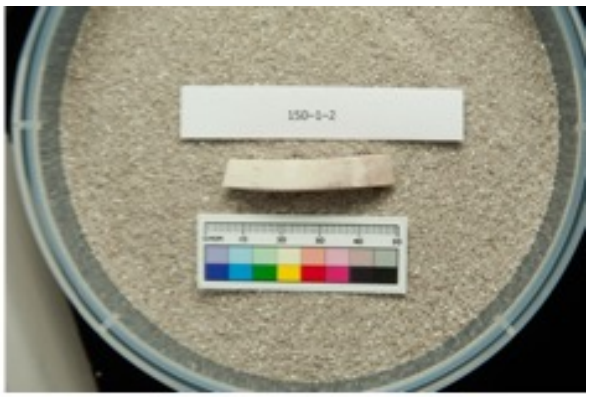
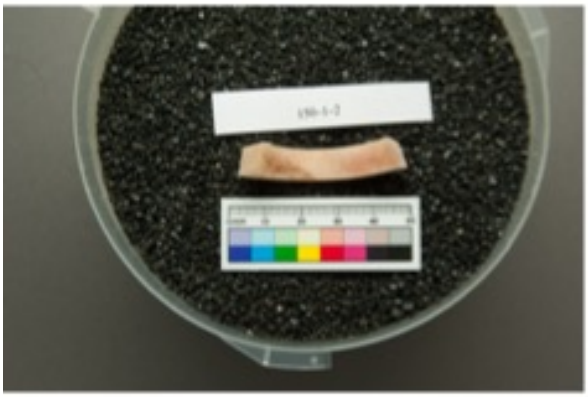
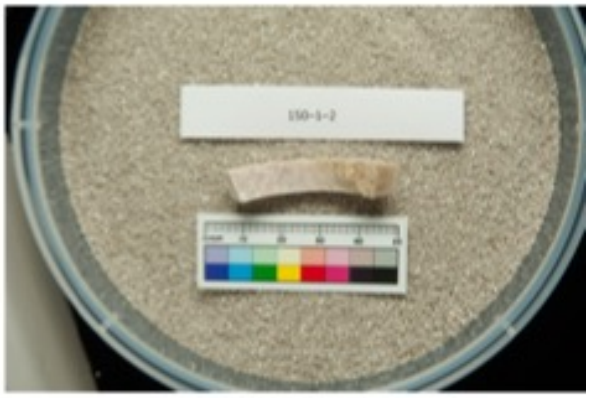
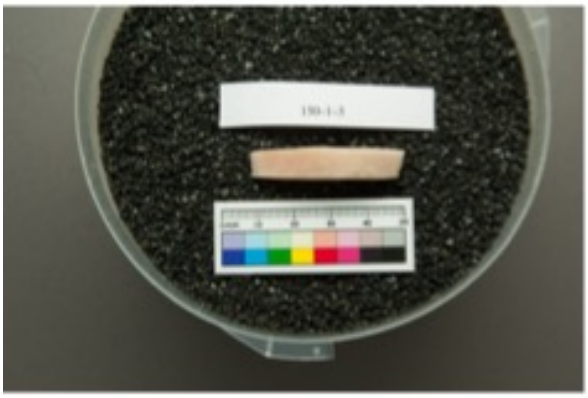

150-0.5-2


150-0.5-2

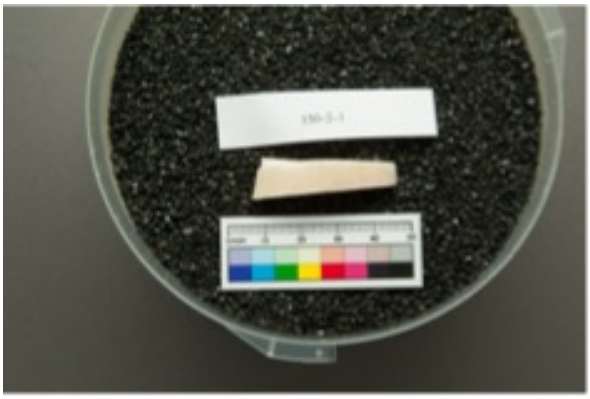




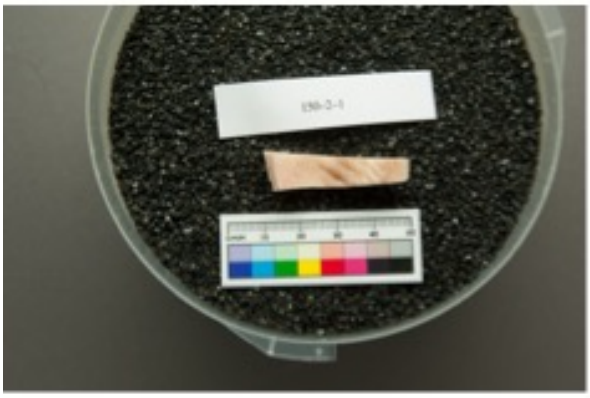


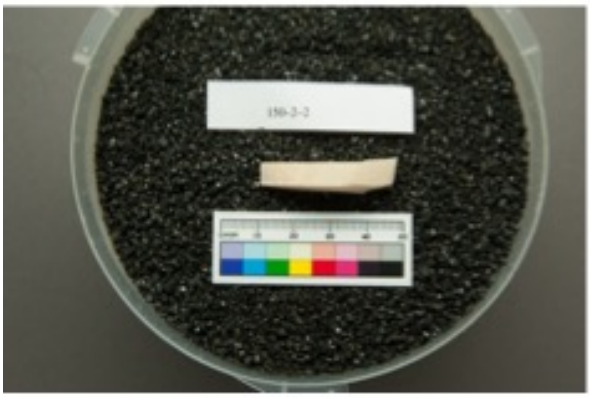


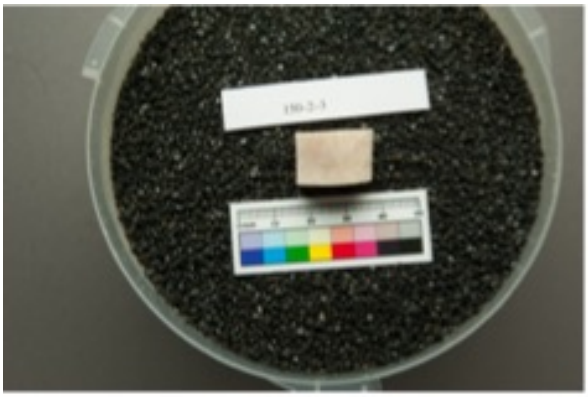
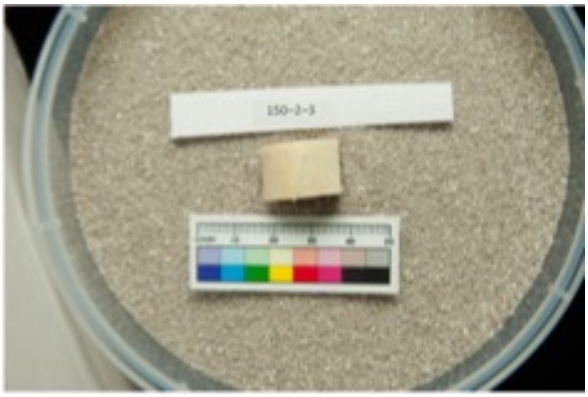


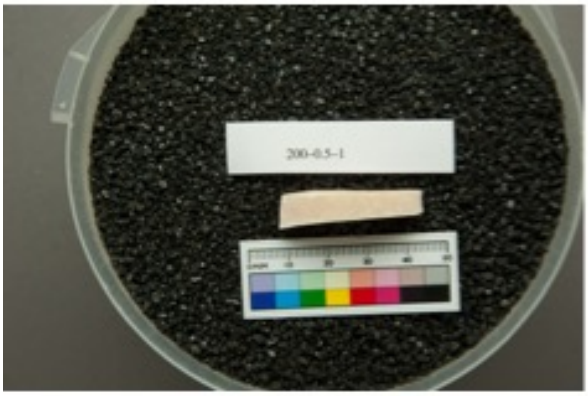



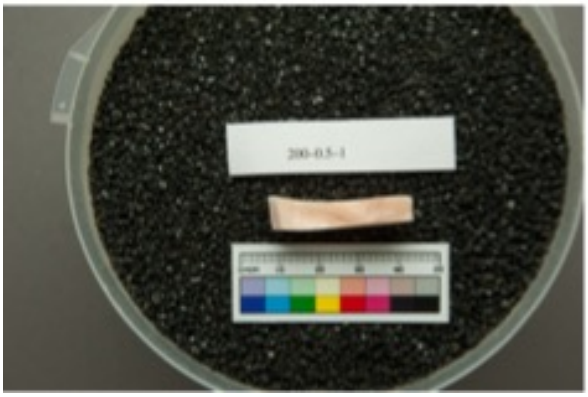


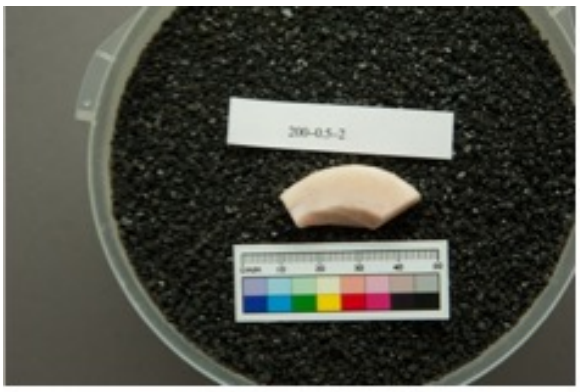




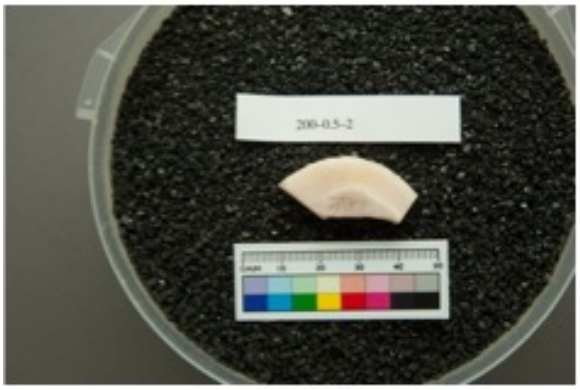




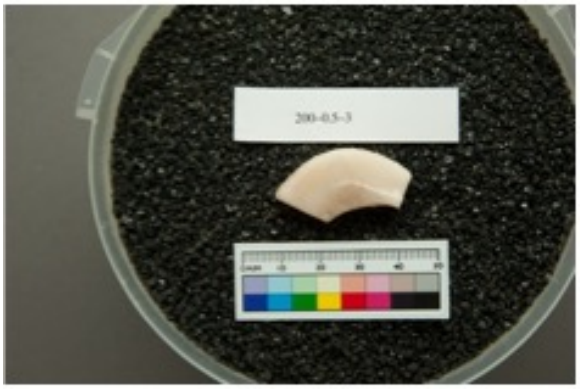




200-0.5-2

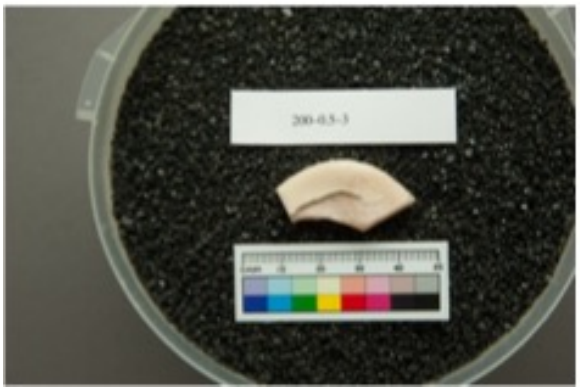

200-0.5-2


200-0.5-2


200-0.5-2

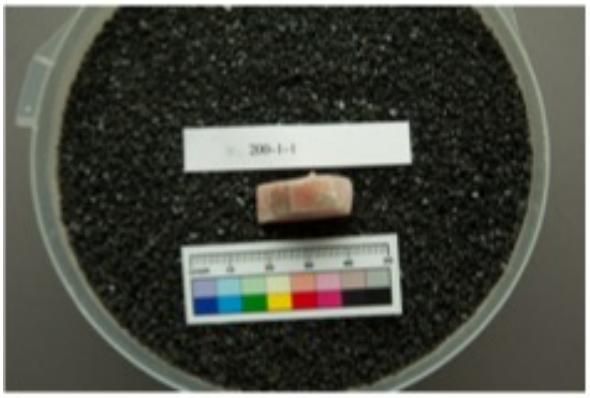

200-0.5-3

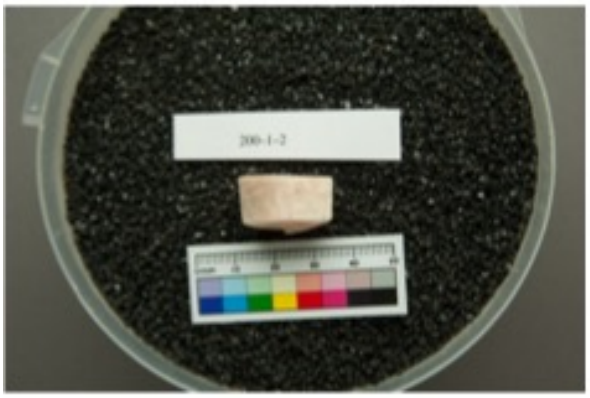

200-0.5-3

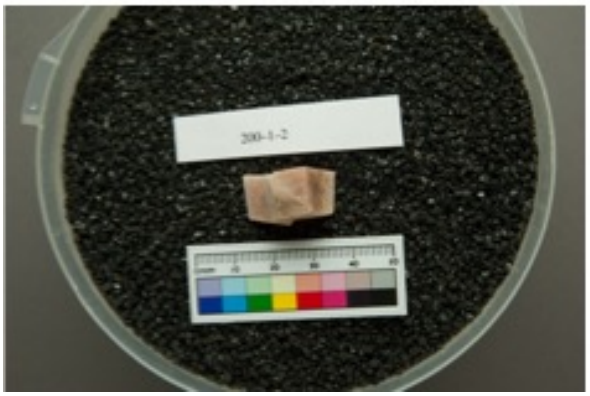

200-0.5-3

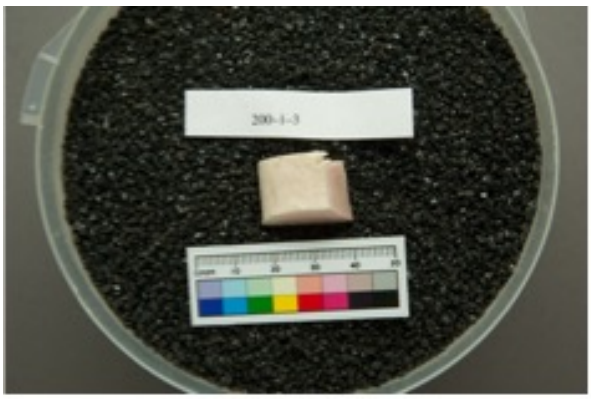

200-0.5-3



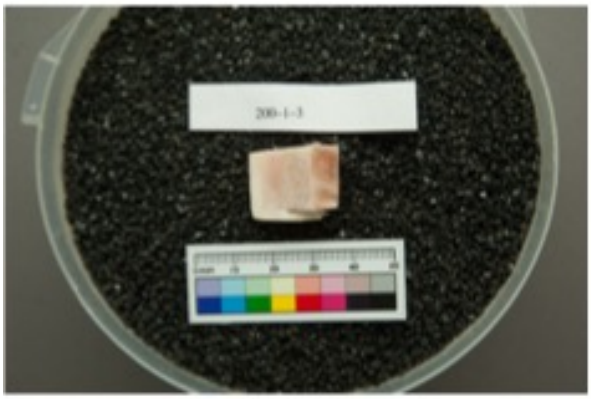




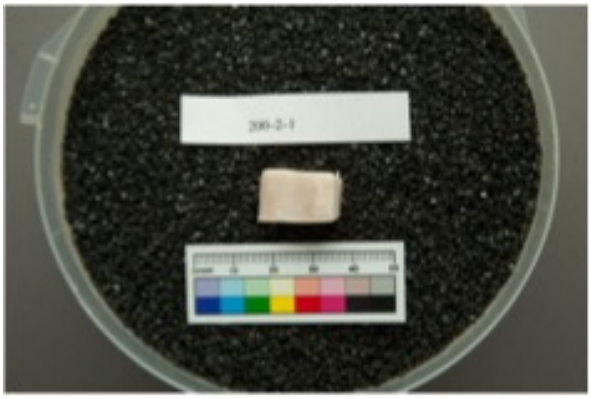


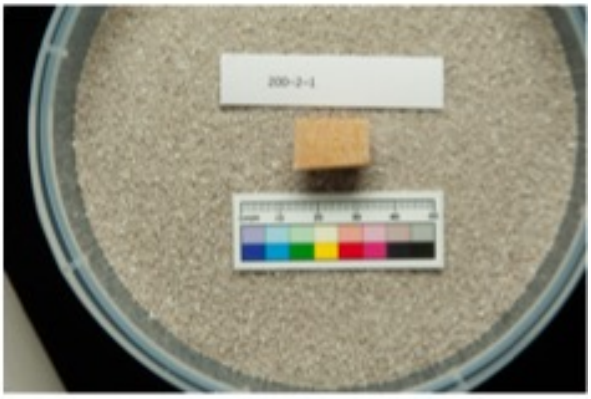


200-1-3

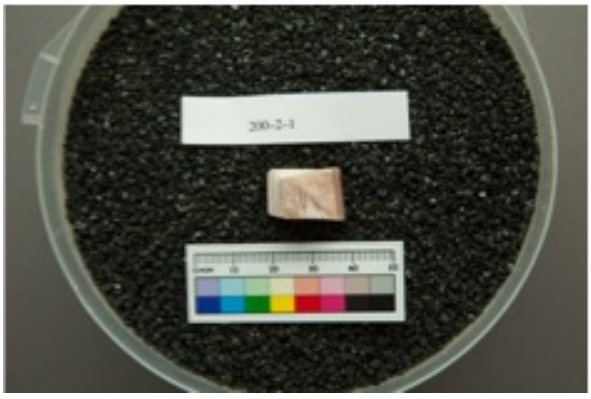

200-1-3


200-1-3

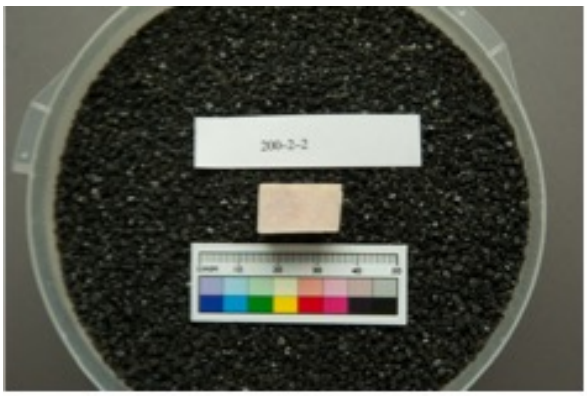

200-1-3


200-2-1

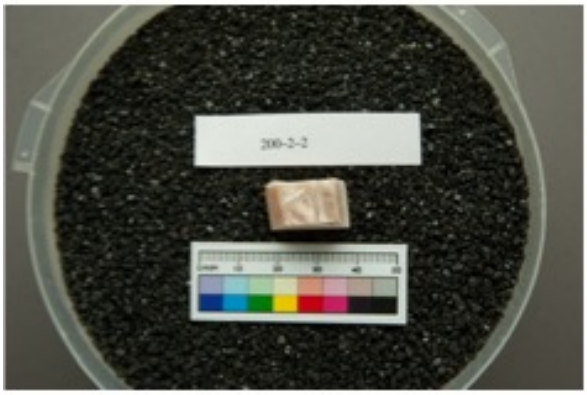

200-2-1


200-2-1

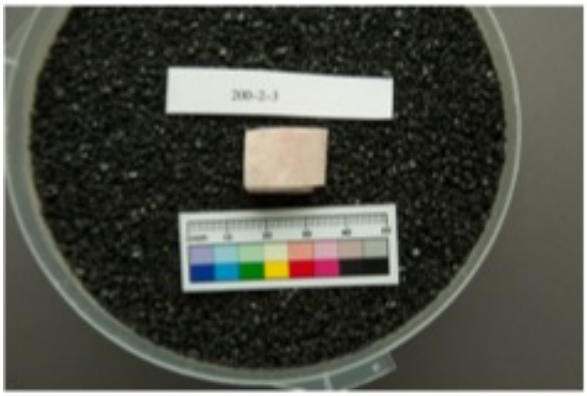

200-2-1

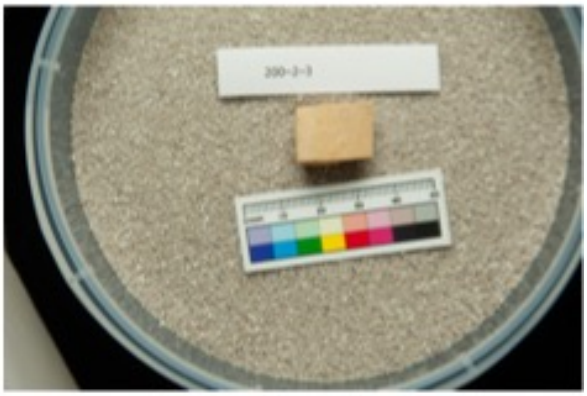

200-2-2


200-2-2


200-2-2


200-2-2

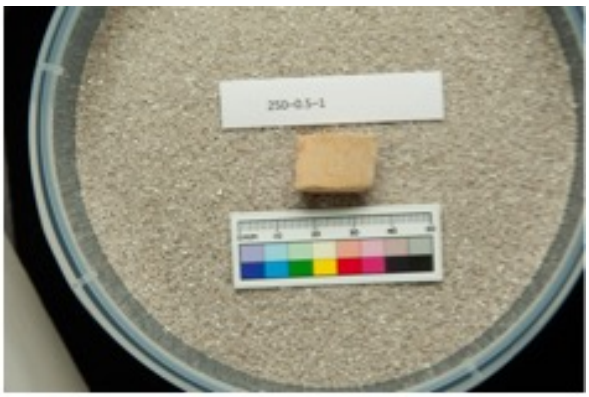

200-2-3

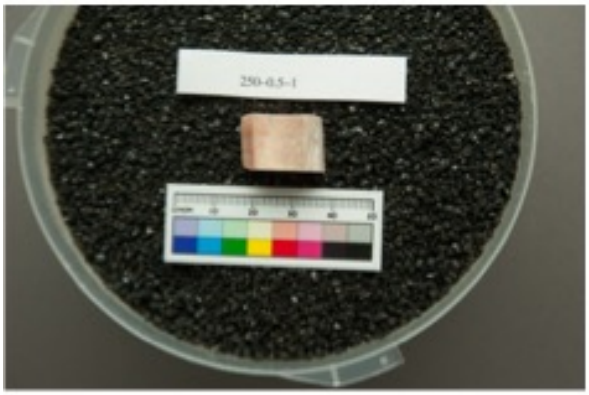

200-2-3


200-2-3

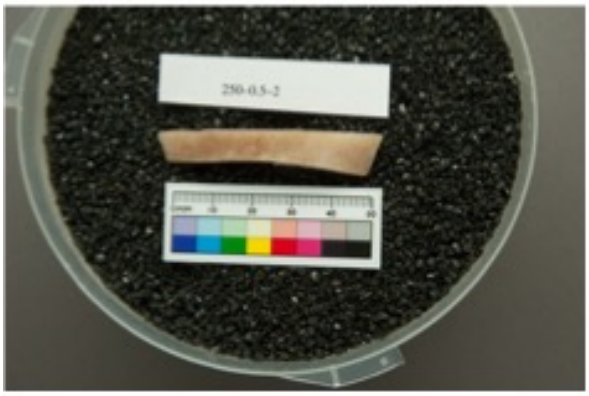

200-2-3

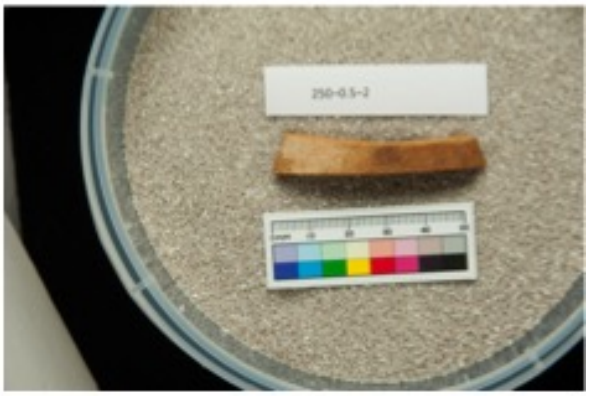

250-0.5-1


250-0.5-1

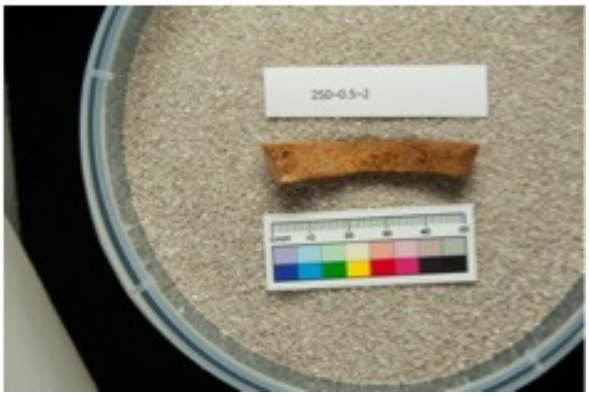

250-0.5-1

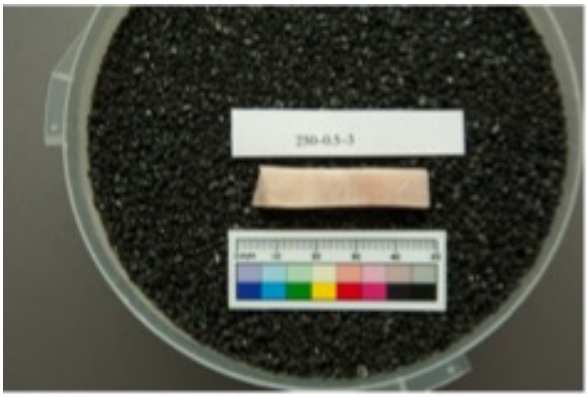

250-0.5-1


250-0.5-2

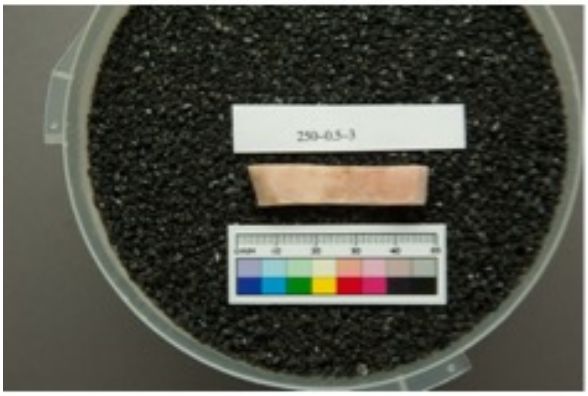

250-0.5-2


250-0.5-2

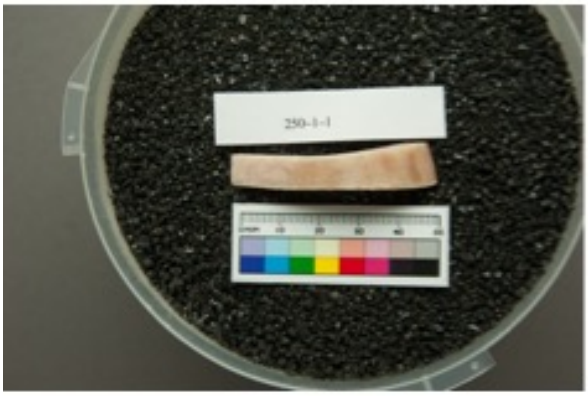

250-0.5-2


250-0.5-3

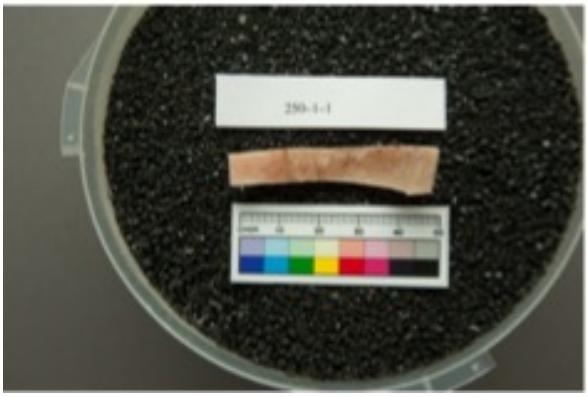

250-0.5-3


250-0.5-3

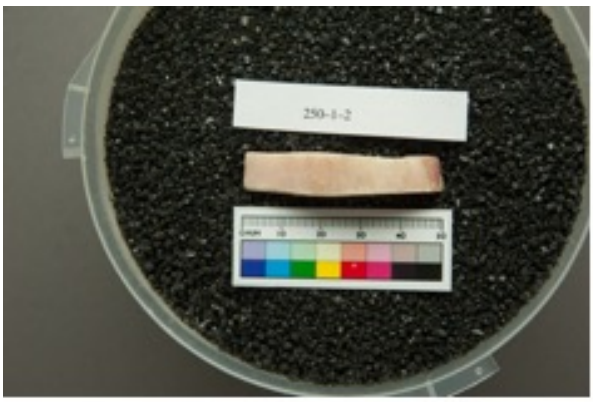

250-0.5-3


250-1-1

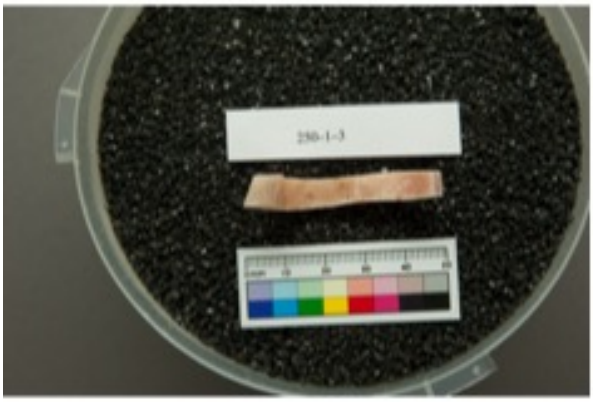

250-1-1


250-1-1

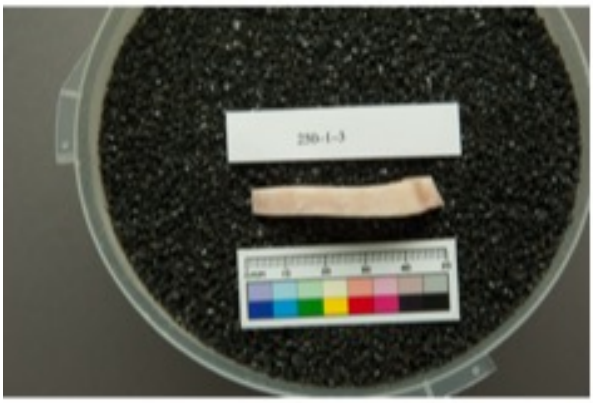

250-1-1


250-1-2

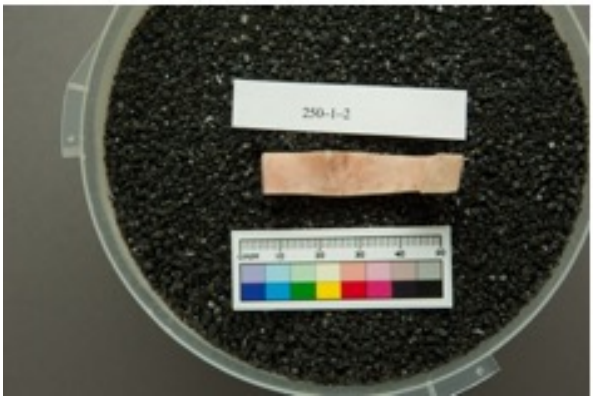

250-1-3


250-1-3


250-1-3

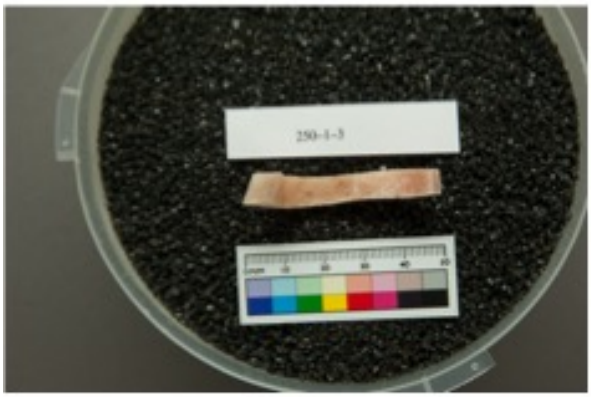

250-1-3


250-2-1

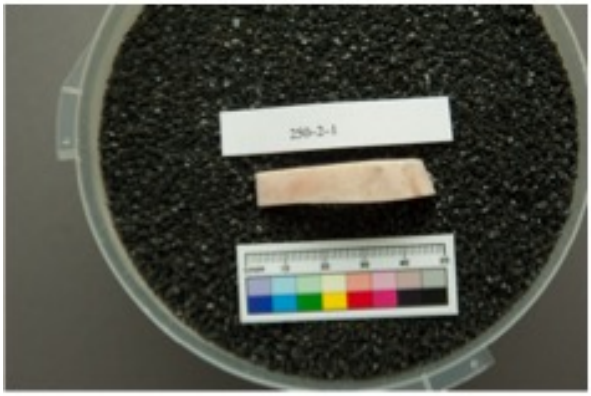

250-1-2


250-2-1

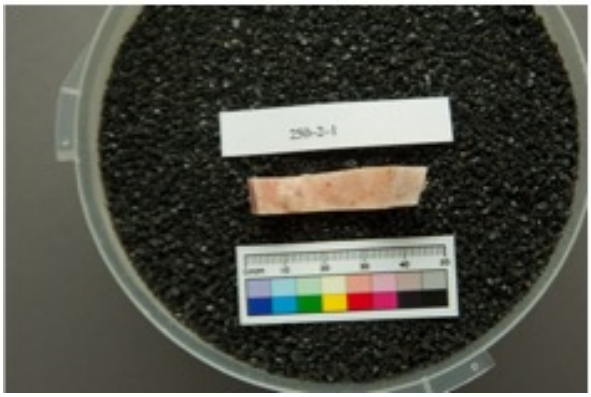

250-1-3


250-1-3

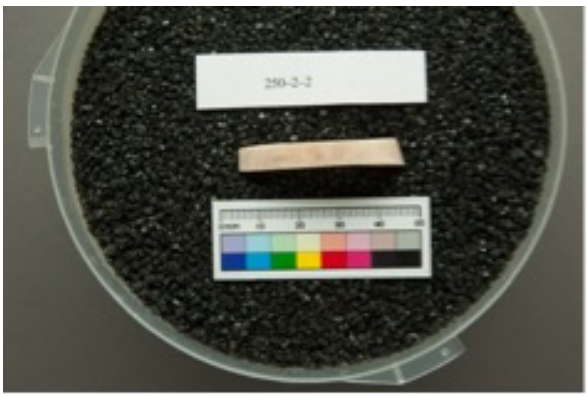

250-1-3


250-2-1

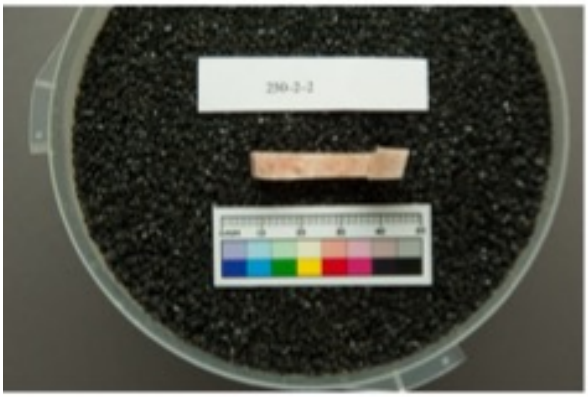

250-2-1


250-2-1

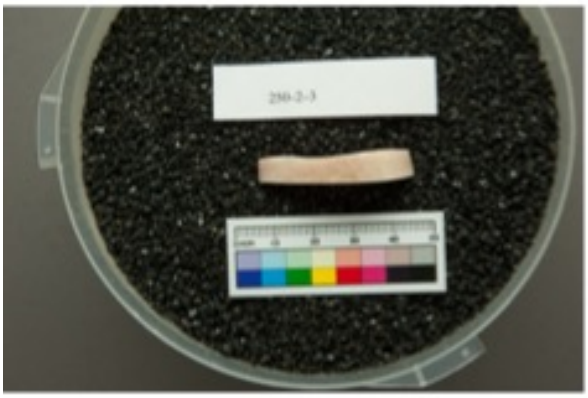

250-2-1


250-2-2

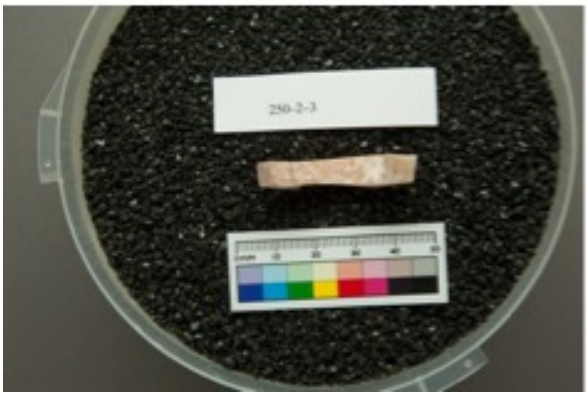

250-2-2


250-2-2

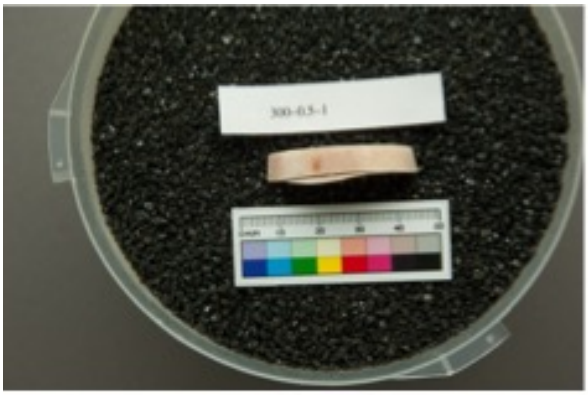

250-2-2


250-2-3

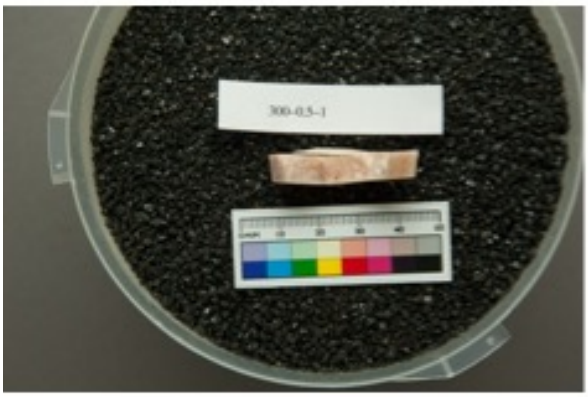

250-2-3


250-2-3

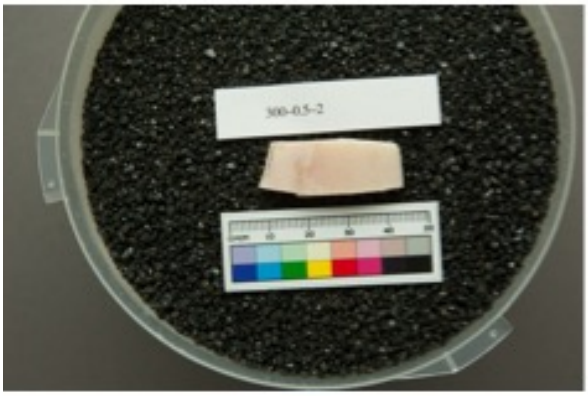

250-2-3


300-0.5-1

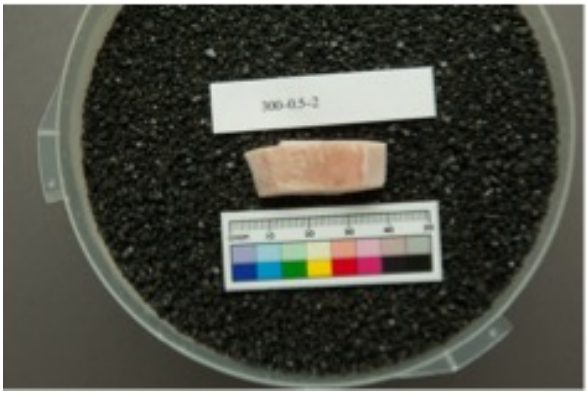

300-0.5-1


300-0.5-1


300-0.5-1


300-0.5-2

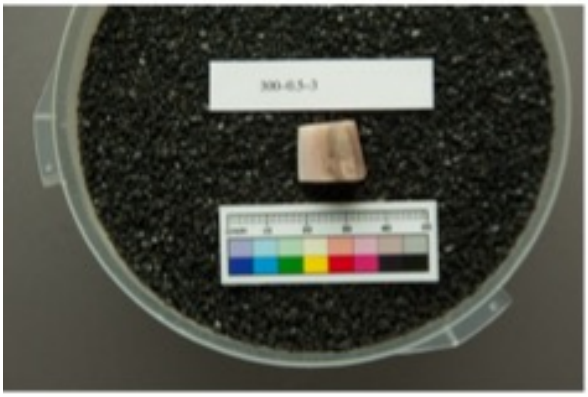

300-0.5-2


300-0.5-2

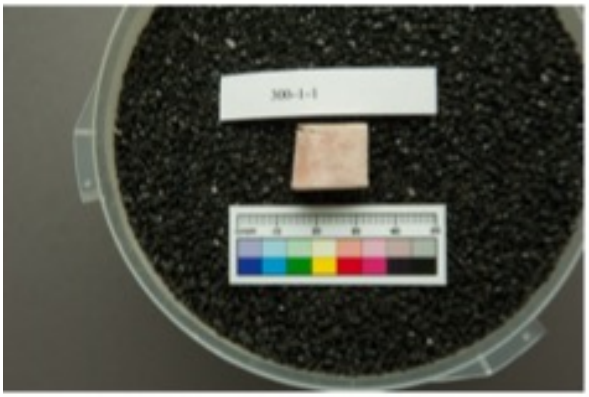

300-0.5-2

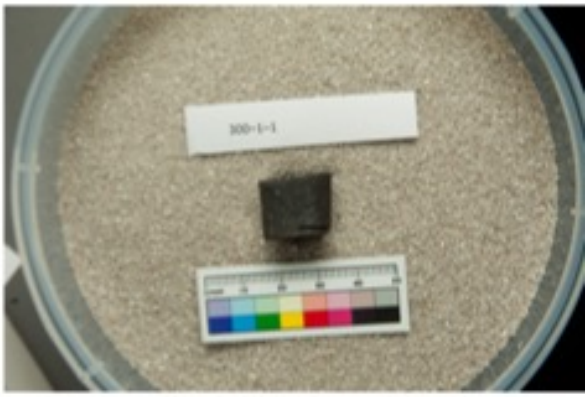

300-0.5-3

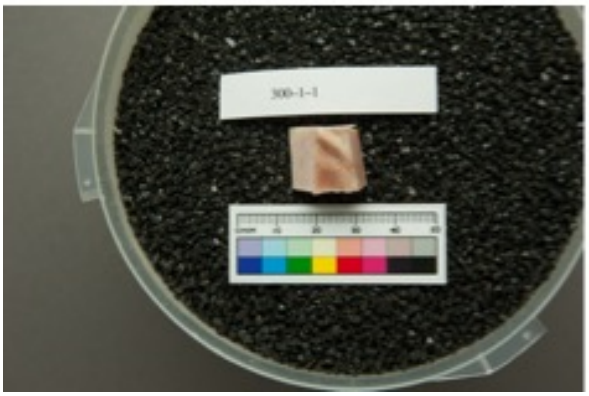

300-0.5-3


300-0.5-3

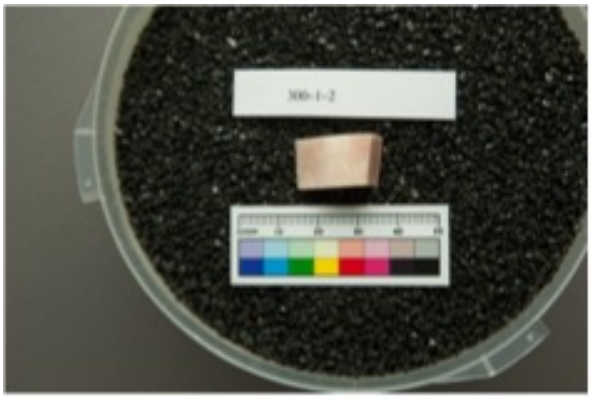

300-0.5-3

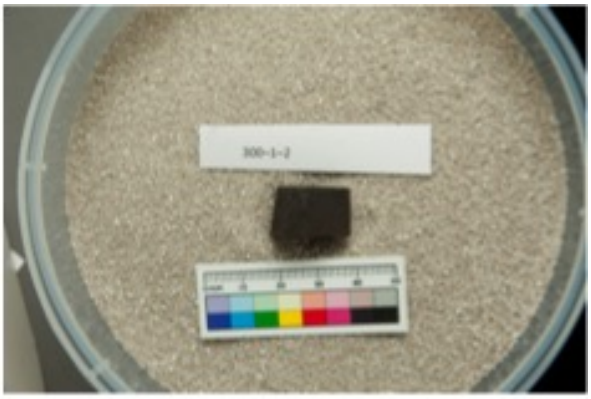

300-1-1

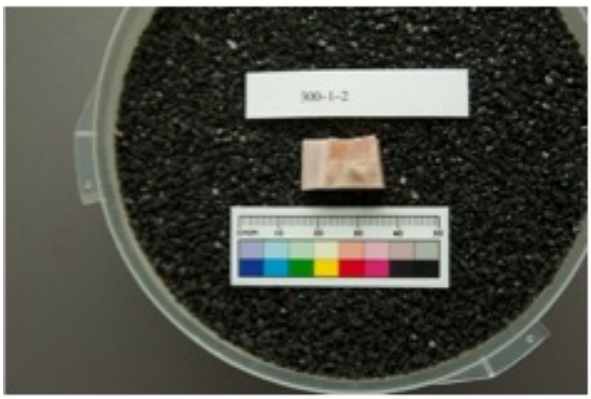

300-1-1

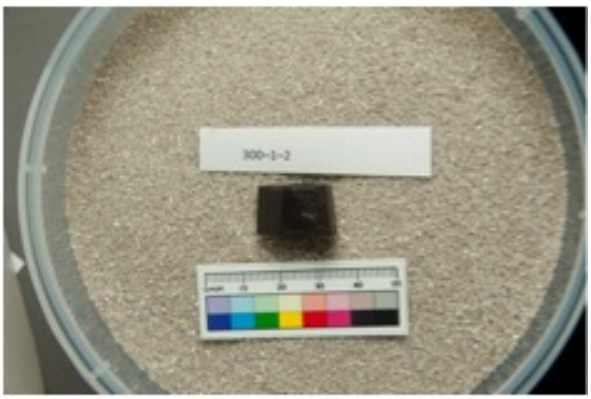

300-1-1

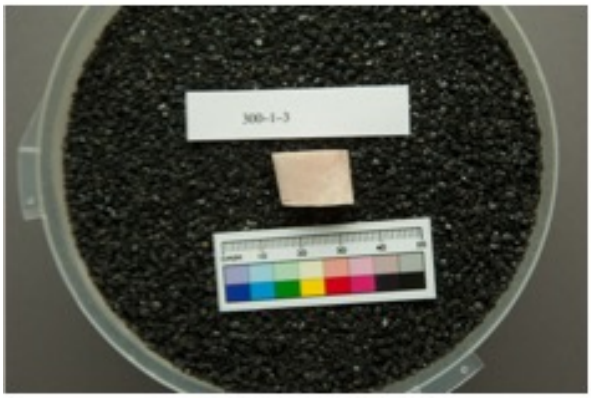

300-1-1


300-1-2

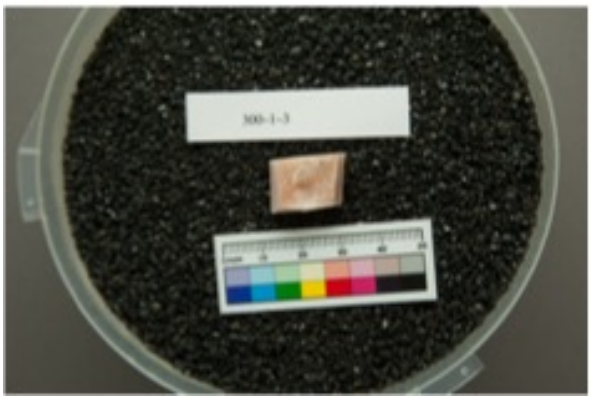

300-1-2

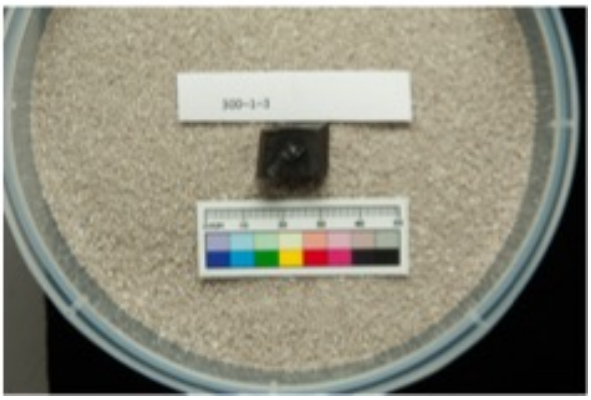

300-1-2

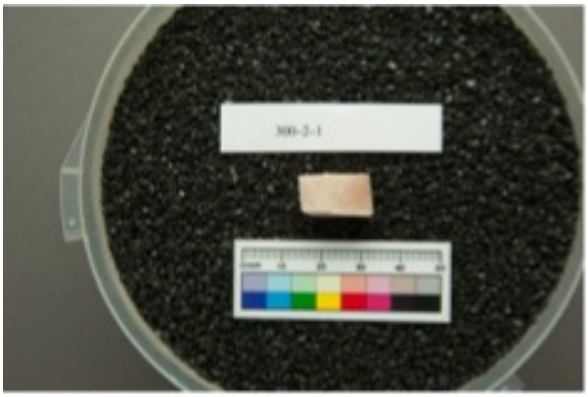

300-1-2

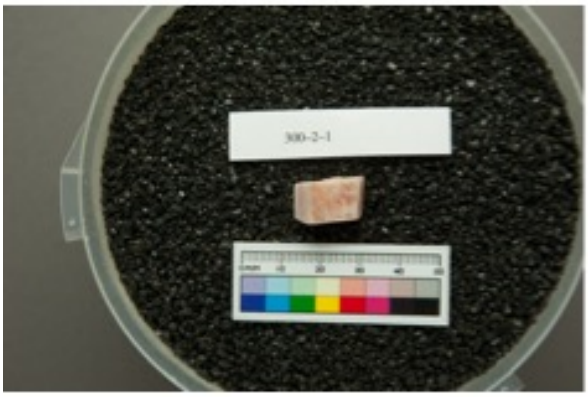

300-1-3

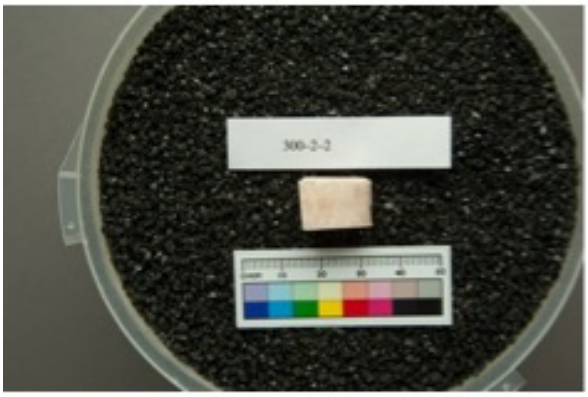
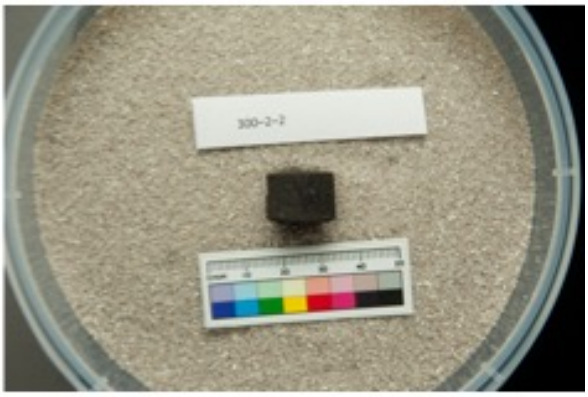

300-1-3


300-1-3

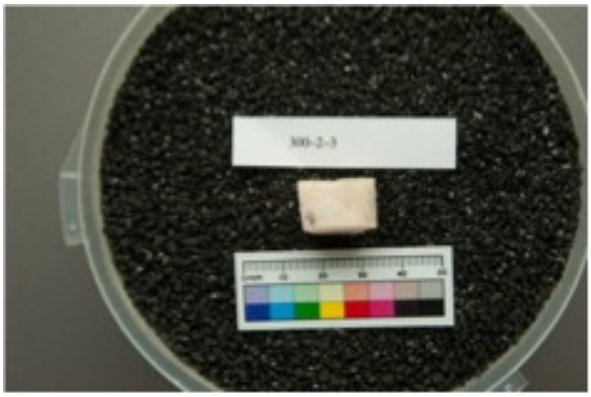

300-1-3

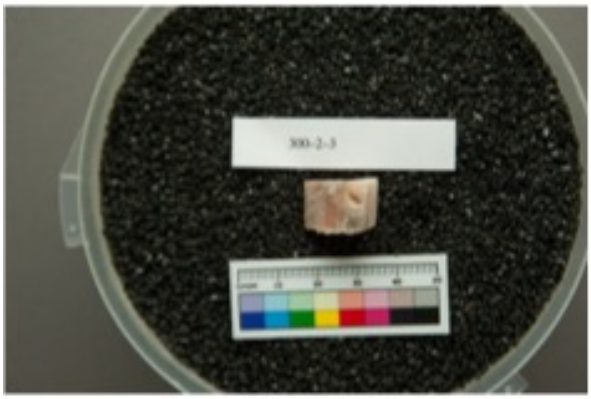


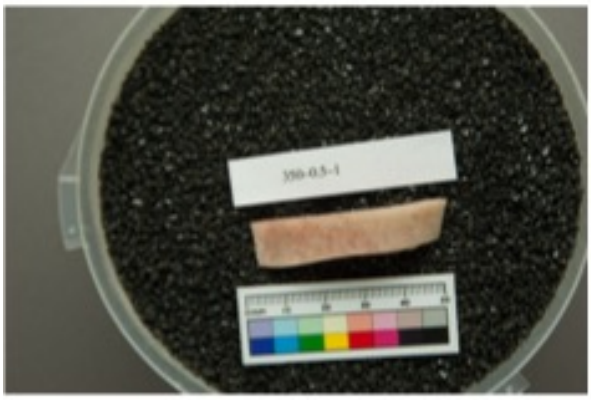


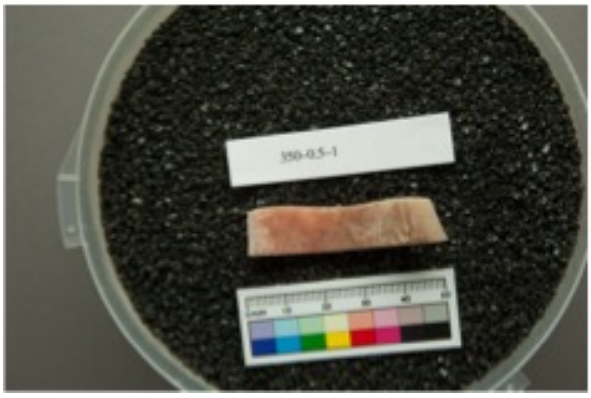



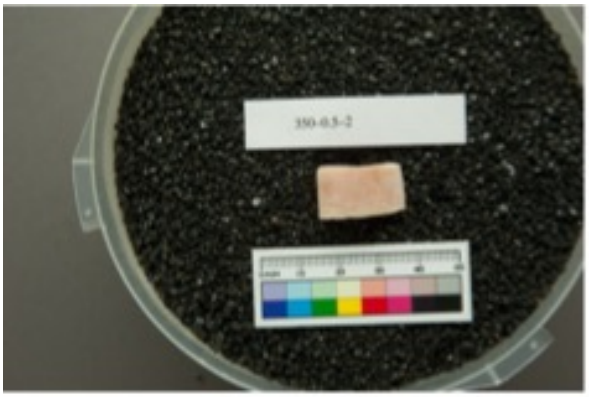


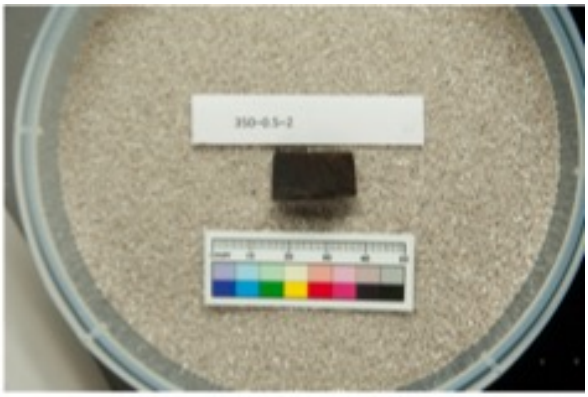


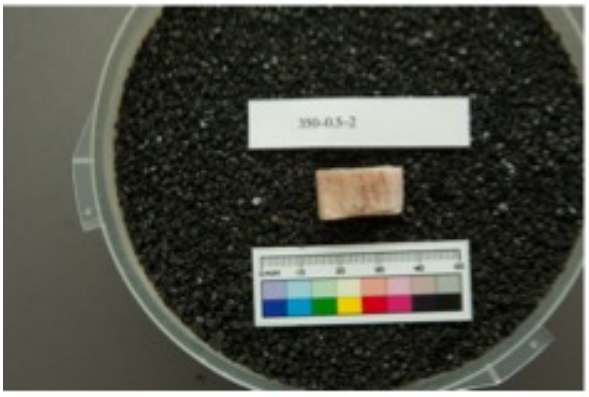


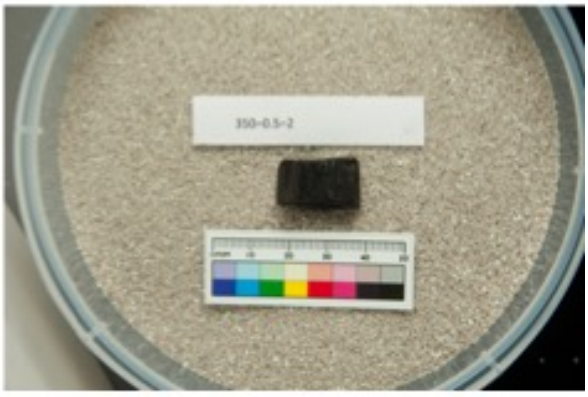






350-0.5-2


350-0.5-2


350-0.5-2

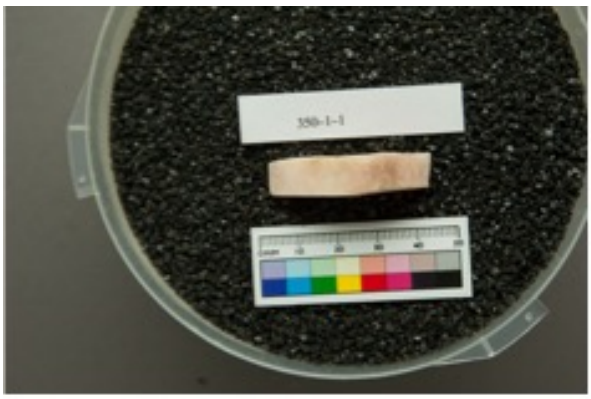

350-0.5-2


350-0.5-3

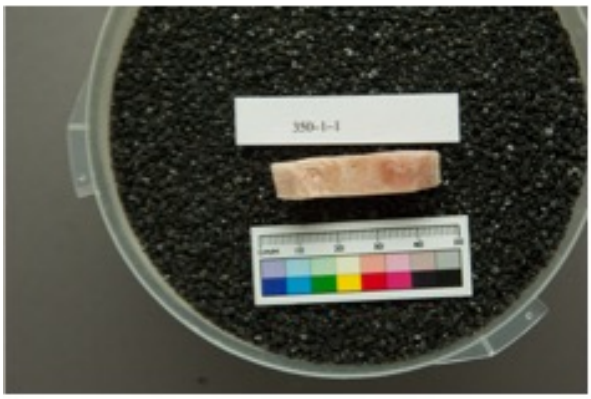

350-0.5-1


350-0.5-3

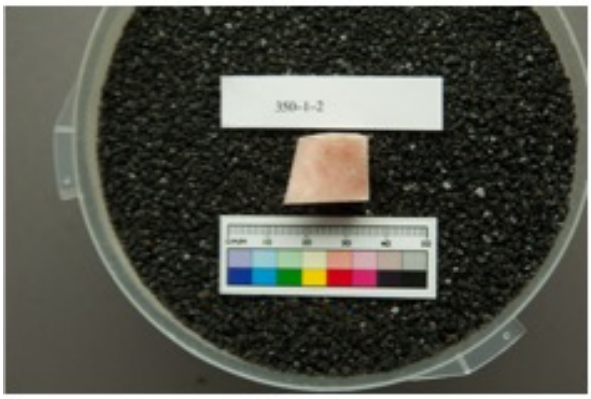

350-0.5-1

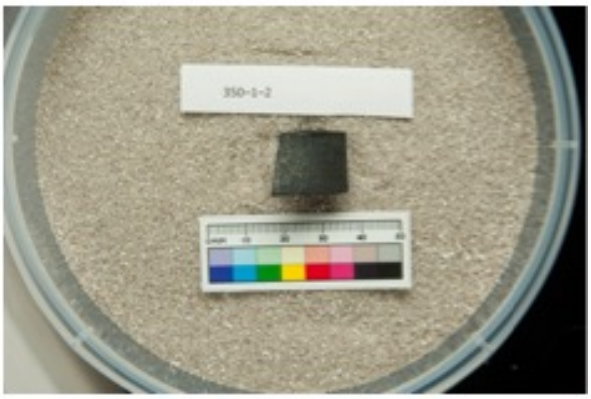

350-1-1

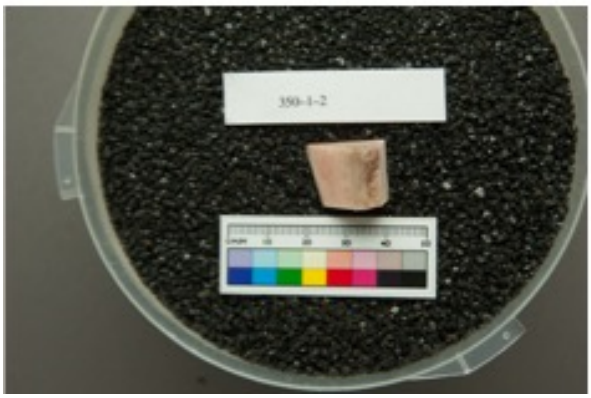

350-1-1


350-1-1

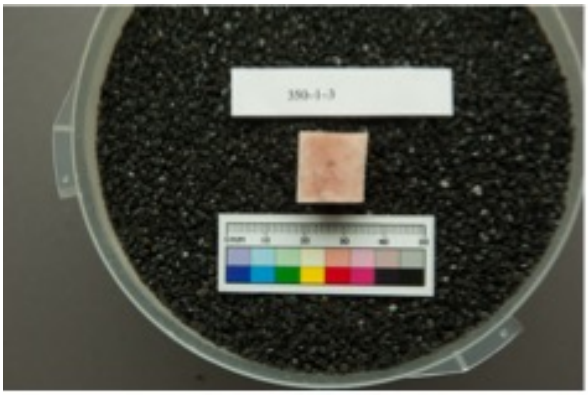

350-1-1

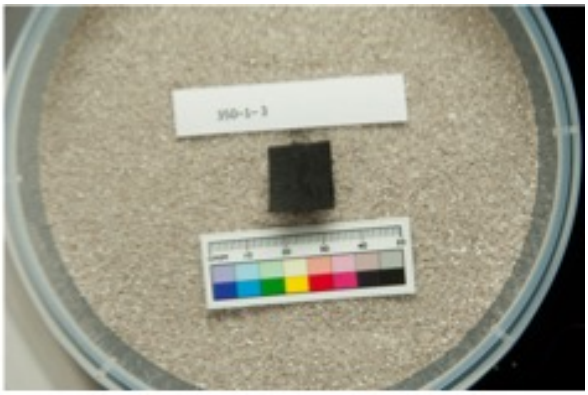

350-1-2

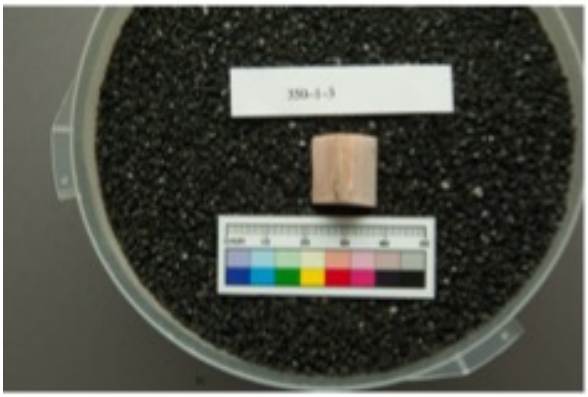

350-1-2


350-1-2

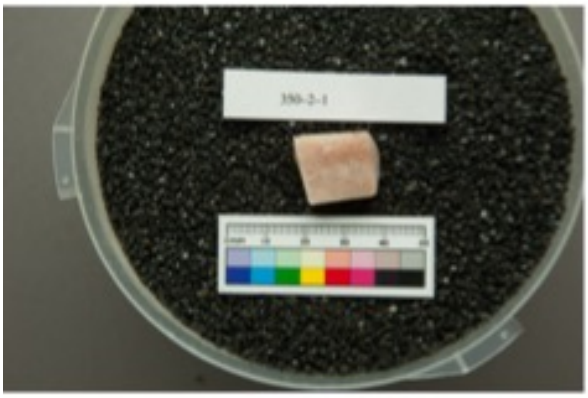

350-1-2


350-1-3

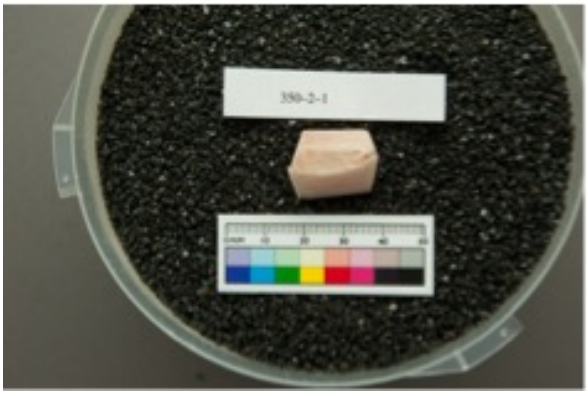

350-1-3


350-1-3

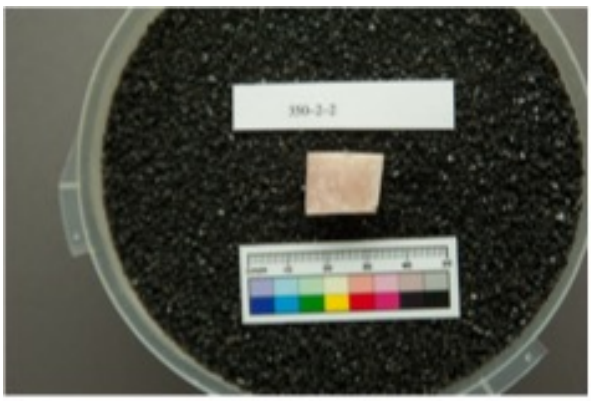

350-1-3

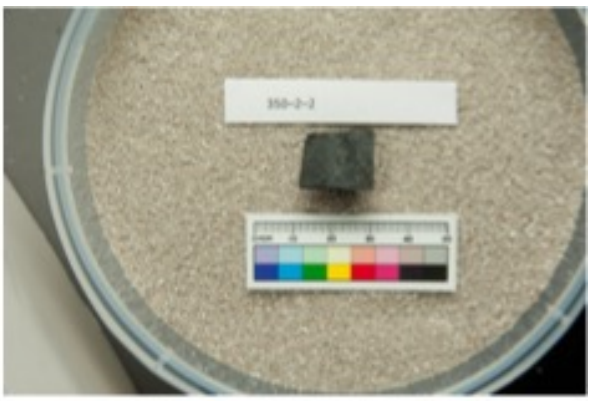

350-2-1

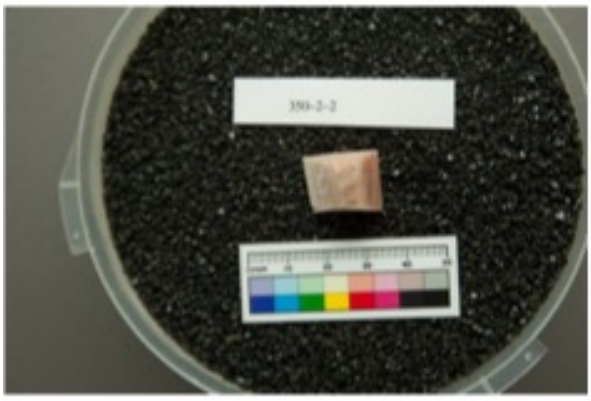

350-2-1

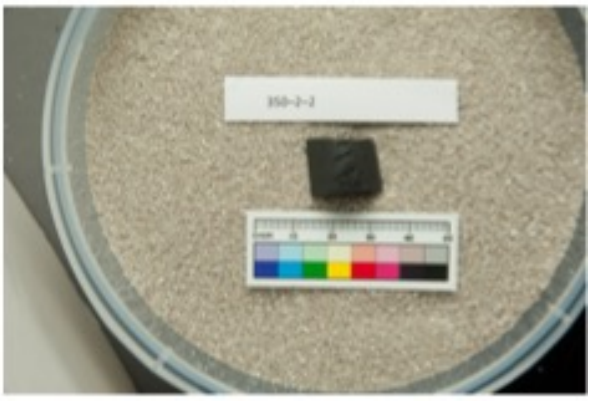

350-2-1

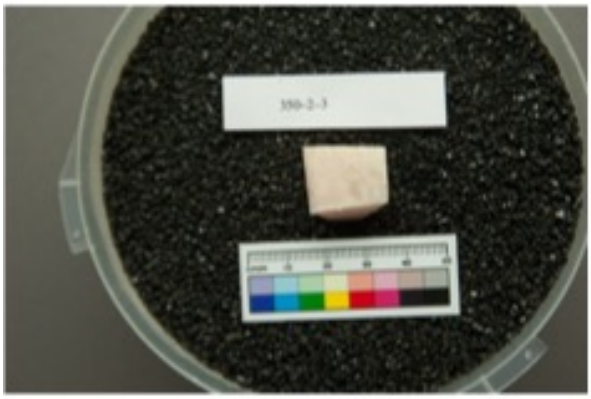

350-2-1

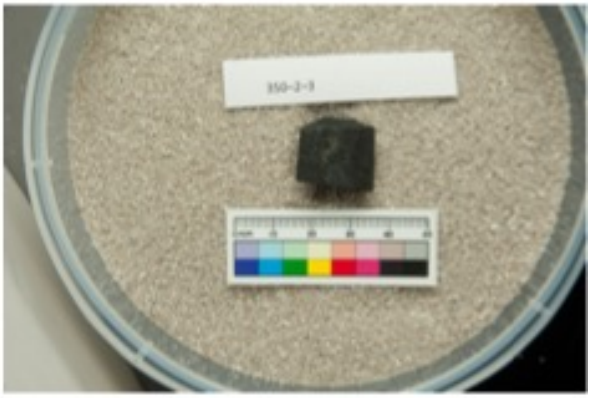

350-2-2

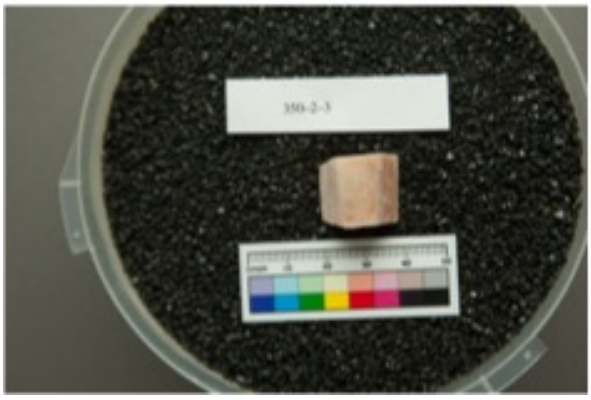

350-2-2


350-2-2

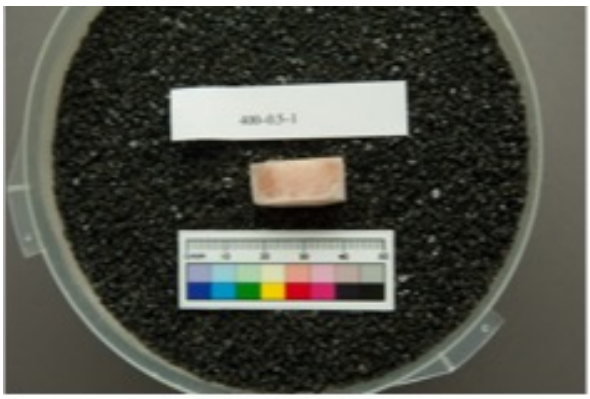
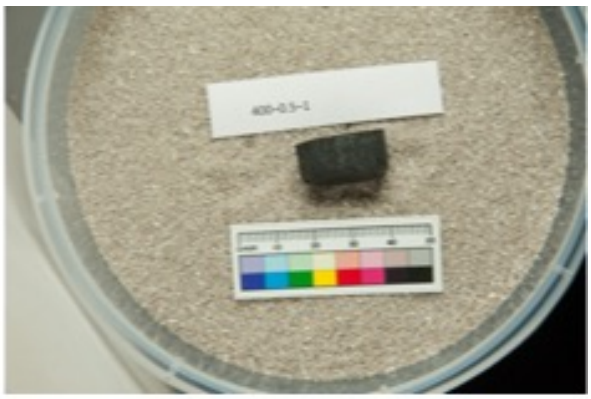
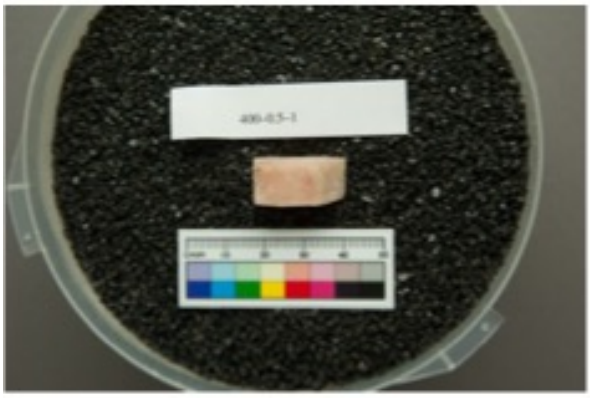
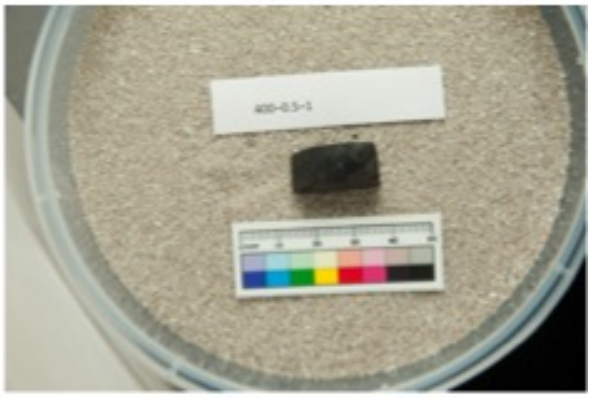
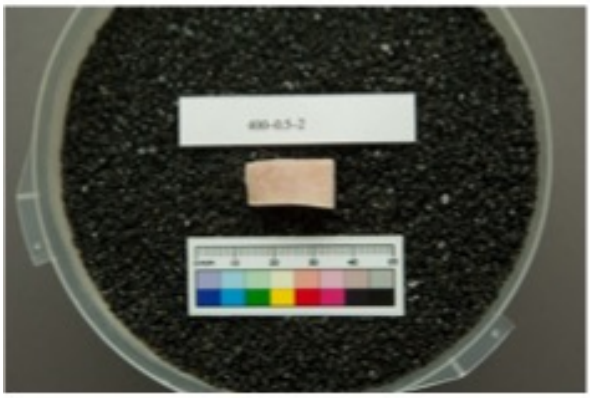
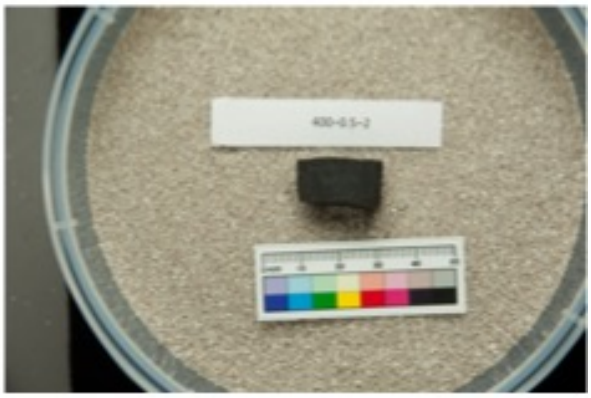
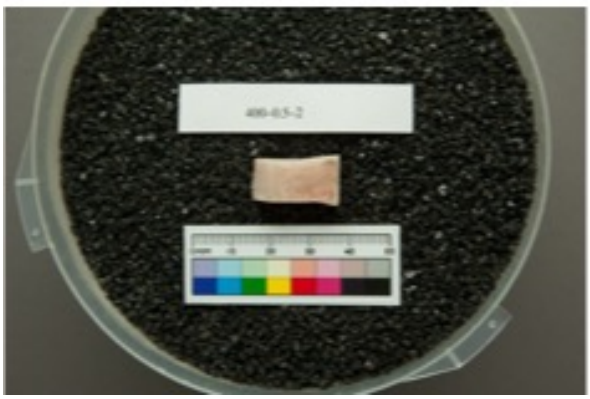

350-2-2

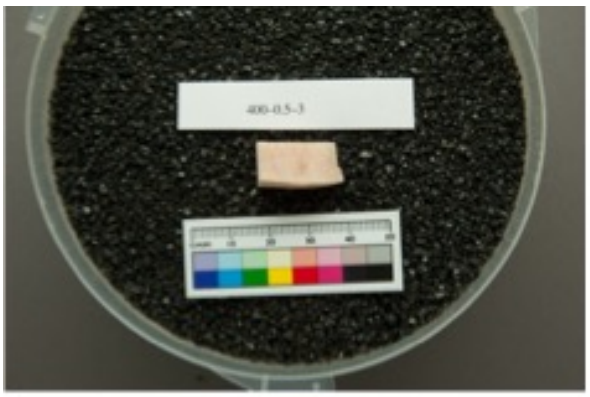

350-2-3


350-2-3


350-2-3

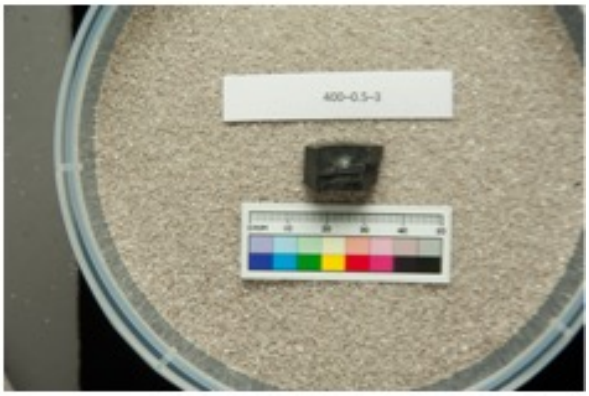

350-2-3

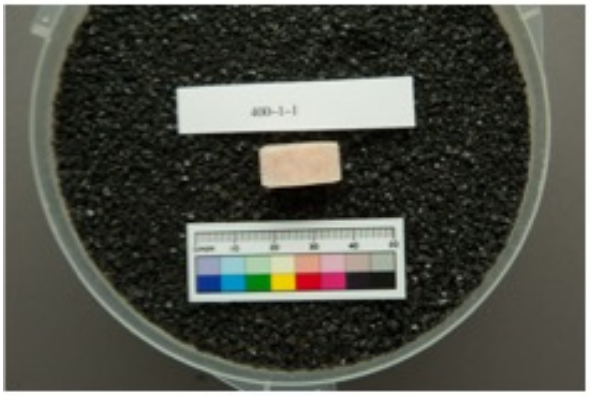










400-0.5-3

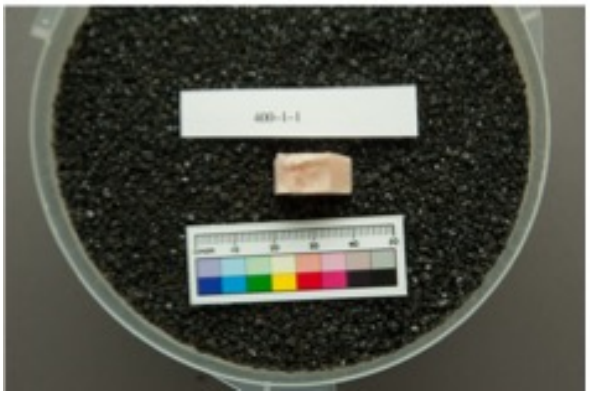

400-0.5-3


400-0.5-3

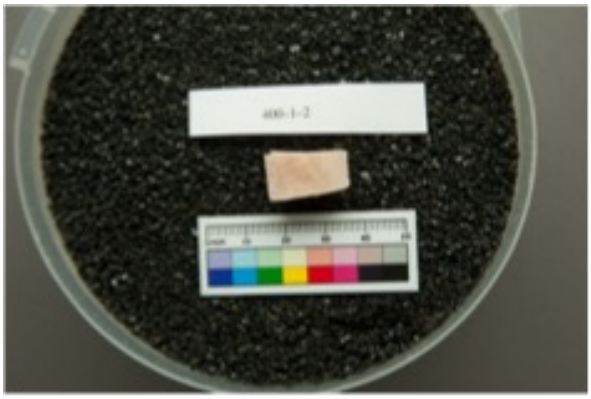
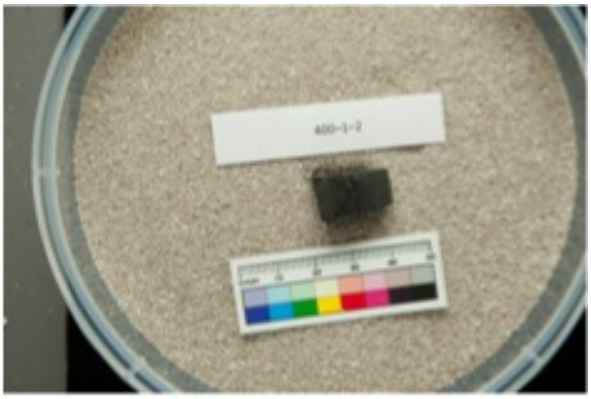
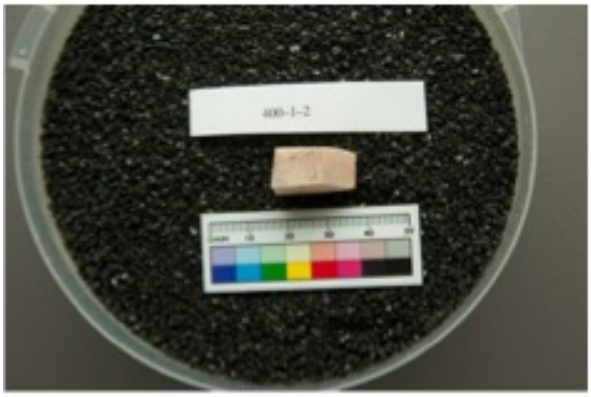
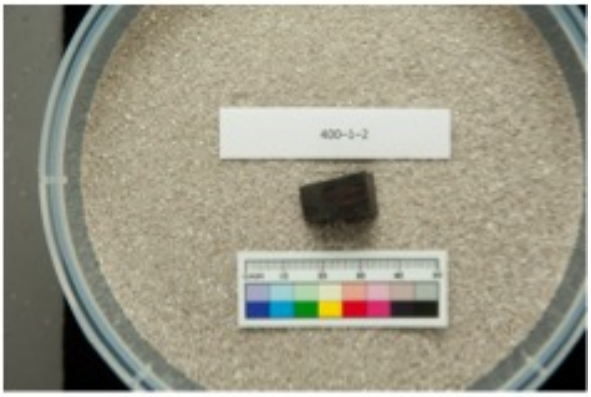
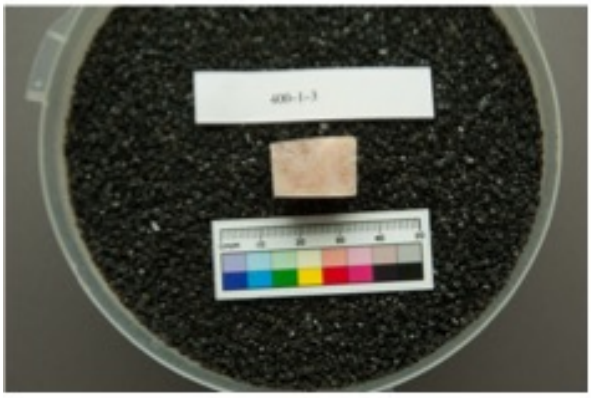
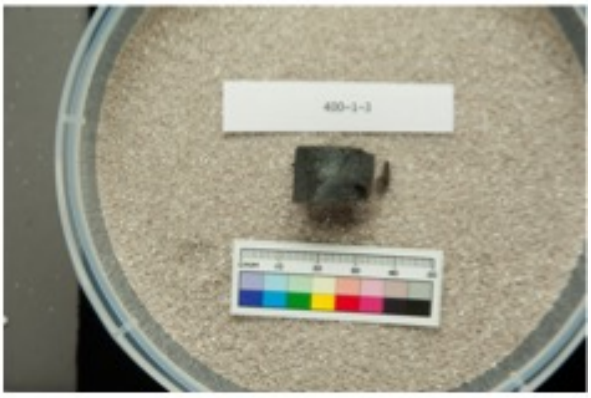
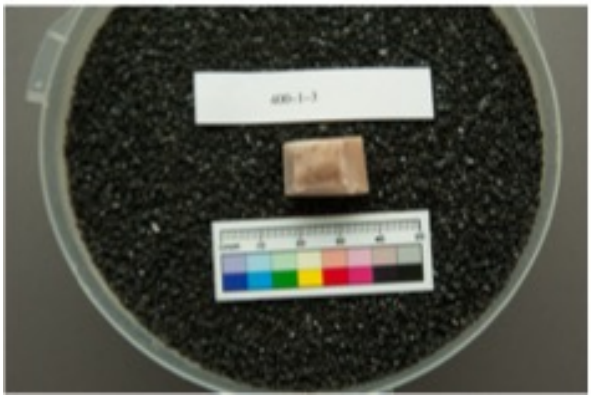
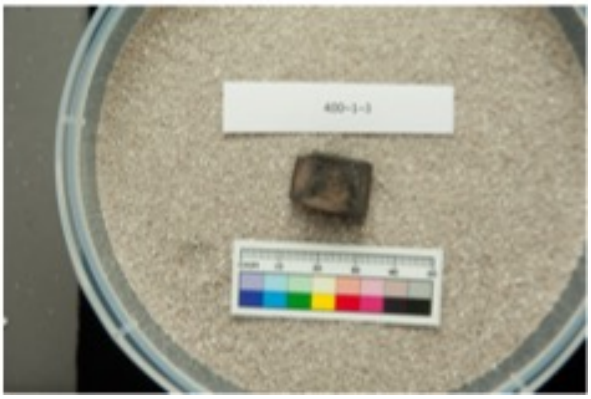

400-0.5-3

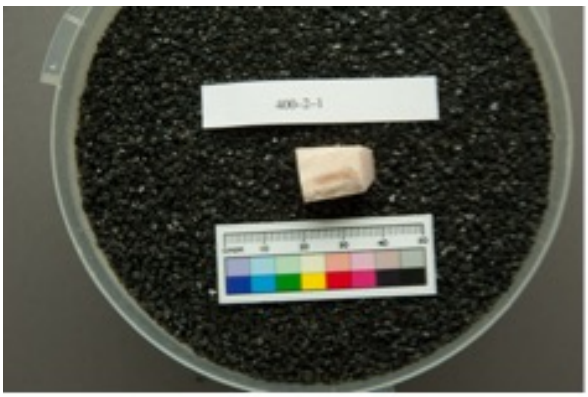
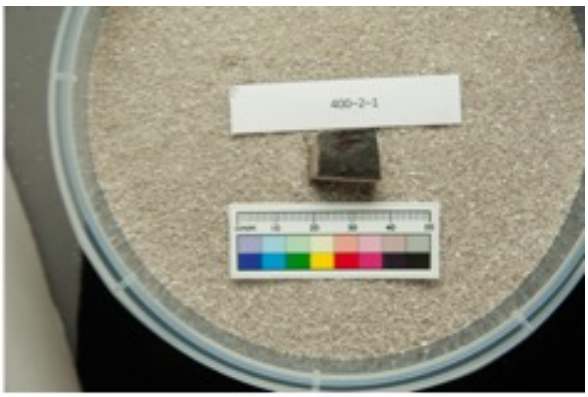
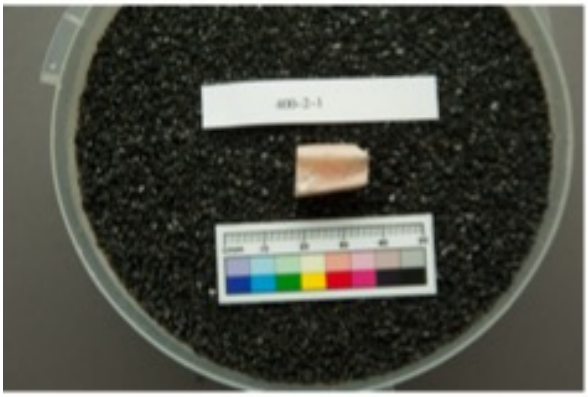

400-1-1

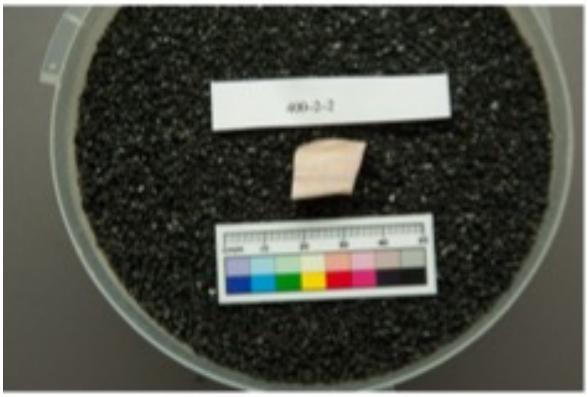

400-1-1

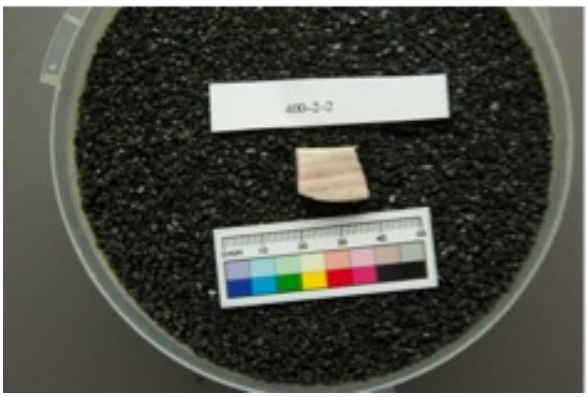

400-1-1

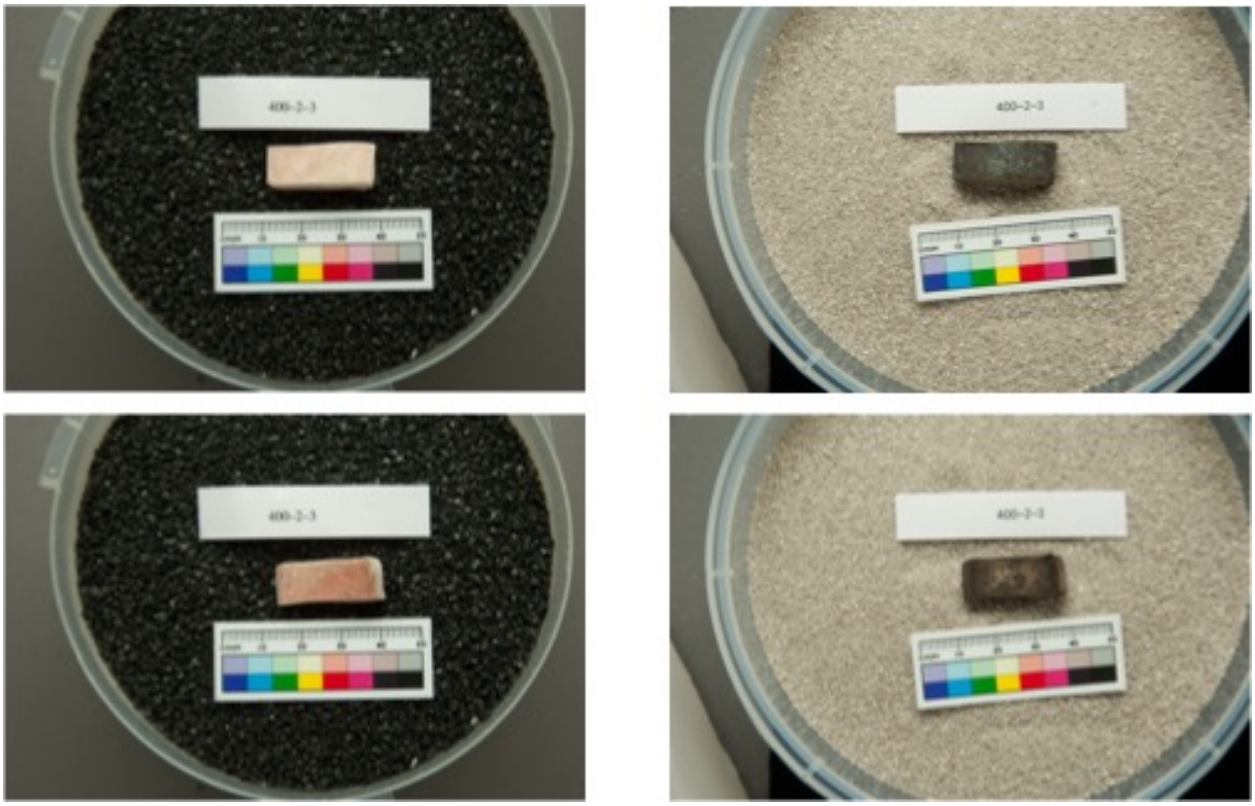

400-1-1





- Left hand column shows samples before heating, right hand column shows samples after heating.
- Conventions used in numbering the samples reflect heating conditions. The first number is the target temperature, the second number is the length of exposure, the final number is an arbitrary designation to separate the three samples exposed to the same conditions. Thus, sample '100-0.5-1' was the first of three samples heated to 100°C for 0.5 hours.
- For the three control samples the letters following the sample number reflect the position along the humeral shaft at which the sample was taken. P = proximal, C = central and D = distal.

Appendix 5 – Raw Colour Data from the Controlled Heating Experiment

Measurements Before Heating:

Sample	Light	Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Control-1(p)	SCI	L*	76.37	71.29	73.34	74.69	70.21	66.97	63.77	68.15	76.72	72.71	56.00	55.32	58.27	60.26	60.37	55.17	55.37	61.18	60.94	56.74
		a*	0.99	1.44	1.00	0.63	0.13	0.86	1.96	0.65	-0.60	0.93	5.09	4.91	4.40	3.76	4.46	5.27	5.31	2.83	2.63	3.45
		b*	7.69	8.43	8.44	9.38	7.94	10.39	8.00	9.85	6.82	8.34	11.52	11.15	11.88	11.92	12.41	11.32	10.57	12.44	12.07	11.61
	-	G	72	78	75	75	65	77	81	78	76	76	83	84	82	80	79	84	84	83	81	84
	SCE	L*	74.41	68.89	71.12	72.54	68.15	64.33	60.74	65.54	74.65	70.43	52.10	51.30	54.68	56.96	57.14	51.13	51.38	57.68	57.67	52.90
		a*	1.05	1.53	1.05	0.66	0.10	0.89	2.10	0.66	-0.65	0.97	5.73	5.51	4.86	4.10	4.88	5.89	5.95	3.08	2.85	3.81
		b*	8.46	9.39	9.31	10.31	8.93	11.69	9.12	11.02	7.46	9.21	13.85	13.42	14.00	13.86	14.42	13.64	12.69	14.36	13.96	13.76
Control-2@	SCI	L*	83.64	80.31	73.94	76.39	85.40	83.78	81.41	75.48	82.89	81.77	87.44	77.31	76.22	74.92	78.72	77.85	79.04	78.03	78.45	81.80
		a*	2.36	2.04	2.86	2.61	-0.16	1.25	2.73	2.62	1.79	3.60	-0.10	2.34	2.68	1.23	3.08	3.39	2.48	3.54	2.70	1.54
		b*	12.45	11.96	11.30	9.14	10.50	14.42	13.31	10.11	10.83	12.10	11.21	12.10	9.91	12.56	14.33	15.04	13.91	16.19	13.88	13.31
	-	G	66	61	73	73	69	69	68	72	60	70	60	70	72	76	74	84	74	81	75	68
	SCE	L*	82.10	78.77	71.83	74.38	83.84	82.17	79.73	73.47	81.47	80.07	86.14	75.43	74.23	72.76	76.80	75.60	77.12	75.88	76.49	80.14
		a*	2.50	2.17	3.06	2.77	-0.16	1.34	2.89	2.78	1.90	3.82	-0.08	2.49	2.86	1.31	3.27	3.62	2.63	3.78	2.88	1.63
		b*	13.43	12.94	12.46	9.99	11.26	15.50	14.37	11.09	11.66	13.09	11.96	13.20	10.85	13.68	15.59	16.47	15.09	17.67	15.09	14.34
Control-3(d)	SCI	L*	75.06	69.66	73.19	69.81	67.95	70.45	72.10	71.03	69.47	73.59	75.24	77.83	75.79	61.22	61.48	69.92	65.58	61.06	65.50	61.62
		a*	0.12	1.53	0.45	1.19	1.75	0.79	0.15	0.80	1.03	-0.23	1.22	1.08	1.39	2.93	2.98	1.45	1.99	2.79	0.95	3.40
		b*	9.85	10.22	10.38	10.86	10.23	11.15	10.27	10.72	10.59	9.70	7.72	8.05	7.93	9.93	11.14	11.03	12.44	10.80	10.86	10.80
	-	G	69	77	73	78	79	76	70	75	78	71	67	68	68	82	82	75	80	83	77	79
	SCE	L*	73.11	67.17	71.05	67.32	65.31	68.04	69.96	68.68	66.96	71.51	73.35	76.02	73.91	57.93	58.23	67.58	62.73	57.72	62.74	58.47
		a*	0.12	1.63	0.47	1.27	1.87	0.84	0.13	0.83	1.09	-0.26	1.29	1.14	1.47	3.20	3.25	1.53	2.13	3.04	0.99	3.70
		b*	10.78	11.40	11.44	12.10	11.48	12.39	11.33	11.90	11.80	10.64	8.49	8.81	8.71	11.54	12.94	12.32	14.15	12.59	12.32	12.46
100-0.5-1	SCI	L*	77.30	71.69	73.61	74.90	80.07	80.73	79.66	77.32	76.13	70.35	75.69	76.38	76.90	77.83	75.78	72.55	73.49	78.04	79.82	77.68
		a*	1.37	2.06	2.13	1.31	1.39	1.57	1.89	1.86	1.58	1.80	2.11	1.88	1.90	1.72	1.79	2.02	2.75	2.35	2.96	3.65
		b*	12.69	11.27	11.89	12.61	9.00	8.55	8.07	7.83	8.23	11.71	10.00	9.13	9.68	9.30	9.04	9.29	10.13	11.15	11.43	11.51
	-	G	63	68	65	64	63	63	67	68	69	71	69	68	67	68	72	73	70	65	64	63
	SCE	L*	75.62	69.61	71.70	73.09	78.48	79.17	77.95	75.50	74.23	68.11	73.79	74.52	75.08	75.70	73.77	70.38	71.43	76.34	77.65	75.99
		a*	1.44	2.18	2.27	1.39	1.47	1.66	2.00	1.96	1.66	1.91	2.22	1.98	2.00	1.82	1.88	2.14	2.91	2.48	3.12	3.86
		b*	13.76	12.39	13.01	13.74	9.73	9.25	8.77	8.54	8.99	12.95	10.93	9.96	10.54	10.13	9.88	10.23	11.11	12.08	12.35	12.48
100-0.5-2	SCI	L*	57.64	55.89	61.56	60.23	60.53	70.70	71.71	73.30	82.58	84.03	57.93	60.00	57.63	63.47	60.96	59.72	59.63	60.04	56.28	54.59
		a*	2.96	3.23	1.45	2.25	2.92	1.31	1.15	1.68	-0.09	-0.31	2.99	3.43	4.06	1.27	2.20	2.55	1.97	2.00	3.51	3.80
		b*	8.41	8.38	7.35	7.68	8.16	7.36	7.29	7.86	7.66	7.95	10.39	11.25	11.25	10.95	11.18	10.93	10.14	10.27	9.89	9.96
	-	G	82	82	80	80	77	75	73	71	76	67	79	78	78	75	77	79	78	77	80	80
	SCE	L*	53.99	52.04	58.39	56.93	57.36	68.37	69.47	71.20	80.97	82.46	54.45	56.76	53.85	60.65	57.86	56.44	56.36	56.84	52.59	50.70
		a*	3.27	3.59	1.55	2.44	3.19	1.39	1.22	1.78	-0.09	-0.32	3.26	3.72	4.48	1.34	2.38	2.78	2.12	2.15	3.90	4.25
		b*	9.95	10.01	8.49	8.94	9.43	8.20	8.08	8.67	8.28	8.56	12.17	13.04	13.22	12.44	12.89	12.70	11.79	11.91	11.74	11.99
100-0.5-3	SCI	L*	78.97	77.75	73.75	74.04	74.37	73.53	75.19	73.50	75.57	74.40	75.40	74.50	78.79	73.80	74.62	74.75	75.07	76.76	80.59	81.91
		a*	0.46	0.81	1.58	1.96	1.46	1.80	2.02	1.57	1.66	1.95	1.28	1.62	0.95	1.85	1.77	1.82	2.10	2.21	1.71	0.91
		b*	10.49	10.67	9.70	9.84	8.97	10.15	9.76	9.09	8.76	9.63	8.80	7.64	7.69	8.63	9.10	8.97	8.69	8.77	9.20	9.08
	-	G	66	68	71	71	69	67	68	70	70	70	64	66	62	68	68	68	66	65	61	62
	SCE	L*	77.26	75.94	71.70	71.98	72.40	71.56	73.28	71.46	73.60	72.40	73.59	72.13	77.18	71.83	72.69	72.81	73.20	75.01	79.06	80.40
		a*	0.49	0.84	1.68	2.07	1.54	1.91	2.14	1.66	1.76	2.05	1.36	1.72	1.01	1.96	1.87	1.92	2.22	2.33	1.81	0.96
		b*	11.33	11.57	10.61	10.78	9.81	11.13	10.63	9.97	9.57	10.53	9.60	8.38	8.34	9.47	9.95	9.81	9.49	9.54	9.91	9.75
100-1-1	SCI	L*	69.38	72.70	70.35	65.07	74.40	68.41	66.22	66.98	71.91	64.87	78.99	78.46	82.94	81.07	74.04	77.93	76.36	71.73	72.78	76.17
		a*	3.57	1.54	2.29	2.76	0.49	3.89	4.26	3.54	3.02	3.52	0.14	0.25	-0.23	-0.24	-0.03	-0.27	0.25	0.66	0.59	0.16
		b*	12.44	11.58	11.90	12.28	10.81	12.69	13.04	13.10	12.09	12.56	8.72	8.85	8.17	8.87	10.11	8.46	9.38	9.75	9.61	9.54
	-	G	73	70	76	78	73	73	75	76	71	77	63	67	65	68	67	66	66	71	72	66
	SCE	L*	67.01	70.62	67.95	62.23	72.31	65.98	63.58	64.38	69.76	62.09	77.35	76.71	81.41	79.04	72.11	76.17	74.57	69.56	70.64	74.36
		a*	3.82	1.63	2.44	2.99	0.51	4.17	4.60	3.81	3.21	3.82	0.15	0.26	-0.23	-0.25	-0.05	-0.27	0.26	0.68	0.62	0.16
		b*	13.84	12.72	13.21	13.89	11.86	14.18	14.69	14.73	13.36	14.22	9.43	9.58	8.78	9.56	11.03	9.20	10.22	10.75	10.57	10.39

Measurements Before Heating:

Sample	Light	Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
100-1-2	SCI	L*	79.72	80.57	81.33	82.34	84.04	86.06	82.79	80.88	82.05	86.22	86.64	86.24	86.32	84.51	82.49	84.49	85.32	86.53	86.09	84.60
		a*	4.27	4.10	3.92	3.32	2.33	1.15	3.01	3.95	3.38	1.01	1.69	1.36	1.58	3.06	3.89	2.73	1.93	1.40	1.55	2.70
		b*	10.27	9.49	10.57	10.74	11.18	10.89	11.06	10.11	10.56	10.76	11.38	11.77	11.28	10.22	11.88	10.86	11.24	11.45	11.60	11.22
	-	G	65	62	66	65	63	59	64	64	66	58	58	61	63	61	65	61	62	60	63	63
	SCE	L*	78.06	79.00	79.70	80.76	82.57	84.75	81.25	79.29	80.46	84.92	85.36	84.88	84.92	83.10	80.92	83.10	83.92	85.21	84.70	83.15
		a*	4.52	4.34	4.15	3.50	2.46	1.22	3.17	4.17	3.57	1.08	1.79	1.45	1.68	3.23	4.11	2.87	2.04	1.49	1.64	2.85
		b*	11.10	10.24	11.39	11.54	11.97	11.60	11.87	10.91	11.36	11.46	12.11	12.55	12.04	10.95	12.77	11.63	12.01	12.20	12.38	12.00
100-1-3	SCI	L*	84.54	84.32	83.19	82.50	83.16	86.38	83.27	85.46	84.28	85.55	80.84	82.47	82.59	83.05	81.03	82.05	82.95	82.79	83.52	84.44
		a*	1.06	1.20	0.90	0.75	0.43	0.21	0.74	0.87	1.44	0.89	1.67	1.16	1.31	1.01	1.86	1.47	1.15	1.24	1.06	0.84
		b*	10.03	8.58	8.92	9.15	8.82	7.17	8.74	8.20	11.48	8.17	10.04	9.92	9.87	10.09	10.40	10.36	10.30	10.11	9.70	9.79
	-	G	58	58	61	63	62	58	61	58	62	57	64	64	63	63	65	65	64	62	64	64
	SCE	L*	83.22	82.97	81.75	80.98	81.70	85.10	81.83	84.16	82.84	84.26	79.25	80.92	81.08	81.54	79.41	80.48	81.43	81.27	82.02	82.96
		a*	1.12	1.28	0.96	0.80	0.47	0.23	0.79	0.94	1.53	0.94	1.77	1.23	1.38	1.08	1.96	1.55	1.22	1.31	1.12	0.90
		b*	10.73	9.21	9.58	9.84	9.46	7.67	9.38	8.79	12.28	8.74	10.84	10.68	10.61	10.84	11.22	11.16	11.07	10.85	10.42	10.48
100-2-1	SCI	L*	84.48	83.70	82.28	82.98	83.28	82.74	84.26	83.61	83.73	83.46	84.78	84.31	84.28	82.78	84.67	82.07	82.45	84.23	83.69	84.38
		a*	1.25	1.27	2.24	2.72	2.36	2.16	1.41	1.72	1.54	1.86	1.18	1.35	1.37	2.20	1.18	2.87	3.01	2.18	2.24	1.62
		b*	10.11	10.16	10.87	10.32	11.25	10.55	9.79	10.21	10.39	11.06	10.52	10.53	10.71	11.08	10.48	10.60	10.78	9.87	10.49	9.91
	-	G	59	61	61	59	59	59	60	61	60	59	61	63	62	64	63	59	60	58	61	60
	SCE	L*	83.11	82.27	80.80	81.57	81.89	81.32	82.88	82.19	82.33	82.06	83.39	82.86	82.84	81.24	83.23	80.65	81.01	82.89	82.27	82.99
		a*	1.33	1.35	2.37	2.88	2.49	2.28	1.50	1.82	1.63	1.98	1.25	1.43	1.46	2.33	1.26	3.03	3.17	2.30	2.36	1.71
		b*	10.81	10.88	11.68	11.08	12.05	11.32	10.49	10.94	11.13	11.85	11.24	11.27	11.46	11.88	11.21	11.38	11.60	10.57	11.24	10.60
100-2-2	SCI	L*	80.99	79.07	79.59	83.09	84.48	84.02	82.96	83.89	82.78	83.54	86.25	84.73	82.21	82.57	80.64	77.97	80.51	82.19	86.35	86.17
		a*	1.32	1.66	1.52	0.86	0.77	1.43	1.17	0.76	1.62	0.65	0.76	1.04	1.89	2.14	3.18	3.72	2.66	1.77	0.64	1.04
		b*	11.27	10.13	8.68	8.73	9.27	10.50	10.07	9.01	10.51	8.61	10.67	10.72	10.75	8.21	11.34	10.93	7.92	10.36	10.10	10.94
	-	G	66	67	64	60	58	60	61	59	61	59	57	64	65	62	65	69	62	64	60	56
	SCE	L*	79.37	77.37	77.97	81.66	83.13	82.63	81.52	82.51	81.32	82.16	84.98	83.27	80.64	81.08	79.03	76.15	78.96	80.64	85.02	84.93
		a*	1.39	1.76	1.61	0.92	0.83	1.51	1.24	0.81	1.71	0.70	0.81	1.11	1.99	2.26	3.36	3.95	2.81	1.88	0.70	1.11
		b*	12.13	10.97	9.39	9.38	9.93	11.25	10.81	9.65	11.23	9.24	11.37	11.47	11.56	8.84	12.23	11.87	8.57	11.14	10.78	11.66
100-2-3	SCI	L*	79.19	79.48	79.99	80.77	81.60	81.36	81.77	81.41	80.73	80.84	78.03	77.71	79.09	78.51	78.53	77.87	78.37	78.86	81.61	82.54
		a*	1.22	1.26	1.10	1.03	0.97	1.18	0.90	0.97	1.04	1.02	2.84	2.88	2.18	2.66	2.84	2.84	2.75	2.33	1.35	1.48
		b*	13.16	12.24	10.61	11.02	10.97	11.02	10.28	9.82	11.68	9.62	9.58	9.77	9.34	9.75	9.79	9.78	9.83	9.60	9.30	9.99
	-	G	66	65	62	65	64	65	63	63	67	62	67	70	68	69	66	68	67	69	64	62
	SCE	L*	77.50	77.80	78.41	79.16	80.03	79.75	80.23	79.86	79.06	79.30	76.27	75.84	77.32	76.70	76.80	76.08	76.62	77.08	80.05	81.06
		a*	1.29	1.33	1.16	1.09	1.04	1.25	0.96	1.03	1.11	1.08	3.00	3.05	2.31	2.82	3.00	3.01	2.91	2.47	1.43	1.56
		b*	14.19	13.20	11.44	11.88	11.79	11.86	11.04	10.57	12.58	10.36	10.41	10.62	10.14	10.59	10.63	10.63	10.68	10.43	10.02	10.72
150-0.5-1	SCI	L*	79.82	77.02	75.90	74.72	74.82	74.53	74.90	74.78	74.72	77.18	77.84	80.18	78.98	78.72	76.62	73.81	74.86	77.16	79.04	73.39
		a*	0.89	1.75	1.90	2.10	1.79	1.98	2.01	1.78	1.72	1.38	1.11	0.59	1.09	1.47	1.20	2.11	1.94	1.68	2.21	1.75
		b*	12.74	10.88	10.86	11.17	11.47	10.12	9.94	10.24	10.66	9.67	8.38	9.72	5.48	9.99	8.25	9.78	10.25	10.16	11.01	7.92
	-	G	62	65	67	69	68	69	70	70	70	66	67	65	65	66	68	67	66	66	68	68
	SCE	L*	78.25	75.27	74.03	72.75	72.88	72.56	72.92	72.79	72.72	75.41	76.06	78.55	77.29	77.01	74.76	71.85	73.00	75.39	77.29	71.39
		a*	0.95	1.86	2.01	2.23	1.90	2.10	2.12	1.88	1.82	1.45	1.18	0.64	1.15	1.55	1.27	2.23	2.06	1.77	2.33	1.85
		b*	13.70	11.81	11.82	12.20	12.52	11.05	10.86	11.17	11.64	10.51	9.10	10.48	6.00	10.82	9.00	10.70	11.18	11.02	11.90	8.71
150-0.5-2	SCI	L*	60.42	61.02	56.76	65.79	68.62	67.06	60.81	56.80	55.94	55.86	72.43	76.64	79.67	75.65	72.53	74.52	76.56	71.72	79.14	72.20
		a*	3.77	4.42	6.55	3.68	3.21	3.89	5.10	6.70	4.96	6.58	2.15	1.80	0.56	2.05	2.17	1.79	1.42	2.28	1.08	1.26
		b*	12.42	13.27	12.32	15.26	15.29	14.96	14.22	12.50	11.09	11.75	9.05	10.72	11.06	9.55	9.42	9.09	8.02	9.97	10.97	10.77
	-	G	80	80	82	76	74	73	79	81	83	82	72	68	65	68	71	72	69	71	66	72
	SCE	L*	57.13	57.81	53.00	63.11	66.19	64.55	57.61	53.19	52.06	52.03	70.27	74.79	78.00	73.75	70.40	72.47	74.66	69.54	77.43	70.04
		a*	4.14	2.87	7.34	3.97	3.43	4.19	5.60	7.49	5.57	7.36	2.29	1.91	0.60	2.18	2.32	1.90	1.51	2.43	1.14	1.35
		b*	14.44	15.36	14.66	17.20	17.07	16.77	16.46	14.82	13.26	14.04	9.98	11.66	11.94	10.43	10.39	9.95	8.75	11.00	11.85	11.85

Measurements Before Heating:

Sample	Light	Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
150-0.5-3	SCI	L*	63.91	56.11	61.25	58.64	55.63	59.50	58.79	66.80	74.40	70.64	72.07	81.03	78.21	72.47	79.29	76.17	81.51	80.52	77.71	80.08
		a*	3.34	4.37	4.24	3.10	3.63	5.90	4.82	2.60	2.36	2.23	2.18	0.41	0.35	1.33	0.30	1.97	0.78	1.12	1.74	0.82
		b*	13.52	10.79	12.48	10.37	10.56	10.94	10.19	12.72	13.99	11.82	9.28	11.32	11.90	9.04	11.87	9.99	8.20	10.21	10.07	8.14
	-	G	76	82	78	81	81	79	82	76	69	73	74	65	67	73	66	68	64	66	66	65
	SCE	L*	61.08	52.31	58.14	55.15	51.83	56.16	55.28	64.18	72.43	68.35	69.77	79.41	76.45	70.27	77.61	74.30	79.93	78.82	75.94	78.44
		a*	3.63	4.88	4.64	3.42	4.04	6.53	5.35	2.79	2.50	2.37	2.32	0.45	0.37	1.40	0.33	2.09	0.84	1.20	1.85	0.88
		b*	15.35	12.82	15.54	12.16	12.58	12.78	11.99	14.28	15.30	13.08	10.25	12.19	12.87	9.96	12.80	10.89	8.85	11.01	10.93	8.81
150-1-1	SCI	L*	75.94	76.56	74.68	78.16	74.88	74.53	73.11	70.07	69.29	65.84	64.92	72.67	67.83	82.77	84.10	81.72	76.56	74.42	72.29	74.66
		a*	2.18	1.97	2.52	1.20	2.32	1.16	0.85	0.74	0.96	1.52	2.62	0.79	0.86	-0.60	-1.03	-0.27	1.14	2.81	3.74	3.85
		b*	9.75	10.28	10.77	8.91	10.45	10.03	9.13	9.05	9.52	9.63	10.43	9.56	7.34	8.04	8.95	8.85	8.99	9.56	10.75	9.83
	-	G	65	65	66	64	67	66	69	71	70	72	73	67	70	53	57	58	64	67	69	66
	SCE	L*	74.16	74.78	72.82	76.49	72.98	72.63	71.08	67.82	67.01	63.29	62.26	70.69	65.47	81.50	82.78	80.30	74.82	72.51	70.20	72.76
		a*	2.31	2.08	2.68	1.27	2.46	1.22	0.89	0.77	1.00	1.61	2.82	0.83	0.90	-0.61	-1.06	-0.26	1.21	2.99	3.98	4.09
		b*	10.62	11.17	11.75	9.65	11.40	10.94	10.01	10.00	10.55	10.81	11.76	10.48	8.17	8.61	9.57	9.49	9.79	10.46	11.82	10.75
150-1-2	SCI	L*	73.59	76.04	76.25	73.70	74.35	73.65	73.98	72.89	70.54	74.49	73.75	73.88	75.35	79.66	79.29	80.04	79.70	80.57	81.38	81.16
		a*	2.31	1.49	1.71	2.23	1.85	1.86	1.64	1.81	2.07	1.47	1.54	1.49	1.36	0.33	1.04	1.24	1.70	1.67	1.57	1.69
		b*	11.16	8.99	9.25	8.71	8.54	9.14	8.76	8.01	8.54	9.25	10.11	9.81	9.56	8.62	9.08	8.57	8.28	8.88	9.51	9.57
	-	G	65	63	64	70	73	72	71	75	73	70	69	71	70	65	64	63	64	62	62	60
	SCE	L*	71.70	74.30	74.48	71.66	72.25	71.55	71.92	70.65	68.25	72.48	71.74	71.82	73.39	78.01	77.64	78.44	78.06	79.02	79.85	79.67
		a*	2.46	1.58	1.82	2.38	1.96	1.97	1.74	1.92	2.20	1.54	1.62	1.56	1.43	0.35	1.09	1.31	1.80	1.76	1.66	1.78
		b*	12.23	9.79	10.08	9.58	9.39	10.07	9.63	8.86	9.48	10.13	11.11	10.79	10.47	9.34	9.84	9.27	8.96	9.59	10.25	10.31
150-1-3	SCI	L*	76.04	77.31	76.32	74.35	70.51	75.39	75.30	78.71	80.68	81.11	79.57	78.61	76.95	76.46	78.34	79.80	78.35	77.60	76.70	76.57
		a*	0.89	0.38	0.36	0.95	2.30	0.70	0.80	0.45	0.57	0.74	1.53	1.57	1.64	1.26	0.99	0.79	1.43	1.70	1.62	1.72
		b*	12.82	13.17	13.36	12.98	11.94	12.36	12.25	9.68	9.33	9.39	9.41	9.43	9.91	9.08	8.30	8.79	9.34	9.71	9.93	9.64
	-	G	65	65	67	70	72	70	69	66	65	66	60	64	65	64	62	67	68	68	70	69
	SCE	L*	74.24	75.56	74.49	72.33	68.24	73.41	73.35	76.98	79.05	79.48	78.03	76.93	75.21	74.70	76.70	78.11	76.56	75.79	74.80	74.67
		a*	0.93	0.39	0.38	1.00	2.45	0.74	0.84	0.48	0.60	0.79	1.61	1.66	1.74	1.33	1.04	0.83	1.50	1.78	1.70	1.81
		b*	13.93	14.25	14.49	14.20	13.25	13.49	13.37	10.48	10.07	10.12	10.18	10.23	10.77	9.89	9.02	9.51	10.15	10.54	10.80	10.51
150-2-1	SCI	L*	81.27	79.70	78.37	78.78	75.87	74.54	80.13	83.13	81.82	83.23	84.87	84.70	83.70	81.75	83.31	83.18	81.18	81.66	82.10	83.77
		a*	1.02	1.22	1.59	1.12	1.74	2.59	2.20	1.70	2.42	1.57	0.93	0.32	0.38	1.10	0.36	0.35	-0.27	0.28	1.10	0.27
		b*	11.33	11.99	12.49	13.39	13.01	12.15	12.95	13.62	13.74	12.88	13.06	11.03	11.33	11.11	10.99	10.69	10.32	6.94	11.16	10.33
	-	G	63	64	65	66	69	71	66	63	63	63	57	57	60	62	63	64	59	62	62	61
	SCE	L*	79.72	78.08	76.67	77.06	73.97	72.50	78.46	81.65	80.29	81.75	83.57	83.39	82.30	80.23	81.81	81.67	79.72	80.15	80.59	82.34
		a*	1.09	1.29	1.69	1.19	1.85	2.76	2.34	1.81	2.55	1.67	1.00	0.36	0.43	1.18	0.40	0.39	-0.27	0.30	1.17	0.32
		b*	12.19	12.95	12.53	14.49	14.18	13.32	13.98	14.60	14.76	13.81	13.93	11.77	12.11	11.94	11.77	11.44	11.08	7.48	11.97	11.05
150-2-2	SCI	L*	86.47	84.80	86.71	87.65	87.55	87.24	85.33	87.41	86.31	83.14	82.04	84.68	84.55	81.46	81.04	83.13	86.67	83.65	81.42	84.30
		a*	0.68	1.12	0.71	0.48	0.33	0.34	0.26	0.28	0.24	0.35	0.69	0.49	0.81	2.64	3.42	2.77	1.10	1.60	2.95	0.77
		b*	13.98	13.92	13.96	13.80	12.78	13.35	11.89	13.05	11.15	11.13	11.80	14.06	14.90	14.72	15.00	15.28	13.39	11.86	11.85	14.79
	-	G	59	61	60	60	62	63	68	63	66	72	67	65	64	68	66	65	61	64	67	64
	SCE	L*	85.17	83.40	85.39	86.35	86.21	85.87	83.78	86.03	84.85	81.42	80.42	83.19	83.07	79.79	79.41	81.59	85.34	82.15	79.78	82.81
		a*	0.74	1.20	0.78	0.54	0.38	0.40	0.30	0.34	0.29	0.39	0.75	0.54	0.88	2.81	3.65	2.95	1.19	1.71	3.14	0.84
		b*	14.95	14.95	14.92	14.73	13.66	14.25	12.72	13.93	11.92	11.94	12.71	15.05	15.97	15.91	16.23	16.46	14.90	12.77	12.84	15.86
150-2-3	SCI	L*	61.03	62.72	68.33	74.67	73.45	61.21	62.72	71.73	61.78	68.34	64.71	69.77	78.21	65.04	64.16	62.10	60.99	73.64	77.74	69.93
		a*	3.36	3.08	2.45	1.56	1.00	3.45	3.79	2.29	3.77	2.71	3.20	1.73	0.63	3.59	2.29	3.39	3.17	2.34	1.36	2.56
		b*	11.68	12.27	13.93	14.78	13.41	12.06	11.74	13.14	11.65	12.73	11.23	9.83	12.12	9.47	10.32	11.33	11.56	10.92	9.93	10.25
	-	G	86	85	82	76	75	86	89	83	88	84	85	79	77	89	87	86	87	76	71	82
	SCE	L*	57.56	59.43	65.60	72.51	71.24	57.74	59.29	69.17	58.27	65.54	61.61	67.24	76.16	61.81	60.95	58.72	57.49	71.42	75.85	67.31
		a*	3.71	3.38	2.64	1.66	1.07	3.82	4.21	2.45	4.18	2.93	3.51	1.86	0.68	3.94	2.51	3.75	3.51	2.52	1.45	2.76
		b*	13.57	14.15	15.70	16.24	14.77	14.00	13.60	14.66	13.59	14.37	12.79	10.96	13.22	10.89	11.87	13.14	13.48	12.05	10.84	11.49

Measurements Before Heating:

Sample	Light	Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
200-0.5-1	SCI	L*	81.65	81.55	81.28	81.01	82.30	83.02	82.30	83.21	82.02	82.49	86.76	86.04	85.22	82.09	81.97	84.28	84.57	82.36	82.79	83.54
		a*	1.13	0.61	0.75	0.70	0.70	0.62	0.71	0.57	0.59	0.52	0.10	0.16	-0.06	1.23	1.32	1.40	1.31	1.29	1.26	0.86
		b*	14.07	11.83	11.92	12.28	12.35	11.44	11.41	10.98	11.22	10.34	12.78	12.16	7.62	12.21	12.38	13.52	12.89	12.28	12.50	11.83
	-	G	67	70	72	70	70	67	70	68	68	70	65	63	64	66	67	66	64	66	67	65
	SCE	L*	80.01	79.84	79.50	79.26	80.62	81.42	80.61	81.61	80.36	80.80	85.33	84.63	83.76	80.49	80.34	82.76	83.10	80.76	81.19	82.02
		a*	1.21	0.64	0.80	0.75	0.76	0.68	0.76	0.61	0.63	0.55	0.13	0.20	-0.04	1.32	1.41	1.49	1.40	1.38	1.35	0.92
		b*	15.19	12.81	12.92	13.29	13.33	12.30	12.30	11.83	12.11	11.18	13.67	13.00	8.19	13.17	13.37	14.53	13.84	13.26	13.49	12.72
200-0.5-2	SCI	L*	79.19	76.54	76.86	75.85	75.91	77.83	79.12	76.15	76.99	78.66	78.38	72.53	75.87	70.47	72.33	76.92	73.19	80.73	77.91	78.94
		a*	1.27	1.33	0.99	1.11	0.92	1.71	1.19	1.01	1.11	1.19	0.89	1.25	0.53	0.21	0.79	0.43	0.91	0.18	0.70	0.61
		b*	14.03	14.74	14.03	13.72	13.18	13.06	11.09	13.94	14.11	14.35	11.93	10.77	9.96	8.85	9.26	9.12	8.83	9.30	10.98	11.74
	-	G	72	74	73	74	77	73	73	77	74	71	74	78	75	86	86	76	75	69	71	71
	SCE	L*	77.34	74.52	74.89	73.79	73.79	75.89	77.23	74.03	74.99	76.82	76.43	70.20	73.79	67.75	69.74	74.85	70.97	79.00	76.03	77.11
		a*	1.36	1.42	1.06	1.19	0.98	1.82	1.26	1.08	1.19	1.28	0.96	1.34	0.57	0.21	0.84	0.47	0.96	0.20	0.75	0.66
		b*	15.24	16.11	15.31	15.04	14.47	14.24	12.06	15.29	15.41	15.59	12.98	11.89	10.88	9.81	10.19	9.94	9.73	10.06	11.95	12.71
200-0.5-3	SCI	L*	76.67	73.12	69.54	72.06	77.40	76.54	71.95	72.70	80.91	82.44	84.50	83.00	76.56	81.27	84.84	69.64	65.26	82.18	84.05	82.61
		a*	0.32	1.05	2.93	2.38	0.45	0.38	1.27	1.30	0.83	0.51	0.56	0.71	1.86	0.94	0.39	1.15	2.91	0.72	1.92	1.39
		b*	12.04	12.59	13.54	12.76	9.43	10.40	11.40	12.92	11.87	10.58	12.37	14.25	12.12	13.02	12.21	9.96	10.09	9.04	12.97	13.02
	-	G	72	75	81	82	77	81	80	75	70	66	65	68	72	69	65	84	79	59	68	67
	SCE	L*	74.71	70.90	66.93	69.55	75.32	74.32	69.52	70.45	79.18	80.85	83.00	81.37	74.59	79.57	83.36	66.94	62.42	80.72	82.46	80.99
		a*	0.34	1.12	3.17	2.57	0.48	0.40	1.36	1.40	0.90	0.55	0.62	0.77	1.98	1.01	0.44	1.23	3.17	0.78	2.05	1.48
		b*	13.12	13.88	15.09	14.19	10.27	11.29	12.60	14.25	12.84	11.41	13.28	15.34	13.24	14.06	13.10	11.09	11.44	9.78	13.97	14.04
200-1-1	SCI	L*	71.80	69.86	67.39	62.10	67.34	66.62	67.80	69.06	61.97	69.19	58.90	57.58	60.02	59.06	58.33	60.27	58.23	57.26	59.20	60.61
		a*	1.95	1.99	1.56	1.60	1.86	1.33	1.89	1.32	2.02	2.47	3.39	3.51	3.31	3.80	4.69	3.03	3.50	3.72	3.58	3.03
		b*	11.91	11.15	10.65	9.28	11.06	9.85	11.42	10.31	9.86	12.06	9.63	9.83	10.54	10.71	9.76	9.70	10.17	9.99	10.59	9.68
	-	G	80	84	85	90	85	86	85	84	89	83	88	90	88	89	90	87	90	92	89	88
	SCE	L*	69.37	67.17	64.47	58.58	64.44	63.64	64.92	66.31	58.45	66.47	55.14	53.56	56.34	55.22	54.36	56.68	54.29	53.10	55.39	57.02
		a*	2.10	2.16	1.70	1.75	2.01	1.43	2.05	1.41	2.21	2.68	3.80	3.96	3.69	4.26	5.29	3.37	3.94	4.22	4.01	3.37
		b*	13.21	12.47	12.00	10.67	12.48	11.12	12.88	11.55	11.12	13.52	11.37	11.71	12.38	12.67	11.60	11.36	12.09	11.99	12.51	11.32
200-1-2	SCI	L*	66.53	63.37	65.22	66.90	68.03	60.09	68.55	71.18	67.53	69.44	64.68	64.23	66.13	62.55	73.76	55.93	54.75	76.07	72.51	54.78
		a*	1.82	3.06	2.32	2.03	1.92	3.26	1.17	1.17	2.43	1.21	2.52	2.82	1.68	1.18	0.90	4.78	4.61	1.95	2.41	4.03
		b*	10.98	10.67	10.56	9.81	8.82	11.14	8.37	8.08	10.23	8.48	8.35	11.38	9.54	7.39	10.58	10.13	9.80	12.64	11.38	9.01
	-	G	83	84	83	82	78	88	80	78	81	80	86	86	85	93	81	91	91	77	79	89
	SCE	L*	63.65	60.20	62.21	64.06	65.42	56.45	65.89	68.78	64.78	66.85	61.53	61.04	63.14	58.19	71.39	51.63	50.31	73.96	70.31	50.45
		a*	1.97	3.36	2.52	2.20	2.06	3.63	1.25	1.25	2.62	1.28	2.75	3.09	1.82	1.26	0.97	5.47	5.30	2.09	2.59	4.61
		b*	12.42	12.26	12.04	11.10	9.92	13.02	9.39	8.99	11.54	9.49	9.51	13.01	10.76	8.42	11.67	12.24	11.96	13.87	12.63	10.96
200-1-3	SCI	L*	70.63	71.47	72.10	70.80	70.22	70.27	75.27	75.60	72.99	71.60	79.76	76.65	77.59	79.15	75.62	77.77	70.79	70.35	81.52	78.11
		a*	1.78	2.04	2.09	2.12	2.12	2.60	1.60	1.30	1.75	2.18	1.95	2.04	2.01	3.03	2.64	2.33	4.47	4.15	1.70	2.83
		b*	11.02	11.92	12.06	12.32	11.78	12.10	10.53	10.79	11.55	12.01	11.64	9.40	10.40	13.26	12.92	12.11	13.85	13.56	15.73	12.92
	-	G	79	77	76	78	78	80	74	73	75	77	63	70	69	66	69	67	73	73	66	67
	SCE	L*	68.14	69.10	69.80	68.37	67.75	67.74	73.20	73.57	70.76	68.64	78.15	74.74	75.76	77.44	73.69	75.98	68.51	68.03	79.90	76.36
		a*	1.92	2.19	2.24	2.28	2.29	2.80	1.70	1.40	1.88	2.35	2.06	2.17	2.13	3.21	2.81	2.47	4.80	4.46	1.82	3.00
		b*	12.29	13.24	13.36	13.73	13.14	13.51	11.57	11.86	12.77	13.36	12.62	10.29	11.35	14.39	14.14	13.17	15.37	15.07	16.95	14.03
200-2-1	SCI	L*	87.96	86.36	87.00	88.10	87.45	86.36	70.36	82.80	81.29	84.34	74.11	79.89	82.99	85.40	80.70	80.40	82.56	81.28	80.96	79.04
		a*	0.29	0.79	0.53	0.20	0.28	0.53	2.53	1.47	1.10	0.71	2.24	1.68	1.36	0.48	1.40	1.66	1.39	1.76	1.64	1.58
		b*	10.76	13.41	12.66	10.79	10.60	13.19	10.68	11.62	11.93	10.30	9.46	10.29	12.39	13.38	8.67	10.30	12.18	11.10	10.47	10.50
	-	G	59	63	60	61	63	61	73	62	64	60	64	61	60	63	61	59	61	60	59	62
	SCE	L*	86.68	84.96	85.69	86.80	86.08	85.01	68.04	81.32	79.72	82.95	72.26	78.35	81.56	83.97	79.18	78.92	81.11	79.81	79.50	77.45
		a*	0.34	0.86	0.59	0.23	0.31	0.58	2.72	1.56	1.19	0.77	2.39	1.79	1.46	0.54	1.48	1.77	1.49	1.88	1.75	1.68
		b*	11.49	14.32	13.51	11.52	11.32	14.08	11.84	12.51	12.83	11.06	10.36	11.12	13.30	14.30	9.36	11.11	13.08	11.96	11.29	11.36

Measurements Before Heating:

Sample	Light	Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
200-2-2	SCI	L*	85.60	84.24	83.54	73.24	84.07	83.74	74.76	85.01	68.07	70.06	86.56	84.84	84.21	83.70	67.91	75.22	85.37	84.66	83.06	83.68
		a*	0.40	0.44	0.47	1.63	0.32	0.69	1.54	0.36	3.08	2.28	0.08	0.89	1.15	0.46	2.84	1.35	0.27	0.39	0.62	0.44
		b*	13.06	11.81	11.69	9.59	9.63	12.56	9.35	9.72	13.02	11.60	8.94	12.74	13.31	8.02	12.58	8.90	12.00	10.80	9.94	9.35
	-	G	69	68	69	75	70	71	75	71	79	75	59	61	62	62	80	76	73	68	71	71
	SCE	L*	84.04	82.65	81.92	71.02	82.44	82.08	72.63	83.38	65.42	67.68	85.26	83.45	82.78	82.25	65.24	73.09	83.72	83.10	81.37	82.01
		a*	0.44	0.48	0.50	1.74	0.35	0.73	1.63	0.39	3.32	2.45	0.11	0.96	1.23	0.50	3.06	1.43	0.30	0.43	0.66	0.46
		b*	13.96	12.66	12.56	10.57	10.35	13.51	10.26	10.44	14.61	12.91	9.57	13.61	14.25	8.63	14.12	9.75	12.88	11.59	10.70	10.05
200-2-3	SCI	L*	83.68	84.32	84.88	86.17	81.96	70.95	83.78	85.55	82.84	83.21	66.02	63.86	84.51	84.84	83.08	78.32	83.03	84.75	84.80	82.39
		a*	0.44	0.18	0.02	-0.56	-0.18	1.62	0.15	0.36	1.39	1.15	3.33	3.80	0.85	1.31	1.03	1.89	0.69	0.84	1.32	0.78
		b*	9.35	12.73	12.99	8.79	11.80	10.25	12.78	11.74	12.12	12.29	11.61	11.08	9.83	11.47	10.56	9.61	9.98	9.93	11.74	9.88
	-	G	71	68	68	61	68	73	74	67	64	64	79	79	61	61	63	68	64	62	61	65
	SCE	L*	82.01	82.74	83.32	84.81	80.30	68.69	82.05	84.04	81.31	81.69	63.24	60.90	83.11	83.46	81.59	76.54	81.51	83.33	83.40	80.83
		a*	0.46	0.21	0.05	-0.56	-0.17	1.72	0.18	0.40	1.49	1.23	3.60	4.15	0.91	1.39	1.11	2.01	0.74	0.90	1.40	0.83
		b*	10.05	13.63	13.90	9.42	12.69	11.37	13.77	12.58	13.02	13.19	13.10	12.62	10.54	12.26	11.34	10.42	10.72	10.64	12.57	10.64
250-0.5-1	SCI	L*	67.02	64.62	62.53	66.39	74.03	67.95	68.06	66.62	77.40	77.47	81.03	81.89	78.87	82.06	82.81	81.21	78.10	80.72	80.01	78.93
		a*	5.58	4.87	4.40	3.28	3.63	4.53	5.02	4.35	1.17	1.07	1.05	-0.32	2.52	1.46	1.80	1.47	2.95	2.00	1.81	2.61
		b*	14.51	12.42	11.10	10.87	13.18	13.94	13.82	13.12	8.80	8.17	7.62	8.38	10.74	10.47	12.67	10.20	10.50	11.21	10.25	11.01
	-	G	82	81	83	80	75	79	82	81	64	69	65	64	66	63	64	64	66	65	64	66
	SCE	L*	64.19	61.67	59.31	63.61	71.85	65.30	65.33	63.82	75.68	75.62	79.32	80.34	77.17	80.53	81.29	79.64	76.36	79.09	78.39	77.21
		a*	6.09	5.34	4.85	3.57	3.89	4.92	5.46	4.74	1.25	1.13	1.13	-0.33	2.68	1.55	1.91	1.56	3.13	2.12	1.92	2.77
		b*	16.47	14.15	12.79	12.30	14.50	15.66	15.56	14.84	9.58	8.89	8.25	9.05	11.65	11.27	13.60	11.01	11.41	12.10	11.09	11.93
250-0.5-2	SCI	L*	60.21	61.84	63.46	62.13	60.09	55.54	55.75	53.29	53.83	55.51	72.70	70.31	71.98	71.84	67.79	71.03	74.96	76.23	74.40	75.11
		a*	0.87	1.67	2.17	1.64	2.30	3.41	3.19	3.35	3.71	1.92	2.15	3.22	2.02	1.64	2.35	2.44	2.37	1.74	3.44	3.84
		b*	11.23	12.77	15.16	12.64	11.58	9.89	10.15	7.84	8.75	7.77	10.11	10.20	7.51	7.66	7.99	9.47	8.96	9.04	10.91	11.45
	-	G	80	79	79	80	81	83	84	85	85	84	71	73	75	74	78	74	72	70	70	70
	SCE	L*	56.91	58.71	60.49	59.00	56.73	51.60	51.82	48.96	49.61	51.51	70.07	68.01	69.71	69.57	65.15	68.73	72.92	74.29	72.40	73.13
		a*	0.91	1.80	2.34	1.77	2.51	3.82	3.57	3.80	4.21	2.12	2.29	3.45	2.16	1.74	2.52	2.61	2.52	1.86	3.67	4.10
		b*	12.98	14.66	17.29	14.49	13.42	11.83	12.13	9.54	10.61	9.30	11.16	11.35	8.34	8.49	8.98	10.49	9.83	9.88	11.96	12.55
250-0.5-3	SCI	L*	68.45	72.02	73.46	76.07	76.18	75.62	75.64	75.31	77.67	77.92	77.03	76.74	77.71	76.78	76.16	80.69	77.32	73.16	75.57	79.54
		a*	1.80	1.30	1.14	0.51	0.20	0.96	1.88	2.07	1.79	1.86	1.62	1.38	1.33	1.30	1.57	0.76	0.93	1.84	1.68	0.57
		b*	9.45	10.69	12.22	11.36	10.26	10.95	9.20	8.61	8.67	8.93	10.34	9.16	9.70	8.86	9.08	9.09	9.85	9.44	10.24	8.76
	-	G	73	72	72	74	79	72	71	71	69	66	66	66	67	68	69	67	67	72	69	68
	SCE	L*	66.04	69.84	71.34	74.01	74.00	73.62	73.65	73.32	75.84	76.16	75.25	74.95	75.94	74.95	74.26	79.02	75.52	71.02	73.66	77.81
		a*	1.93	1.38	1.22	0.54	0.20	1.02	2.01	2.21	1.90	1.97	1.71	1.46	1.40	1.37	1.67	0.80	0.98	1.95	1.78	0.60
		b*	10.54	11.78	13.42	12.42	11.27	11.96	10.07	9.42	9.44	9.72	11.24	9.97	10.53	9.65	9.90	9.82	10.70	10.38	11.18	9.49
250-1-1	SCI	L*	65.82	71.80	71.73	68.22	66.09	64.05	70.03	66.66	61.88	66.36	68.01	65.45	63.07	64.94	69.30	69.64	72.40	72.70	80.05	86.84
		a*	0.42	0.14	0.92	2.03	1.72	1.56	1.71	1.46	2.74	1.59	1.02	1.01	1.10	1.06	0.94	1.53	1.05	1.67	1.72	0.09
		b*	8.05	8.04	8.26	7.77	7.36	8.41	8.46	8.51	8.26	7.69	7.85	9.30	8.52	9.45	7.83	7.43	6.29	7.32	8.21	8.78
	-	G	80	74	71	73	74	78	77	76	80	80	74	75	79	81	80	80	78	75	67	62
	SCE	L*	62.97	69.55	69.56	65.80	63.48	61.17	67.58	64.01	58.74	63.58	65.55	62.76	60.07	62.01	66.72	67.07	70.04	70.47	78.34	85.48
		a*	0.41	0.14	0.97	2.17	1.83	1.66	1.82	1.57	2.99	1.71	1.08	1.06	1.16	1.13	0.98	1.63	1.10	1.78	1.82	0.11
		b*	8.99	8.83	9.11	8.69	8.27	9.52	9.41	9.57	9.51	8.67	8.77	10.47	9.74	10.73	8.76	8.30	7.00	8.10	8.92	9.40
250-1-2	SCI	L*	69.34	67.98	64.68	67.60	68.74	65.14	66.40	74.84	80.16	80.11	76.48	75.40	63.28	64.43	72.57	70.84	71.78	67.21	68.87	69.27
		a*	0.54	0.09	0.54	0.42	0.45	2.08	2.26	1.15	0.49	1.22	0.04	0.60	2.91	1.14	1.30	1.03	0.36	1.30	0.48	0.71
		b*	10.91	9.70	9.92	10.16	10.63	10.83	10.86	8.78	9.97	9.89	7.98	6.89	8.21	7.07	8.09	9.53	9.18	10.37	10.29	9.64
	-	G	77	77	80	76	75	78	79	74	68	66	69	67	74	75	69	73	73	77	77	76
	SCE	L*	66.89	65.42	61.77	65.04	67.34	62.33	63.63	72.74	78.45	78.44	74.59	73.54	60.46	61.69	70.52	68.56	69.54	64.57	66.34	66.80
		a*	0.56	0.06	0.54	0.43	0.46	2.24	2.43	1.22	0.53	1.29	0.04	0.63	3.15	1.21	1.38	1.08	0.36	1.38	0.48	0.73
		b*	12.13	10.80	11.19	11.34	11.79	12.25	12.24	9.60	10.77	10.68	8.67	7.53	9.33	7.89	8.91	10.55	10.13	11.60	11.45	10.71

Measurements Before Heating:

Sample	Light	Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
250-1-3	SCI	L*	70.20	69.86	68.41	66.68	67.74	72.75	73.61	82.63	81.76	79.45	76.28	78.75	73.97	66.65	63.74	71.06	69.23	72.52	74.83	69.43
		a*	0.76	0.40	0.61	1.31	1.42	1.37	1.19	0.17	1.06	2.03	1.83	0.70	1.43	1.82	1.54	0.65	0.70	0.26	0.33	0.62
		b*	11.32	10.88	10.99	10.86	11.52	10.35	10.54	9.56	9.45	10.33	8.95	8.40	8.70	7.60	7.78	8.15	10.58	8.60	7.61	10.33
	-	G	74	76	78	86	80	72	73	67	68	70	65	62	67	74	78	71	74	74	71	73
	SCE	L*	67.86	67.44	65.82	63.68	65.02	70.58	71.48	81.02	80.09	77.66	74.50	77.14	72.03	64.09	60.82	68.86	66.84	70.31	72.81	67.05
		a*	0.80	0.41	0.64	1.40	1.51	1.45	1.27	0.19	1.13	2.16	1.94	0.74	1.52	1.95	1.64	0.67	0.73	0.26	0.34	0.65
		b*	12.52	12.08	12.27	12.33	12.94	11.41	11.56	10.28	10.20	11.18	9.74	9.09	9.52	8.51	8.80	9.00	11.73	9.45	8.31	11.45
250-2-1	SCI	L*	69.49	69.95	67.71	70.05	74.90	74.80	67.60	70.01	79.12	78.49	73.30	79.65	75.70	72.81	69.00	67.61	70.70	70.87	74.12	76.67
		a*	1.76	1.15	2.68	1.74	1.88	1.92	2.95	1.29	0.87	1.24	2.43	0.96	1.77	1.26	1.93	2.21	1.43	0.87	0.77	0.81
		b*	10.55	10.59	11.38	9.75	11.05	10.46	11.24	10.66	8.81	8.42	10.10	8.70	8.99	8.50	9.93	9.91	8.22	7.87	7.77	7.21
	-	G	74	72	77	75	72	72	75	74	71	70	73	65	68	71	73	74	71	73	72	71
	SCE	L*	67.10	67.64	65.12	67.67	72.85	72.75	65.05	67.66	77.27	76.66	71.14	77.99	73.80	70.70	66.62	65.13	68.46	68.58	72.05	74.73
		a*	1.88	1.22	2.88	1.85	2.00	2.04	3.16	1.38	0.92	1.32	2.58	1.02	1.88	1.34	2.06	2.36	1.52	0.91	0.82	0.87
		b*	11.71	11.71	12.73	10.80	12.08	11.46	12.53	11.79	9.53	9.12	11.10	9.40	9.80	9.34	11.03	11.06	9.08	8.68	8.48	7.82
250-2-2	SCI	L*	78.08	80.69	81.63	81.38	80.05	80.87	78.70	82.22	85.06	82.06	80.77	80.53	82.00	80.34	78.78	79.55	78.84	81.51	80.11	78.95
		a*	3.06	2.21	1.77	1.83	2.24	1.97	3.03	2.17	1.29	2.24	3.23	3.07	2.45	2.61	2.90	2.28	3.17	2.15	2.52	3.45
		b*	10.96	10.67	10.81	10.74	10.64	10.93	11.37	10.76	9.89	9.80	10.03	10.97	10.57	11.30	11.07	10.19	10.59	9.96	10.11	10.42
	-	G	67	68	67	64	65	65	67	68	65	67	67	68	67	65	70	69	67	63	69	69
	SCE	L*	76.31	78.99	79.99	79.80	78.40	79.26	76.95	80.56	83.61	80.42	79.09	78.84	80.38	78.71	76.97	77.78	77.09	79.96	78.37	77.16
		a*	3.25	2.34	1.88	1.95	2.37	2.11	3.23	2.30	1.37	2.39	3.42	3.25	2.59	2.77	3.08	2.42	3.36	2.29	2.68	3.65
		b*	11.89	11.51	11.62	11.54	11.46	11.75	12.30	11.56	10.57	10.53	10.82	11.82	11.37	12.18	11.97	11.01	11.44	10.70	10.90	11.25
250-2-3	SCI	L*	77.16	74.71	76.34	74.31	68.89	67.71	67.47	68.09	70.49	71.39	73.77	75.23	74.96	75.79	76.46	78.65	80.74	79.91	80.23	74.36
		a*	2.94	3.55	2.70	2.67	3.41	2.87	2.22	1.83	1.87	1.17	2.15	1.12	1.35	0.95	1.60	1.70	1.82	2.80	1.32	2.07
		b*	10.03	11.68	12.11	12.27	11.54	10.90	11.66	9.41	7.97	7.19	10.30	10.12	9.60	8.09	9.00	10.12	9.81	9.40	10.06	9.31
	-	G	71	73	75	72	75	75	76	75	74	74	65	65	71	70	71	65	61	66	62	73
	SCE	L*	75.25	72.62	74.28	72.25	66.44	65.19	64.90	65.58	68.15	69.12	71.88	73.41	72.95	73.84	74.50	76.97	79.23	78.24	78.68	72.28
		a*	3.13	3.80	2.86	2.85	3.67	3.10	2.40	1.96	1.99	1.23	2.28	1.19	1.43	1.02	1.70	1.80	1.93	2.98	1.41	2.20
		b*	10.91	12.77	13.20	13.40	12.84	12.17	13.01	10.45	8.80	7.91	11.25	11.01	10.47	8.82	9.79	10.95	10.55	10.15	10.83	10.19
300-0.5-1	SCI	L*	76.74	78.72	82.39	77.74	80.67	80.72	84.33	78.23	76.97	82.92	79.04	82.56	78.64	77.43	77.20	80.83	78.15	76.24	79.52	76.61
		a*	2.92	2.15	0.99	1.07	0.75	1.41	0.55	1.89	3.29	1.17	1.90	0.85	1.78	2.02	2.59	1.57	2.46	2.88	1.80	2.76
		b*	10.12	9.87	8.49	9.04	10.15	11.22	10.25	8.28	9.59	10.97	9.03	9.45	10.70	10.24	9.84	10.00	9.46	9.95	9.99	10.22
	-	G	69	64	61	72	67	70	65	69	71	67	66	68	66	68	74	68	71	71	65	78
	SCE	L*	74.86	77.04	80.93	75.82	78.99	78.98	82.82	76.42	75.05	81.34	77.34	80.93	76.91	75.62	75.20	79.13	76.29	74.29	77.85	74.47
		a*	3.10	2.29	1.06	1.14	0.82	1.52	0.60	2.00	3.50	1.25	2.02	0.91	1.90	2.15	2.75	1.67	2.62	3.06	1.92	2.94
		b*	10.99	10.67	9.13	9.80	10.92	12.08	10.96	8.99	10.44	11.76	9.76	10.15	11.56	11.11	10.71	10.76	10.24	10.81	10.78	11.17
300-0.5-2	SCI	L*	85.44	84.46	82.31	80.04	81.27	79.96	78.25	79.20	79.13	81.74	73.02	78.16	80.36	82.89	79.70	79.76	82.26	82.68	79.40	81.15
		a*	0.08	0.35	1.11	2.00	1.56	1.87	2.46	1.85	1.81	0.85	1.73	0.69	1.08	0.38	1.24	1.21	0.73	0.87	1.37	0.65
		b*	10.13	9.40	9.55	9.86	9.34	9.49	9.68	9.56	9.56	9.21	9.61	9.86	9.59	7.78	8.01	8.74	9.09	9.26	8.94	7.98
	-	G	55	60	63	65	64	64	65	64	64	62	66	63	61	65	65	67	65	66	67	65
	SCE	L*	84.20	83.08	80.79	78.41	79.70	78.34	76.52	77.54	77.46	80.23	71.05	76.50	78.82	81.35	78.04	78.06	80.70	81.11	77.68	79.54
		a*	0.11	0.39	1.19	2.13	1.66	1.99	2.60	1.96	1.92	0.92	1.83	0.73	1.16	0.41	1.32	1.29	0.79	0.94	1.46	0.70
		b*	10.79	10.05	10.25	10.64	10.06	10.25	10.48	10.32	10.33	9.90	10.53	10.69	10.32	8.37	8.67	9.44	9.76	9.93	9.67	8.60
300-0.5-3	SCI	L*	73.18	73.72	76.12	70.10	66.17	65.72	63.76	78.35	73.65	72.72	65.61	69.69	69.40	60.40	59.79	77.71	78.40	73.36	57.90	56.52
		a*	1.90	1.30	0.70	2.29	3.20	3.90	1.15	0.45	2.17	1.51	2.98	3.26	3.42	4.76	3.70	0.75	0.17	1.27	1.77	1.89
		b*	11.81	12.02	11.51	11.94	11.24	12.10	8.73	10.44	10.83	11.02	11.97	11.47	11.78	11.47	10.84	8.96	9.16	12.27	8.62	7.93
	-	G	67	69	75	77	79	77	75	68	74	74	77	76	77	82	82	66	65	70	81	82
	SCE	L*	71.20	71.72	74.06	67.65	63.41	62.97	60.96	76.56	71.49	70.52	62.87	67.25	66.90	57.04	56.38	75.97	76.69	71.31	54.36	52.75
		a*	2.02	1.39	0.76	2.46	3.47	4.23	1.20	0.48	2.32	1.61	3.24	3.49	3.68	5.26	4.07	0.79	0.18	1.35	1.92	2.06
		b*	12.90	13.12	12.54	13.26	12.67	13.63	9.90	11.26	11.86	12.07	13.45	12.74	13.11	13.28	12.59	9.72	9.90	13.43	10.07	9.34

Measurements Before Heating:

Sample	Light	Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
300-1-1	SCI	L*	79.78	78.15	75.18	69.84	71.53	79.68	83.31	71.92	70.95	76.36	69.81	64.65	66.55	67.94	68.63	81.19	80.59	79.31	81.31	81.51
		a*	1.91	1.82	2.47	3.74	3.78	1.50	1.06	1.30	1.81	2.04	4.23	5.09	4.54	3.58	4.63	1.93	1.71	1.78	1.14	1.00
		b*	12.56	10.96	11.89	12.76	12.73	14.67	11.46	9.16	9.68	12.40	12.53	13.34	12.50	12.10	11.94	10.53	9.50	8.94	8.54	9.09
	-	G	64	66	68	71	72	70	66	73	74	72	79	81	82	77	74	68	68	67	69	69
	SCE	L*	78.15	76.42	73.28	67.56	69.33	77.90	81.76	69.69	68.63	74.38	67.26	61.69	63.69	65.35	66.18	79.51	78.89	77.58	79.61	79.82
		a*	2.03	1.93	2.62	4.02	4.04	1.61	1.14	1.39	1.95	2.18	4.55	5.55	4.92	3.85	4.99	2.05	1.82	1.90	1.21	1.06
		b*	13.52	11.86	12.94	14.11	14.01	15.81	12.27	10.05	10.67	13.49	13.96	15.28	14.12	13.55	13.31	11.34	10.24	9.67	9.23	9.81
300-1-2	SCI	L*	77.53	77.89	73.68	69.31	70.51	75.11	74.04	74.26	77.62	79.79	78.58	79.06	79.26	76.52	77.65	77.46	77.62	75.79	82.37	80.80
		a*	2.14	1.50	2.53	3.98	3.29	1.97	2.38	2.70	1.83	1.46	2.57	1.71	1.62	2.22	2.01	2.26	1.93	2.18	1.20	2.29
		b*	12.07	10.90	10.19	12.04	10.40	10.37	11.44	10.44	11.35	11.51	10.28	9.28	8.57	9.61	8.86	9.93	8.97	8.99	9.87	11.29
	-	G	73	76	79	79	81	80	79	79	76	71	65	66	66	70	68	69	68	69	65	66
	SCE	L*	75.56	15.87	71.53	66.73	67.96	72.84	71.75	71.96	75.60	77.98	76.87	77.36	77.56	74.61	75.84	75.61	75.80	73.87	80.80	79.17
		a*	2.28	1.59	2.71	4.30	3.54	2.10	2.55	2.89	1.95	1.57	2.73	1.82	1.71	2.36	2.13	2.39	2.05	2.32	1.28	2.43
		b*	13.11	11.85	11.19	13.41	11.53	11.38	12.55	11.45	12.32	12.42	11.11	10.03	9.28	10.44	9.62	10.78	9.73	9.79	10.58	12.13
300-1-3	SCI	L*	77.23	80.34	81.85	80.71	68.84	75.65	75.75	77.38	82.72	70.92	74.08	80.05	72.16	74.14	74.68	76.97	77.50	79.75	75.96	81.89
		a*	2.51	1.40	0.66	0.55	2.32	1.48	2.48	2.27	0.67	2.56	2.63	0.94	3.15	2.80	2.53	1.74	1.59	1.12	1.91	0.34
		b*	11.41	11.26	10.86	9.81	9.71	9.60	10.83	10.95	11.03	9.57	9.29	7.79	9.08	9.51	9.06	7.88	7.66	8.26	8.38	7.84
	-	G	73	72	69	69	77	70	73	74	77	76	72	66	71	74	73	74	68	66	71	66
	SCE	L*	75.25	78.52	80.17	78.98	66.32	73.69	73.73	75.41	80.87	68.56	72.00	78.37	70.00	72.00	72.60	74.98	75.67	78.07	73.99	80.29
		a*	2.67	1.50	0.72	0.60	2.49	1.58	2.64	2.42	0.79	2.73	2.81	1.01	3.37	2.99	2.69	1.86	1.70	1.21	2.04	0.38
		b*	12.40	12.15	11.66	10.52	10.75	10.44	11.80	11.89	11.82	10.54	10.16	8.41	9.98	10.39	9.90	8.59	8.31	8.91	9.14	8.45
300-2-1	SCI	L*	79.87	75.52	74.76	71.56	73.01	72.39	71.21	74.11	80.09	71.95	80.83	83.25	82.95	78.57	77.22	78.10	79.62	80.74	82.00	79.52
		a*	1.17	2.06	1.98	2.86	2.40	2.46	2.48	2.37	0.99	2.32	1.18	0.42	0.28	1.44	1.85	1.48	1.21	0.86	0.46	1.08
		b*	10.88	12.06	13.85	13.35	12.47	12.18	12.65	11.41	10.04	11.68	10.44	9.00	9.58	9.15	9.79	9.61	9.06	9.02	9.07	8.80
	-	G	65	67	73	72	71	71	72	72	65	72	70	67	67	70	71	75	73	70	69	68
	SCE	L*	78.22	73.66	72.67	69.35	70.91	70.25	68.98	72.01	78.54	69.78	79.08	81.67	81.36	76.75	75.32	76.13	77.74	78.98	80.33	77.78
		a*	1.25	2.19	2.12	3.06	2.56	2.62	2.66	2.54	1.07	2.47	1.26	0.47	0.31	1.54	1.96	1.57	1.29	0.92	0.50	1.16
		b*	11.72	13.12	15.12	14.69	13.64	13.36	13.91	12.45	10.80	12.82	11.22	9.65	10.25	9.91	10.62	10.43	9.80	9.72	9.74	9.51
300-2-2	SCI	L*	79.88	78.03	79.98	81.61	81.42	75.22	68.57	68.64	71.84	71.50	82.83	83.49	79.65	78.93	81.78	76.36	72.09	78.01	79.69	79.33
		a*	0.97	1.22	0.46	-0.08	0.13	1.71	2.48	2.87	1.89	2.26	0.28	0.12	0.79	0.91	0.59	1.76	1.66	0.31	0.73	0.90
		b*	15.67	14.79	12.01	11.39	11.60	12.78	12.45	13.11	11.77	13.10	9.06	9.55	10.51	9.64	9.41	9.76	8.85	9.25	10.07	9.52
	-	G	64	66	65	63	62	70	74	74	72	72	70	68	69	72	71	72	70	69	69	72
	SCE	L*	78.26	76.30	78.34	80.08	79.89	73.25	66.12	66.21	69.65	69.30	81.16	81.90	77.90	77.06	80.05	74.40	69.98	76.18	77.92	77.49
		a*	1.04	1.30	0.51	-0.06	0.16	1.82	2.65	3.08	2.01	2.41	0.31	0.15	0.84	0.98	0.64	1.88	1.78	0.34	0.77	0.96
		b*	16.84	15.96	12.91	12.22	12.43	13.92	13.83	14.58	12.92	14.41	9.74	10.23	11.35	10.44	10.12	10.67	9.73	10.01	10.88	10.31
300-2-3	SCI	L*	74.69	73.52	72.88	72.72	70.65	71.77	73.12	64.19	65.04	63.85	76.32	76.85	75.85	81.98	75.73	78.05	69.93	69.75	73.24	75.38
		a*	-0.16	0.40	1.19	0.92	1.65	0.94	0.16	2.75	2.95	2.93	0.26	-0.04	-0.37	-0.44	0.40	0.07	1.91	2.03	0.88	0.16
		b*	11.12	12.01	12.60	12.18	11.80	11.15	10.84	10.85	12.15	11.38	10.37	10.11	11.27	9.00	10.99	9.41	11.47	11.24	11.30	11.31
	-	G	67	69	71	72	72	71	70	77	76	77	73	73	68	63	71	72	80	83	76	70
	SCE	L*	72.77	71.49	70.78	70.58	68.38	69.61	71.05	61.36	62.30	60.99	74.33	74.87	73.96	80.45	73.74	76.15	67.38	67.07	70.98	73.40
		a*	-0.17	0.42	1.28	0.97	1.75	1.00	0.17	2.97	3.18	3.18	0.28	-0.03	-0.38	-0.45	0.42	0.09	2.05	2.17	0.94	0.18
		b*	12.10	13.10	13.79	13.33	13.01	12.25	11.87	12.27	13.68	12.88	11.30	10.98	12.24	9.65	11.96	10.19	12.76	12.55	12.43	12.30
350-0.5-1	SCI	L*	59.27	55.86	60.08	61.16	59.61	56.97	58.05	59.27	61.56	60.10	79.93	78.40	78.55	75.92	76.44	72.91	72.63	69.09	68.27	68.05
		a*	3.19	5.18	3.40	3.19	3.22	3.68	4.40	4.56	6.40	9.03	2.16	2.31	2.18	2.04	1.48	1.78	2.09	2.58	2.17	2.30
		b*	11.90	11.00	11.26	12.28	12.50	11.72	12.43	12.18	13.42	13.69	10.32	10.34	10.62	9.79	9.78	11.60	11.25	11.03	9.51	9.28
	-	G	76	79	77	77	77	79	78	78	77	79	60	67	67	69	68	69	69	74	78	78
	SCE	L*	56.05	52.17	56.88	58.07	56.39	53.42	54.62	55.99	58.51	56.86	78.40	76.66	76.79	74.01	74.56	70.84	70.57	66.68	65.68	65.44
		a*	3.49	5.79	3.73	3.47	3.53	4.06	4.87	5.02	7.02	9.95	2.29	2.46	2.31	2.17	1.57	1.88	2.22	2.76	2.31	2.45
		b*	13.80	13.02	12.97	14.09	14.45	13.77	14.52	14.11	15.38	15.83	11.14	11.21	11.50	10.67	10.65	12.74	12.36	12.22	10.58	10.34

Measurements Before Heating:

Sample	Light	Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
350-0.5-2	SCI	L*	68.41	67.34	69.94	69.47	71.81	71.40	65.60	65.70	66.78	68.62	75.51	72.62	71.06	69.20	67.05	77.54	72.10	74.24	75.83	72.16
		a*	1.99	1.99	1.99	1.99	1.99	1.99	1.99	1.99	1.99	1.99	1.99	1.99	1.99	1.99	1.99	1.99	1.99	1.99	1.99	1.99
		b*	12.64	12.03	10.87	11.72	13.25	13.02	12.34	11.96	12.35	12.40	10.17	12.67	12.87	11.50	11.31	10.55	13.03	12.52	9.46	12.98
	-	G	76	76	72	71	70	70	74	76	77	76	73	74	68	71	73	70	67	73	74	73
	SCE	L*	65.90	64.76	67.65	67.18	69.69	69.24	62.95	62.99	64.13	66.13	73.47	70.41	68.95	66.91	64.56	75.67	70.06	72.13	73.78	69.96
		a*	3.01	3.05	2.30	2.48	2.40	2.40	3.53	3.42	3.22	2.89	1.76	2.25	1.76	1.86	2.03	0.18	1.61	1.80	1.59	2.13
		b*	14.08	13.42	12.02	12.98	14.57	14.34	13.85	13.44	13.83	13.81	11.12	13.95	14.14	12.70	12.61	11.41	14.29	13.72	10.35	14.28
350-0.5-3	SCI	L*	78.38	76.90	76.18	72.99	76.63	83.06	79.02	77.37	76.89	83.57	73.81	67.81	76.91	74.80	74.19	75.05	77.71	79.52	77.48	78.61
		a*	1.70	1.51	1.27	1.12	0.02	0.51	0.82	0.40	0.07	0.27	2.74	3.07	0.74	1.93	1.87	1.60	0.98	1.07	2.75	3.38
		b*	12.43	11.25	11.72	12.18	11.33	10.27	11.48	10.37	10.52	9.77	11.12	9.66	8.53	10.98	12.11	11.83	10.23	9.19	9.85	10.70
	-	G	66	68	70	71	66	65	72	74	72	64	69	72	62	66	70	70	69	68	68	68
	SCE	L*	76.65	75.05	74.25	70.89	74.82	81.52	77.16	75.38	74.94	82.06	71.80	65.39	75.23	72.91	72.16	73.07	75.88	77.78	75.65	76.83
		a*	1.82	1.61	1.35	1.19	0.03	0.56	0.88	0.45	0.09	0.31	2.92	3.30	0.79	2.06	1.99	1.70	1.04	1.14	2.93	3.58
		b*	13.42	12.18	12.73	13.33	12.28	11.00	12.36	11.19	11.39	10.46	12.18	10.76	9.26	11.98	13.23	12.88	11.07	9.91	10.68	11.58
350-1-1	SCI	L*	70.90	72.07	71.38	73.26	73.53	74.06	75.39	76.41	77.09	77.91	69.50	69.44	68.13	71.84	73.29	75.48	74.60	74.16	74.25	73.76
		a*	1.92	1.43	1.68	1.22	1.15	0.96	0.59	0.43	0.83	0.79	1.91	2.51	0.98	0.66	0.66	0.33	0.90	0.76	1.09	0.70
		b*	12.41	12.25	12.74	12.45	12.62	12.58	13.68	13.54	12.39	11.46	12.49	11.54	11.56	12.84	13.06	12.57	11.30	13.48	10.25	12.57
	-	G	74	73	73	75	78	73	74	72	70	71	75	72	75	69	72	72	74	73	74	75
	SCE	L*	68.60	69.85	69.14	71.04	71.25	71.95	73.32	74.43	75.19	76.04	67.09	67.10	65.63	69.75	71.16	73.47	72.48	72.05	72.12	71.56
		a*	2.06	1.53	1.79	1.30	1.24	1.03	0.65	0.47	0.89	0.84	2.04	2.68	1.03	0.70	0.71	0.35	0.95	0.80	1.16	0.74
		b*	13.71	13.49	14.05	13.70	13.90	13.76	14.91	14.69	13.40	12.38	13.82	12.78	12.83	14.05	14.30	13.69	12.38	14.75	11.24	13.78
350-1-2	SCI	L*	70.26	67.02	65.12	71.41	72.36	70.81	72.79	71.75	65.48	62.50	80.51	76.87	77.09	77.31	74.53	78.04	81.52	82.48	81.44	81.81
		a*	2.89	3.16	3.42	2.94	3.94	4.26	3.53	2.49	3.65	4.22	0.55	1.10	1.07	0.75	1.18	0.72	1.20	0.83	0.95	1.11
		b*	12.81	13.49	13.26	13.79	15.40	15.09	14.81	13.39	13.74	12.87	9.02	10.52	11.69	11.16	10.45	8.93	10.96	10.01	10.12	10.49
	-	G	71	75	76	71	74	74	71	75	78	83	64	67	68	68	70	67	65	66	63	66
	SCE	L*	68.00	64.43	62.38	69.21	70.14	68.50	70.68	69.47	62.68	59.27	78.92	75.05	75.26	75.49	72.53	76.28	79.92	80.90	79.89	80.20
		a*	3.10	3.40	3.70	3.15	4.22	4.57	3.78	2.66	3.96	4.64	0.58	1.17	1.14	0.79	1.25	0.76	1.27	0.89	1.01	1.17
		b*	14.20	15.15	15.00	15.23	17.01	16.73	16.29	14.84	15.56	14.84	9.74	11.43	12.68	12.11	11.42	9.69	11.81	10.76	10.90	11.29
350-1-3	SCI	L*	74.88	77.71	79.65	73.41	68.12	68.67	73.35	81.97	81.51	81.62	80.97	80.42	79.68	77.12	79.54	80.96	79.89	82.61	82.85	82.84
		a*	3.59	2.41	1.68	2.42	3.48	2.60	2.57	0.80	0.77	0.79	0.78	0.87	0.76	1.55	0.18	0.56	0.82	0.92	1.19	1.05
		b*	14.33	15.60	14.54	14.75	13.61	12.57	12.84	10.70	10.46	10.63	10.50	12.30	10.76	10.24	9.50	10.16	10.05	9.77	10.24	10.12
	-	G	71	68	67	70	75	75	73	68	66	67	64	64	65	67	64	65	65	65	66	62
	SCE	L*	72.86	75.91	77.93	71.35	65.62	66.19	71.21	80.32	79.89	79.97	79.39	78.81	78.02	75.32	77.89	79.36	78.24	81.04	81.27	81.35
		a*	3.82	2.56	1.78	2.59	3.74	2.79	2.74	0.83	0.81	0.84	0.83	0.93	0.81	1.64	0.20	0.60	0.87	0.97	1.26	1.11
		b*	15.71	16.92	15.70	16.20	15.21	14.02	14.12	11.53	11.26	11.45	11.31	13.24	11.61	11.11	10.26	10.96	10.85	10.53	11.01	10.88
350-2-1	SCI	L*	66.03	66.04	68.71	69.03	66.99	64.41	67.91	72.78	74.39	75.17	79.24	78.55	76.09	76.10	75.97	75.56	76.10	76.96	76.81	76.43
		a*	3.54	3.51	2.76	2.64	3.28	4.48	3.31	2.51	2.09	2.19	1.64	1.74	1.45	1.33	2.00	1.85	1.21	1.74	1.64	1.58
		b*	12.53	13.05	13.26	13.41	13.60	13.71	13.57	10.86	9.39	11.19	9.99	9.63	9.32	9.90	9.81	9.15	9.97	8.52	9.15	8.82
	-	G	77	76	74	74	75	79	76	72	73	72	69	66	66	67	70	68	67	70	70	73
	SCE	L*	63.31	63.37	66.28	66.63	64.40	61.51	65.37	70.62	72.29	73.14	77.47	76.82	74.26	74.27	74.03	73.66	74.25	75.07	74.90	74.43
		a*	3.84	3.81	2.97	2.84	3.55	4.89	3.57	2.68	2.23	2.34	1.74	1.84	1.54	1.41	2.12	1.97	1.28	1.85	1.74	1.68
		b*	14.16	14.72	14.77	14.92	15.27	15.61	15.19	11.93	10.29	12.23	10.83	10.45	10.16	10.80	10.72	10.01	10.87	9.29	9.96	9.62
350-2-2	SCI	L*	72.60	65.22	64.99	65.33	65.13	65.65	65.98	68.54	66.10	62.30	71.26	69.30	68.92	67.22	69.51	69.04	67.02	72.79	68.60	70.50
		a*	1.24	3.08	2.79	2.04	2.96	2.49	2.90	2.94	3.04	4.41	1.98	2.41	1.56	2.18	2.39	2.55	2.80	1.71	2.36	2.02
		b*	12.35	11.93	12.25	11.33	11.34	11.86	12.58	11.42	11.00	10.98	10.05	12.10	10.00	9.93	10.78	12.17	10.64	8.89	10.25	9.65
	-	G	71	80	79	78	80	79	79	78	77	80	73	76	74	74	73	76	75	69	73	71
	SCE	L*	70.47	62.34	62.13	62.52	62.24	62.83	63.19	65.96	63.39	59.17	69.02	66.82	66.51	64.68	67.14	66.55	64.45	70.74	66.20	68.26
		a*	1.31	3.34	3.02	2.20	3.22	2.69	3.14	3.16	3.28	4.84	2.12	2.59	1.67	2.35	2.57	2.73	3.02	1.82	2.53	2.15
		b*	13.59	13.56	13.90	12.82	12.88	13.41	14.23	12.76	12.41	12.62	11.08	13.45	11.12	11.11	11.96	13.55	11.92	9.78	11.43	10.68

Measurements Before Heating:

Sample	Light	Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
350-2-3	SCI	L*	70.52	69.80	68.88	67.36	66.65	67.30	69.10	65.11	64.77	62.02	71.40	69.93	69.48	68.80	71.27	70.46	69.13	72.64	71.82	68.12
		a*	0.77	0.33	0.90	2.22	2.01	1.69	0.88	3.29	3.50	4.11	0.66	0.54	1.21	1.47	0.59	0.28	0.75	1.35	1.60	2.41
		b*	10.89	9.97	10.65	12.10	11.75	12.59	10.74	11.83	12.15	12.26	10.85	10.29	11.06	11.17	10.82	9.91	10.56	9.51	9.58	12.00
	-	G	72	72	73	75	75	74	73	75	78	80	70	73	72	73	72	72	73	68	70	74
	SCE	L*	68.26	67.48	66.49	64.79	64.05	64.77	66.73	62.40	61.94	58.87	69.23	67.62	67.14	66.40	69.06	68.18	66.76	70.60	69.68	65.67
		a*	0.81	0.34	0.95	2.39	2.16	1.80	0.94	3.57	3.81	4.51	0.68	0.56	1.28	1.56	0.62	0.29	0.78	1.42	1.70	2.58
		b*	12.05	11.06	11.85	13.57	13.20	14.10	11.93	13.36	13.80	14.12	11.98	11.42	12.28	12.44	11.95	10.97	11.74	10.46	10.56	13.39
400-0.5-1	SCI	L*	68.88	70.53	68.90	67.40	68.22	69.25	68.17	70.59	66.87	67.40	81.62	81.20	80.13	80.35	81.45	80.83	81.68	81.84	79.60	81.56
		a*	3.06	2.23	2.61	2.95	2.47	2.47	3.17	0.51	1.27	1.08	0.39	0.22	0.65	0.51	0.44	0.51	0.35	1.28	1.88	1.41
		b*	12.79	13.21	13.81	14.45	13.38	13.83	13.02	12.01	11.86	12.25	9.59	9.29	9.10	9.19	8.90	8.60	8.76	8.28	9.25	8.27
	-	G	73	73	73	75	74	73	74	70	73	73	63	63	68	64	66	64	62	61	66	61
	SCE	L*	66.49	68.23	66.50	64.84	65.77	66.88	65.70	68.39	64.35	64.91	80.08	79.64	78.40	78.75	79.83	79.24	80.16	80.36	77.93	80.06
		a*	3.28	2.38	2.80	3.18	2.65	2.64	3.41	0.53	1.36	1.14	0.42	0.24	0.69	0.54	0.47	0.54	0.37	1.35	1.98	1.50
		b*	14.26	14.64	15.39	16.19	4.93	15.37	14.54	13.23	13.25	13.65	10.31	10.01	9.83	9.91	9.58	9.28	9.43	8.92	10.02	8.92
400-0.5-2	SCI	L*	82.23	81.49	81.45	79.59	81.25	81.86	79.91	74.38	74.94	69.90	83.95	83.05	83.38	82.89	84.23	82.74	82.89	82.75	83.02	82.42
		a*	0.36	0.64	0.53	0.67	0.68	0.60	0.81	0.75	0.58	1.11	0.24	0.55	0.27	0.37	0.56	0.36	0.56	0.49	1.04	1.03
		b*	11.77	11.08	11.77	11.95	11.86	11.25	11.45	13.38	12.50	13.78	9.42	8.92	8.47	8.91	11.21	8.84	8.91	9.66	9.01	8.15
	-	G	66	65	68	70	69	67	67	67	66	71	64	61	64	67	64	69	66	65	60	63
	SCE	L*	80.64	79.91	79.78	77.79	79.56	80.24	78.22	72.45	73.07	67.63	82.45	81.61	81.86	81.30	82.74	81.09	81.33	81.19	81.59	80.91
		a*	0.39	0.68	0.57	0.71	0.73	0.64	0.86	0.79	0.61	1.18	0.26	0.59	0.30	0.40	0.61	0.38	0.59	0.52	1.11	1.09
		b*	12.64	11.93	12.65	12.91	12.76	12.09	12.36	14.60	13.64	15.23	10.10	9.59	9.11	9.57	11.99	9.50	9.58	10.38	9.69	8.78
400-0.5-3	SCI	L*	81.88	82.57	82.22	80.73	82.00	82.00	83.00	70.27	69.05	69.99	84.15	83.08	82.99	83.93	83.36	83.64	82.74	81.62	83.41	84.70
		a*	0.33	0.21	0.14	0.03	0.31	0.22	0.25	2.51	3.80	2.68	0.10	0.44	0.30	0.41	0.38	0.31	0.30	2.09	1.48	0.35
		b*	11.36	11.08	11.04	11.59	11.12	10.86	11.06	16.42	14.66	15.95	10.73	10.72	10.05	9.06	8.94	8.85	9.78	9.45	9.54	8.64
	-	G	66	67	68	70	68	66	64	72	73	73	62	68	64	64	67	67	65	63	61	60
	SCE	L*	80.28	80.95	80.59	78.99	80.36	80.40	81.48	67.99	66.66	67.68	82.71	81.47	81.48	82.44	81.78	82.07	81.18	80.08	81.98	83.32
		a*	0.36	0.23	0.17	0.05	0.34	0.24	0.28	2.68	4.07	2.88	0.12	0.47	0.33	0.45	0.40	0.33	0.32	2.21	1.56	0.38
		b*	12.20	11.89	11.84	12.44	11.96	11.68	11.85	18.15	16.28	17.65	11.46	11.52	10.78	9.72	9.61	9.52	10.52	10.19	10.25	9.27
400-1-1	SCI	L*	80.79	79.26	77.42	81.27	78.91	78.50	80.33	74.28	72.42	75.69	84.28	82.27	82.05	80.77	83.63	83.57	82.57	80.66	80.47	78.32
		a*	0.65	0.66	0.95	0.50	0.70	0.90	0.79	2.50	2.79	2.02	0.20	0.43	0.63	1.01	0.46	0.39	0.51	1.29	1.12	2.04
		b*	11.99	10.53	12.71	10.95	11.80	11.86	9.97	16.73	15.07	15.66	10.86	10.35	8.97	9.10	7.87	9.20	9.89	8.73	7.93	8.52
	-	G	66	69	75	71	72	70	65	69	70	68	68	65	61	64	63	64	63	64	64	68
	SCE	L*	79.14	77.47	75.41	79.52	77.05	76.65	78.71	72.29	70.32	73.79	82.71	80.69	80.58	79.18	82.15	82.07	81.04	79.08	78.88	76.54
		a*	0.70	0.69	1.00	0.53	0.75	0.95	0.84	2.67	2.97	2.15	0.22	0.46	0.67	1.07	0.50	0.42	0.54	1.36	1.18	2.16
		b*	12.92	11.39	13.81	11.80	12.77	12.85	10.76	18.28	16.58	17.05	11.65	11.13	9.65	9.83	8.47	9.89	10.62	9.42	8.58	9.26
400-1-2	SCI	L*	77.99	75.73	75.15	67.74	69.33	72.76	75.35	75.37	71.12	71.82	78.83	77.70	79.27	80.51	75.94	73.78	78.15	73.42	78.31	77.99
		a*	0.97	1.06	1.39	2.38	2.75	1.97	1.32	1.08	2.42	2.29	1.06	0.74	0.68	0.48	1.27	2.11	1.08	2.65	1.32	1.49
		b*	13.59	14.32	13.47	12.63	12.15	12.89	12.70	13.66	16.38	13.77	9.53	10.14	10.51	8.76	9.96	10.88	9.67	10.74	8.29	9.28
	-	G	69	71	70	75	73	71	70	70	70	70	68	68	69	69	72	75	71	69	66	68
	SCE	L*	76.16	73.76	73.17	65.21	66.97	70.66	73.40	73.40	68.94	69.68	77.06	75.87	77.50	78.80	73.96	71.60	76.28	71.40	76.56	76.19
		a*	1.04	1.13	1.48	2.56	2.95	2.10	1.41	1.14	2.58	2.44	1.12	0.80	0.73	0.50	1.35	2.24	1.14	2.81	1.39	1.58
		b*	14.71	15.58	14.66	14.07	13.49	14.14	13.83	14.88	18.08	15.18	10.31	10.99	11.37	9.47	10.86	11.94	10.48	11.80	9.02	10.08
400-1-3	SCI	L*	73.52	72.47	65.23	64.29	66.39	66.97	72.92	64.66	65.10	62.91	74.08	73.80	67.76	64.16	79.61	75.19	73.51	69.39	71.26	67.38
		a*	1.03	1.19	2.82	2.80	2.06	2.42	1.09	2.37	3.16	4.38	1.18	1.11	2.26	1.92	0.10	0.67	1.42	1.96	1.76	3.32
		b*	15.09	12.52	12.55	11.55	10.95	12.46	13.68	10.74	11.42	11.44	13.95	12.61	11.53	9.78	9.70	13.72	15.08	14.58	14.05	14.40
	-	G	67	69	75	76	74	75	70	75	76	78	76	75	74	75	67	73	78	72	72	74
	SCE	L*	71.55	70.39	62.55	61.49	63.81	64.38	70.84	61.91	62.35	59.92	71.89	71.63	65.26	61.37	77.89	73.14	71.22	67.06	69.04	64.88
		a*	1.09	1.26	3.05	3.04	2.21	2.60	1.16	2.57	3.42	4.79	1.25	1.18	2.42	2.07	0.11	0.71	1.51	2.11	1.87	3.58
		b*	16.48	13.75	14.16	13.09	12.29	13.94	14.97	12.16	12.92	13.08	15.27	13.85	12.88	11.07	10.49	14.95	16.56	16.18	15.52	16.12

Measurements Before Heating:

Sample	Light	Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
400-2-1	SCI	L*	78.18	76.84	76.62	77.33	76.70	76.52	76.62	81.90	80.29	80.17	73.37	71.70	71.75	71.92	72.29	73.60	69.32	80.55	80.43	80.69
		a*	0.70	0.54	1.10	1.37	0.68	0.51	0.55	0.77	1.43	1.37	1.85	2.20	2.26	2.37	1.96	1.59	2.75	1.30	1.12	1.20
		b*	12.25	12.06	12.52	12.67	12.76	13.09	11.81	10.93	9.77	9.60	14.37	14.62	14.65	14.15	15.19	13.69	15.68	10.93	10.18	10.62
	-	G	65	67	67	67	68	68	68	61	63	64	69	71	70	72	71	70	73	78	78	79
	SCE	L*	76.46	75.01	74.79	75.55	74.85	74.65	74.76	80.42	78.69	78.56	71.34	69.53	69.60	69.74	70.15	71.56	66.96	78.59	78.46	78.71
		a*	0.74	0.56	1.16	1.45	0.72	0.54	0.57	0.82	1.52	1.45	1.97	2.36	2.40	2.54	2.09	1.68	2.95	1.37	1.18	1.26
		b*	13.28	13.11	13.62	13.75	13.87	14.23	12.84	11.73	10.54	10.36	15.74	16.10	16.13	15.59	16.71	15.00	17.61	11.82	11.01	11.49
400-2-2	SCI	L*	72.38	71.84	74.02	74.71	73.80	74.87	71.95	69.28	65.94	69.80	72.18	71.61	68.41	71.15	70.35	71.34	69.38	75.29	75.28	74.70
		a*	0.61	0.52	0.38	-0.03	0.35	-0.07	0.57	2.13	2.50	2.04	1.30	1.30	2.23	1.68	1.20	1.32	2.08	1.37	0.89	1.43
		b*	11.95	11.13	10.46	10.81	11.41	11.32	11.54	12.29	11.44	12.63	11.30	12.38	12.36	11.50	10.75	11.92	12.26	8.42	9.15	8.31
	-	G	69	71	70	69	69	68	71	71	74	71	70	72	73	72	72	73	73	71	67	72
	SCE	L*	70.30	69.68	72.00	72.76	71.78	72.93	69.80	66.97	63.32	67.53	70.07	69.40	65.99	68.93	68.06	69.10	67.03	73.30	73.41	72.65
		a*	0.64	0.54	0.39	-0.05	0.36	-0.08	0.58	2.27	2.69	2.16	1.38	1.38	2.39	1.79	1.28	1.40	2.22	1.45	0.95	1.50
		b*	13.15	12.26	11.45	11.80	12.50	12.37	12.71	13.66	12.88	14.02	12.44	13.65	13.77	12.69	11.91	13.16	13.61	9.21	10.00	9.11
400-2-3	SCI	L*	78.88	80.16	79.20	80.56	78.32	79.79	79.92	80.11	78.04	80.47	76.53	80.93	77.33	78.30	81.60	78.31	79.14	79.20	76.95	79.75
		a*	5.06	4.84	5.34	4.78	4.50	4.86	4.88	4.64	5.71	4.77	6.52	3.66	4.99	3.88	2.19	4.46	4.27	4.28	6.00	3.69
		b*	10.73	10.15	10.06	10.41	10.19	10.83	10.59	10.52	10.95	10.25	11.49	9.59	10.48	11.64	10.36	9.76	9.59	9.67	12.54	10.66
	-	G	70	69	73	70	71	68	67	69	73	68	66	66	68	63	64	69	67	67	66	69
	SCE	L*	77.06	78.41	77.30	78.82	76.46	78.07	78.21	78.37	76.11	78.76	74.71	79.28	75.51	76.64	80.03	76.50	77.40	77.48	75.15	78.01
		a*	5.38	5.12	5.66	5.05	4.77	5.14	5.17	4.91	6.06	5.05	6.93	3.87	5.29	4.10	2.32	4.73	4.53	4.54	6.36	3.91
		b*	11.64	10.98	10.92	11.25	11.06	11.71	11.45	11.35	11.91	11.08	12.52	10.36	11.40	12.61	11.17	10.60	10.39	10.48	13.65	11.54

Measurements After Heating:

Sample	Light	Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Control-1-p	SCI	L*	60.70	55.27	58.83	61.92	61.98	61.64	60.45	59.90	64.51	60.13	76.65	73.37	76.35	78.58	75.71	75.39	72.53	67.64	60.46	55.42
		a*	3.52	8.62	6.18	4.99	4.86	3.88	4.69	4.93	3.84	2.33	2.95	3.65	1.90	0.92	-0.42	0.96	2.49	3.54	3.07	1.35
		b*	10.65	11.41	12.15	12.37	11.63	12.15	10.55	10.83	13.75	10.84	9.68	9.98	10.02	10.35	9.30	11.66	9.84	9.68	11.58	8.58
	-	G	79	81	80	77	77	77	79	80	77	79	70	73	71	73	71	69	72	76	78	83
	SCE	L*	57.50	51.40	55.42	58.90	58.95	58.59	57.21	56.60	61.71	56.86	74.74	71.23	74.40	76.68	73.72	73.47	70.37	65.06	57.26	51.48
		a*	3.83	9.72	6.83	5.45	5.29	4.22	5.16	5.42	4.15	2.53	3.15	3.90	2.03	0.98	-0.44	1.02	2.65	3.82	3.36	1.46
		b*	12.25	13.67	14.17	14.17	13.30	13.92	12.18	12.52	15.56	12.50	10.55	10.99	10.93	11.24	10.13	12.71	10.83	10.78	13.35	10.18
Control-2-c	SCI	L*	80.50	71.78	70.33	86.50	75.77	85.01	71.56	70.96	72.92	74.48	81.77	82.99	72.70	76.01	86.21	81.53	81.41	78.85	70.61	80.87
		a*	-0.23	0.61	1.20	0.72	2.23	0.61	1.02	1.43	0.93	0.35	3.97	2.92	3.72	2.87	-0.05	4.24	3.46	1.61	3.43	4.08
		b*	11.27	8.43	10.82	11.27	11.91	12.70	11.65	12.44	10.90	10.35	14.23	12.70	13.04	9.74	12.58	15.27	15.89	9.40	8.72	13.38
	-	G	60	70	93	63	70	62	89	89	83	85	73	69	76	69	64	64	73	66	79	74
	SCE	L*	78.99	69.63	67.38	85.10	73.83	83.61	68.80	68.17	70.43	72.04	79.97	81.34	69.75	74.10	84.80	79.96	79.63	77.14	68.31	79.04
		a*	-0.21	0.65	1.29	0.77	2.38	0.67	1.09	1.53	0.98	0.38	4.21	3.10	4.00	3.07	-0.03	4.50	3.68	1.72	3.69	4.34
		b*	12.12	9.28	11.91	12.04	13.01	13.58	12.79	13.66	11.90	11.31	15.35	13.66	14.38	10.64	13.43	16.44	17.16	10.19	9.67	14.46
Control-3-d	SCI	L*	84.10	85.25	81.71	80.44	83.71	84.84	85.80	84.23	80.91	80.28	72.08	72.30	71.35	64.34	67.87	72.81	70.38	67.02	70.36	70.34
		a*	1.09	0.33	1.46	2.17	1.46	0.91	0.29	0.37	2.62	3.57	5.51	5.23	6.23	8.28	6.64	5.04	4.68	6.92	4.58	5.27
		b*	10.88	10.19	10.80	10.38	10.15	10.41	10.57	10.44	9.09	9.70	15.98	14.15	13.82	13.27	14.62	14.66	12.58	14.50	12.17	12.47
	-	G	56	62	66	69	59	58	57	63	64	62	73	72	73	78	76	72	73	77	70	70
	SCE	L*	82.81	83.85	80.09	78.70	82.34	83.51	84.54	82.77	79.31	78.71	69.86	70.12	69.10	61.45	65.32	70.67	68.06	64.37	68.15	68.12
		a*	1.16	0.37	1.56	2.31	1.55	0.98	0.33	0.41	2.78	3.78	5.91	5.60	6.68	9.03	7.19	5.40	5.03	7.51	4.91	5.67
		b*	11.66	10.90	11.61	11.22	10.90	11.16	11.29	11.18	9.83	10.49	17.65	15.61	15.28	15.09	16.39	16.15	13.96	16.33	13.49	13.83
100-0.5-1	SCI	L*	76.23	77.18	78.14	80.17	72.20	72.11	77.63	79.30	75.49	74.41	75.56	75.92	72.41	71.40	72.50	72.12	70.96	66.06	64.63	67.36
		a*	3.78	2.92	2.55	2.20	2.75	3.61	2.52	2.76	3.52	3.33	3.61	3.20	2.68	3.05	1.31	2.71	2.48	2.85	2.69	2.56
		b*	10.87	8.23	9.34	9.11	9.39	10.73	10.01	9.53	9.90	10.32	12.53	12.75	12.66	10.44	6.95	6.50	8.09	10.31	10.47	8.70
	-	G	72	71	69	70	77	77	69	67	69	73	72	77	71	74	71	71	71	77	77	76
	SCE	L*	74.24	75.27	76.32	78.41	69.87	69.76	75.79	77.57	73.55	72.31	73.55	73.77	70.28	69.13	70.36	69.98	68.74	63.36	61.83	64.77
		a*	4.03	3.11	2.72	2.35	2.94	3.87	2.68	2.93	3.74	3.55	3.85	3.40	2.87	3.26	1.40	2.89	2.65	3.07	2.90	2.74
		b*	11.92	9.03	10.20	9.90	10.41	11.90	10.91	10.36	10.86	11.35	13.76	13.98	14.00	11.58	7.70	7.22	8.99	11.62	11.91	9.78
100-0.5-2	SCI	L*	56.64	58.66	58.56	58.87	61.63	61.22	64.60	58.79	60.70	56.47	56.19	69.24	72.55	68.55	79.34	68.71	74.72	81.05	74.41	65.05
		a*	2.13	4.19	3.02	4.62	2.17	0.82	0.06	0.21	1.06	2.79	2.16	1.42	1.51	2.45	1.66	2.53	0.87	-0.98	2.76	2.90
		b*	7.19	8.54	9.96	10.47	11.03	9.62	9.67	6.71	11.34	8.95	5.85	7.87	7.31	6.82	8.29	8.43	7.62	7.53	8.60	5.54
	-	G	84	81	81	82	79	81	79	82	81	83	89	78	76	80	69	81	81	73	73	85
	SCE	L*	52.81	55.15	55.08	55.36	58.49	57.99	61.71	55.24	57.40	52.67	52.04	66.69	70.28	65.88	77.56	66.05	72.41	79.24	72.29	61.96
		a*	2.33	4.65	3.33	5.14	2.37	0.87	0.04	0.18	1.14	3.11	2.42	1.52	1.61	2.64	1.76	2.73	0.91	-1.04	2.96	3.17
		b*	8.62	10.09	11.76	12.35	12.80	11.17	11.07	7.96	13.22	10.75	7.17	8.86	8.15	7.76	9.03	9.50	8.44	8.17	9.48	6.46
100-0.5-3	SCI	L*	84.41	83.08	82.33	81.81	79.35	76.19	79.97	80.89	76.73	80.12	79.74	82.90	79.54	78.59	80.83	77.80	79.54	83.01	79.29	78.84
		a*	1.26	2.06	2.10	2.34	2.49	2.27	0.92	2.41	2.19	2.41	2.18	2.04	2.81	2.97	2.07	3.17	3.09	0.71	2.39	2.83
		b*	9.12	10.46	9.12	9.08	8.39	8.64	8.22	8.93	8.64	8.61	7.72	8.02	9.11	8.58	7.94	8.51	8.47	8.85	8.04	9.41
	-	G	64	67	69	68	71	73	61	65	74	69	63	60	66	66	66	67	65	62	67	67
	SCE	L*	82.92	81.48	80.68	80.14	77.53	74.18	78.43	79.28	74.70	78.38	78.13	81.47	77.85	76.85	79.18	76.04	77.88	81.53	77.56	77.10
		a*	1.34	2.19	2.24	2.49	2.65	2.43	0.99	2.56	2.34	2.57	2.32	2.17	2.99	3.16	2.21	3.37	3.29	0.77	2.55	3.01
		b*	9.82	11.26	9.84	9.82	9.13	9.47	8.93	9.68	9.45	9.35	8.40	8.67	9.91	9.35	8.61	9.29	9.23	9.55	8.75	10.24
100-1-1	SCI	L*	79.46	84.82	82.60	63.78	82.88	79.47	78.47	76.50	62.25	75.79	88.12	87.24	86.66	83.39	88.74	87.96	84.36	79.88	70.44	83.47
		a*	2.50	1.39	1.33	1.75	1.53	2.41	3.02	3.08	5.01	2.97	-0.49	-0.56	-0.22	-0.21	-0.63	0.15	0.84	0.74	1.04	0.94
		b*	7.19	8.13	7.87	11.37	7.80	9.19	8.88	8.35	8.75	8.47	8.16	9.49	7.99	9.90	7.68	7.12	7.50	7.14	9.23	7.88
	-	G	65	60	64	82	63	64	69	71	81	72	64	58	65	62	63	55	61	67	75	62
	SCE	L*	77.79	83.46	81.06	60.72	81.37	77.83	76.66	74.54	59.11	73.80	86.75	85.98	85.23	81.92	87.40	86.77	82.94	78.18	68.07	82.01
		a*	2.67	1.49	1.42	1.91	1.64	2.57	3.21	3.28	5.51	3.17	-0.49	-0.55	-0.20	-0.19	-0.62	0.20	0.91	0.79	1.10	1.01
		b*	7.86	8.75	8.52	13.05	8.44	10.04	9.72	9.19	10.13	9.35	8.72	10.15	8.56	10.67	8.20	7.65	8.10	7.79	10.28	8.51

Measurements After Heating:

Sample	Light	Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
100-1-2	SCI	L*	87.56	87.20	86.83	84.91	84.89	81.81	85.17	84.35	82.22	86.46	81.48	81.88	82.12	82.94	84.42	85.88	86.45	83.41	82.43	82.43
		a*	0.75	0.66	1.06	2.49	1.96	2.98	1.88	2.03	2.74	0.75	3.04	3.03	3.04	2.60	1.85	1.00	0.33	2.18	2.75	2.60
		b*	10.80	11.42	10.54	9.45	10.68	9.70	10.53	10.52	10.26	11.37	8.18	8.90	9.34	9.63	10.07	10.12	10.40	9.93	9.44	9.69
	-	G	60	63	64	63	63	70	65	64	70	65	64	65	67	67	65	64	61	66	67	67
	SCE	L*	86.26	85.83	85.41	83.47	83.44	80.12	83.70	82.87	80.54	85.02	79.91	80.31	80.49	81.35	82.92	84.43	85.11	81.84	80.81	80.81
		a*	0.82	0.73	1.14	2.64	2.09	3.16	2.00	2.16	2.92	0.82	3.23	3.22	3.23	2.77	1.97	1.08	0.39	2.33	2.92	2.76
		b*	11.52	12.20	11.27	10.17	11.48	10.50	11.30	11.32	11.11	12.16	8.87	9.63	10.11	10.40	10.83	10.85	11.12	10.69	10.20	10.47
100-1-3	SCI	L*	85.95	86.30	86.28	84.71	84.62	85.50	86.44	86.21	85.63	85.77	82.70	84.33	85.64	86.03	86.25	85.56	84.33	85.29	85.66	81.72
		a*	1.92	2.07	1.79	1.96	1.81	1.47	1.71	1.99	1.83	2.06	2.59	2.31	1.90	1.26	0.06	1.70	2.24	1.55	1.22	2.77
		b*	10.86	9.22	9.32	10.12	9.58	9.92	8.94	9.62	11.71	10.62	10.72	10.73	10.31	10.10	8.39	10.75	10.46	10.79	10.73	9.93
	-	G	62	59	60	64	63	63	60	60	65	62	64	64	64	66	67	65	65	64	64	67
	SCE	L*	84.56	85.00	84.94	83.24	83.16	84.07	85.11	84.88	84.17	84.37	81.17	82.86	84.20	84.56	84.76	84.10	82.83	83.84	84.21	80.09
		a*	2.05	2.20	1.91	2.08	1.94	1.57	1.82	2.11	1.95	2.20	2.76	2.46	2.02	1.37	0.08	1.82	2.38	1.65	1.31	2.94
		b*	11.61	9.87	9.97	10.85	10.27	10.62	9.56	10.30	12.53	11.36	11.54	11.51	11.04	10.79	8.97	11.51	11.23	11.56	11.48	10.71
100-2-1	SCI	L*	83.76	83.93	85.20	84.70	84.36	83.34	84.68	84.22	84.94	83.98	87.14	86.38	84.28	83.65	84.56	84.15	86.83	84.14	84.06	84.42
		a*	2.07	2.14	1.82	2.01	2.24	2.25	1.62	2.07	2.08	2.24	0.58	0.94	2.34	2.62	1.92	2.32	0.63	1.93	2.36	1.87
		b*	10.20	10.10	9.32	10.84	9.36	10.00	10.51	9.74	8.89	9.73	10.22	10.32	10.32	10.33	10.85	10.36	10.57	10.58	10.31	10.52
	-	G	61	62	62	63	62	63	61	62	61	63	62	64	64	66	67	65	63	66	65	66
	SCE	L*	82.34	82.49	83.79	83.25	82.93	81.86	83.29	82.78	83.56	82.52	85.79	84.96	82.80	82.11	83.03	82.64	85.45	82.60	82.56	82.89
		a*	2.20	2.29	1.95	2.14	2.37	2.39	1.73	2.20	2.21	2.38	0.63	1.02	2.49	2.78	2.05	2.48	0.69	2.06	2.51	1.99
		b*	10.95	10.84	9.98	11.62	10.05	10.75	11.26	10.46	9.54	10.45	10.91	11.02	11.06	11.09	11.63	11.11	11.26	11.34	11.05	11.27
100-2-2	SCI	L*	87.56	84.48	83.92	83.67	83.29	82.89	79.15	82.81	83.55	82.47	81.48	83.21	85.02	81.53	79.91	84.13	80.78	82.49	84.78	82.39
		a*	0.92	2.35	2.71	2.99	2.79	3.12	4.66	3.03	2.64	2.76	3.54	2.60	1.81	2.99	3.73	1.39	2.99	2.04	0.91	2.85
		b*	10.72	10.54	10.97	8.19	10.09	9.04	10.67	11.11	8.65	10.00	10.45	8.12	8.54	8.65	9.87	10.64	8.60	8.62	8.55	9.71
	-	G	59	65	66	64	69	64	71	67	67	69	68	63	63	66	70	65	67	64	62	65
	SCE	L*	86.28	82.99	82.38	82.17	81.67	81.35	77.32	81.21	81.97	80.82	79.81	81.72	83.59	79.92	78.14	82.63	79.12	80.94	83.35	80.83
		a*	1.00	2.50	2.88	3.17	2.96	3.31	4.96	3.22	2.80	2.93	3.77	2.77	1.93	3.19	3.98	1.49	3.18	2.17	0.98	3.03
		b*	11.43	11.31	11.78	8.82	10.86	9.73	11.58	11.96	9.31	10.76	11.27	8.74	9.17	9.35	10.68	11.40	9.31	9.27	9.16	10.45
100-2-3	SCI	L*	83.33	85.34	86.17	80.39	74.54	80.10	85.71	81.57	81.65	80.87	80.36	80.46	82.44	83.93	85.15	84.71	81.46	61.85	59.59	81.14
		a*	1.80	1.95	1.85	2.57	2.73	1.59	1.26	3.02	2.79	2.95	3.96	3.92	3.04	2.24	1.53	1.82	3.51	6.46	6.78	3.72
		b*	9.53	9.40	10.43	8.31	9.01	8.83	11.70	7.89	8.14	8.14	9.68	9.70	8.87	9.45	11.27	9.91	9.23	7.85	7.63	9.46
	-	G	60	59	62	72	80	65	64	69	65	66	68	71	66	65	63	64	67	81	84	68
	SCE	L*	81.91	84.01	84.79	78.58	72.24	78.46	84.28	79.88	80.06	79.23	78.65	78.69	80.85	82.42	83.71	83.23	79.81	58.68	56.06	79.45
		a*	1.92	2.08	1.97	2.73	2.91	1.70	1.36	3.21	2.97	3.15	4.21	4.18	3.22	2.39	1.64	1.95	3.74	7.12	7.54	3.96
		b*	10.23	10.06	11.15	8.97	9.84	9.53	12.49	8.53	8.80	8.81	10.48	10.49	9.55	10.14	12.05	10.61	9.96	9.00	8.83	10.22
150-0.5-1	SCI	L*	83.38	83.17	82.27	80.75	79.04	79.61	80.76	81.64	83.33	82.46	78.83	78.21	79.82	80.69	80.94	81.96	78.77	80.63	82.30	79.84
		a*	2.06	2.17	2.67	2.48	3.37	3.18	2.92	2.93	2.22	1.48	2.83	3.32	3.01	2.94	2.69	2.33	3.56	2.89	2.90	2.89
		b*	10.77	10.09	9.61	9.71	10.07	9.10	9.47	9.71	10.40	12.00	8.47	7.95	9.27	10.22	9.82	10.07	9.21	9.84	11.72	8.76
	-	G	60	63	65	67	70	67	66	66	61	62	70	68	65	67	64	65	66	66	67	66
	SCE	L*	81.96	81.69	80.69	79.07	77.22	77.89	79.12	80.03	81.89	80.96	77.00	76.43	78.17	79.01	79.35	80.38	77.06	79.04	80.68	78.17
		a*	2.18	2.30	2.83	2.63	3.58	3.39	3.10	3.11	2.36	1.58	3.01	3.53	3.20	3.12	2.87	2.48	3.79	3.08	3.07	3.07
		b*	11.57	10.86	10.39	10.50	10.92	9.87	10.25	10.50	11.18	12.88	9.22	8.66	10.05	11.05	10.60	10.87	10.00	10.65	12.62	9.48
150-0.5-2	SCI	L*	76.33	69.32	68.09	62.65	62.39	70.76	71.58	67.07	66.67	70.69	79.97	79.42	78.28	83.27	83.06	82.31	82.52	83.75	82.71	82.46
		a*	4.24	5.77	5.52	5.89	4.12	5.21	4.08	5.47	5.95	4.73	1.78	1.93	2.08	0.30	1.30	2.66	2.16	1.79	2.16	2.36
		b*	13.13	8.95	7.73	9.31	9.04	9.74	9.24	8.23	8.31	10.33	8.68	10.21	9.91	11.87	11.51	8.47	9.18	7.68	9.19	8.74
	-	G	70	75	78	81	82	75	73	78	79	74	68	72	69	68	66	65	65	66	63	64
	SCE	L*	74.42	66.89	65.48	59.52	59.21	68.43	69.33	64.39	63.93	68.36	78.24	77.56	76.46	81.66	81.50	80.75	80.97	82.21	81.21	80.93
		a*	4.53	6.23	5.98	6.48	4.55	5.61	4.38	5.95	6.48	5.10	1.91	2.05	2.23	0.35	1.40	2.83	2.30	1.91	2.30	2.52
		b*	14.35	10.01	8.70	10.72	10.43	10.84	10.26	9.30	9.41	11.50	9.43	11.09	10.76	12.75	12.37	9.16	9.91	8.28	9.91	9.44

Measurements After Heating:

Sample	Light	Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
150-0.5-3	SCI	L*	73.84	68.20	71.86	59.67	70.00	79.22	78.82	59.86	61.59	75.57	85.99	84.44	78.89	75.11	81.82	83.11	84.83	80.17	81.36	84.53
		a*	1.76	1.43	2.25	2.49	1.58	2.51	1.55	2.01	3.23	2.14	0.64	1.09	2.25	2.77	2.56	1.77	1.50	1.94	1.84	1.00
		b*	12.48	9.79	8.84	7.02	10.32	11.48	10.51	9.58	9.50	13.03	10.84	11.21	8.65	7.60	9.94	9.68	9.39	8.56	9.11	9.13
	-	G	72	78	74	84	77	67	69	86	86	73	62	62	74	75	70	67	64	69	66	66
	SCE	L*	71.74	65.60	69.61	56.16	67.55	77.50	77.04	56.27	58.17	73.54	84.60	83.01	76.96	72.98	80.11	81.52	83.36	78.43	79.74	83.00
		a*	1.89	1.54	2.42	2.76	1.70	2.67	1.65	2.21	3.56	2.30	0.70	1.18	2.40	2.97	2.72	1.89	1.61	2.07	1.96	1.09
		b*	13.71	11.00	9.80	8.21	11.50	12.44	11.42	11.21	11.05	14.26	11.61	12.02	9.42	8.35	10.74	10.44	10.08	9.30	9.85	9.81
150-1-1	SCI	L*	65.39	79.75	80.39	83.93	83.89	78.52	77.52	80.74	76.46	77.30	82.53	81.93	84.48	81.92	83.19	83.87	80.69	78.73	74.53	79.77
		a*	0.46	0.21	-0.14	-1.06	-0.35	0.49	2.24	1.62	2.18	1.30	1.23	1.43	0.49	1.36	0.88	0.46	1.21	1.07	1.54	1.19
		b*	11.33	8.36	10.59	11.51	9.64	9.35	8.96	8.38	9.16	8.92	8.40	9.08	8.20	9.16	10.42	9.67	9.40	8.97	9.30	9.23
	-	G	77	62	60	61	60	68	71	68	71	71	62	63	61	66	66	65	64	66	70	65
	SCE	L*	62.62	78.18	78.88	82.51	82.49	76.73	75.63	79.04	74.51	75.40	81.05	80.41	83.08	80.31	81.63	82.35	79.09	77.01	72.54	78.12
		a*	0.48	0.23	-0.13	-1.10	-0.34	0.53	2.39	1.73	2.32	1.39	1.31	1.53	0.54	1.45	0.95	0.50	1.30	1.14	1.65	1.28
		b*	12.82	9.06	11.41	12.33	10.32	10.16	9.76	9.07	10.00	9.73	9.07	9.80	8.82	9.90	11.21	10.38	10.15	9.75	10.20	9.99
150-1-2	SCI	L*	75.41	75.00	78.28	81.21	83.55	84.14	82.80	83.50	82.72	83.37	77.86	82.90	81.43	81.67	74.70	70.78	69.57	70.10	72.33	79.74
		a*	0.95	1.05	0.38	1.20	1.49	1.27	1.47	1.37	1.42	1.47	2.20	1.06	1.96	1.80	1.30	1.25	2.02	0.84	0.99	2.16
		b*	10.92	9.88	10.46	10.45	8.25	8.41	8.17	8.46	8.87	8.23	8.04	8.03	9.12	8.19	9.49	7.59	8.22	9.24	7.97	8.15
	-	G	72	75	72	67	64	63	63	64	65	64	64	59	65	71	74	83	78	81	78	65
	SCE	L*	73.40	72.88	76.38	79.56	82.05	82.67	81.29	81.99	81.15	81.85	76.16	81.50	79.83	79.95	72.58	68.18	67.05	67.54	69.96	78.09
		a*	1.01	1.12	0.41	1.27	1.58	1.36	1.56	1.46	1.51	1.57	2.35	1.14	2.09	1.92	1.39	1.33	2.18	0.89	1.06	2.30
		b*	11.95	10.83	11.37	11.28	8.90	9.05	8.81	9.12	9.57	8.87	8.77	8.67	9.86	8.88	10.41	8.46	9.16	10.30	8.81	8.87
150-1-3	SCI	L*	85.55	86.56	85.72	85.05	86.01	84.44	84.80	84.50	84.55	86.20	83.80	82.52	82.40	81.89	84.48	83.71	82.11	80.99	80.21	81.06
		a*	0.54	0.33	0.64	0.91	0.67	1.09	0.71	0.50	0.94	0.68	1.35	1.66	1.63	1.71	0.97	1.07	1.27	1.31	0.43	1.54
		b*	11.35	11.64	10.84	10.48	10.03	10.26	10.75	10.95	10.56	10.29	9.81	9.36	9.29	9.16	9.42	10.57	10.13	10.59	11.02	10.23
	-	G	57	57	60	64	63	64	65	67	65	62	60	63	62	63	60	65	67	67	68	68
	SCE	L*	84.26	85.24	84.38	83.60	84.61	82.95	83.30	82.96	83.05	84.81	82.39	81.02	80.91	80.37	83.11	82.17	80.49	79.34	78.50	79.38
		a*	0.59	0.37	0.70	0.98	0.73	1.16	0.77	0.55	1.02	0.74	1.45	1.77	1.74	1.83	1.04	1.15	1.35	1.40	0.46	1.64
		b*	12.17	12.44	11.61	11.25	10.75	11.04	11.53	11.75	11.34	11.02	10.54	10.10	10.02	9.90	10.12	11.38	10.94	11.44	11.91	11.07
150-2-1	SCI	L*	84.74	84.32	82.71	80.93	76.85	75.82	83.66	83.15	92.73	82.02	84.98	83.56	82.26	78.25	73.39	78.75	83.21	82.54	80.13	79.53
		a*	0.85	0.92	1.22	1.63	2.52	1.56	1.29	1.60	1.70	1.65	0.81	1.16	1.04	2.56	1.89	1.98	1.31	1.71	1.96	2.03
		b*	12.88	13.19	12.64	16.46	15.43	13.62	16.28	15.27	15.99	16.31	12.81	12.93	15.55	16.48	11.84	15.90	16.12	15.97	16.95	16.63
	-	G	63	61	64	67	73	72	65	65	65	68	62	64	65	71	74	72	66	66	68	69
	SCE	L*	83.30	82.90	81.19	79.27	74.88	73.83	82.13	81.60	81.17	80.36	83.56	82.07	80.68	76.38	71.21	76.88	81.65	80.95	78.40	77.77
		a*	0.92	0.99	1.30	1.74	2.69	1.66	1.38	1.71	1.82	1.76	0.88	1.24	1.12	2.73	2.02	2.11	1.40	1.83	2.09	2.16
		b*	13.82	14.15	13.61	17.76	16.84	14.89	17.49	16.42	17.22	17.59	13.74	13.89	16.73	17.92	13.03	17.29	17.34	17.19	18.53	18.01
150-2-2	SCI	L*	69.73	66.43	68.51	66.22	64.21	68.86	76.71	75.04	68.32	67.31	82.22	77.32	75.64	79.15	67.23	74.50	81.35	68.62	66.22	76.41
		a*	-1.09	-0.03	-0.19	0.40	-0.18	-1.53	1.86	1.49	2.59	0.68	0.59	1.47	1.63	1.35	1.36	1.46	0.85	2.63	2.20	1.47
		b*	12.14	10.56	13.54	12.37	14.88	12.52	13.10	11.78	10.71	11.10	13.72	15.18	15.13	14.90	11.26	14.27	12.14	11.42	10.24	12.57
	-	G	75	80	80	82	78	76	72	75	80	81	64	69	74	67	79	77	73	83	86	76
	SCE	L*	67.31	63.64	65.87	63.34	61.35	66.36	74.74	72.91	65.66	64.54	80.68	75.46	73.57	77.41	64.54	72.28	79.54	65.88	63.18	74.34
		a*	-1.19	-0.07	-0.24	0.41	-0.24	-1.69	1.99	1.60	2.80	0.72	0.64	1.56	1.74	1.44	1.46	1.57	0.92	2.84	2.39	1.56
		b*	13.49	11.93	15.16	14.04	16.95	13.96	14.29	12.94	12.02	12.51	14.76	16.52	16.55	16.14	12.65	15.71	13.15	12.86	11.68	13.77
150-2-3	SCI	L*	82.52	85.52	85.10	82.37	79.87	81.74	82.82	85.97	81.82	80.13	86.34	85.39	86.64	87.71	87.75	85.58	78.83	87.36	86.14	87.01
		a*	0.14	0.07	0.28	1.75	2.16	2.06	0.34	-0.08	1.86	2.40	0.17	0.83	0.37	0.09	-0.13	-0.04	-0.21	0.02	0.51	0.31
		b*	13.15	14.41	14.33	13.84	14.97	14.69	17.49	15.22	15.70	15.02	15.50	15.16	15.26	14.85	14.24	13.27	12.52	14.51	15.46	15.09
	-	G	68	64	64	65	69	69	65	63	69	69	59	61	61	62	63	67	78	64	64	64
	SCE	L*	80.89	84.08	83.64	80.80	78.12	80.05	81.29	84.55	80.13	78.38	85.02	84.01	85.29	86.36	86.39	84.07	76.80	85.97	84.71	85.70
		a*	0.17	0.09	0.32	1.86	2.30	2.20	0.38	-0.05	1.99	2.55	0.21	0.89	0.41	0.12	-0.11	-0.02	-0.22	0.06	0.56	0.35
		b*	14.14	15.41	15.34	14.90	16.22	15.86	18.80	16.26	16.94	16.24	16.57	16.24	16.31	15.83	15.20	14.19	13.51	15.48	16.54	16.14

Measurements After Heating:

Sample	Light	Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
200-0.5-1	SCI	L*	71.90	73.05	73.28	73.01	73.36	78.27	79.15	76.02	74.53	72.36	77.28	80.29	78.03	79.62	72.05	74.57	81.06	77.15	78.87	72.65
		a*	2.42	2.57	2.93	2.99	2.55	2.46	2.42	2.05	2.10	2.78	3.78	2.68	2.66	2.16	2.99	3.59	2.47	2.87	2.70	3.33
		b*	10.03	13.59	9.77	8.80	6.32	8.63	6.65	7.24	7.91	12.68	11.00	8.58	9.23	9.30	9.70	10.86	9.66	9.96	9.64	10.69
	-	G	73	69	69	68	69	66	68	71	73	72	73	70	71	71	77	72	66	67	66	74
	SCE	L*	69.69	70.99	71.26	70.98	71.33	76.52	77.41	74.06	72.44	70.19	75.33	78.53	76.15	77.81	69.72	72.51	79.43	75.35	77.15	70.43
		a*	2.59	2.75	3.13	3.20	2.72	2.61	2.57	2.19	2.24	2.99	4.02	2.85	2.83	2.30	3.20	3.84	2.62	3.05	2.87	3.57
		b*	11.06	14.94	10.73	9.67	6.96	9.37	7.25	7.94	8.71	13.99	12.00	9.32	10.07	10.09	10.73	11.91	10.44	10.86	10.47	11.78
200-0.5-2	SCI	L*	55.31	56.88	65.41	71.84	73.26	79.38	78.63	69.40	71.01	79.64	83.76	85.88	85.87	86.08	84.50	84.17	84.60	84.75	85.17	83.55
		a*	2.75	2.20	1.99	1.54	1.99	1.87	1.51	2.41	2.23	-0.22	1.85	1.08	1.09	0.80	1.11	1.38	1.18	1.08	1.05	1.46
		b*	6.26	5.40	8.16	7.56	6.29	7.83	8.47	8.26	7.95	8.39	11.78	10.85	10.31	10.39	11.41	12.88	10.67	10.29	10.30	11.57
	-	G	92	92	85	78	77	71	71	80	79	76	63	62	63	64	65	67	67	65	64	65
	SCE	L*	50.92	52.68	62.34	69.45	70.98	77.57	76.78	66.79	68.55	77.69	82.27	84.48	84.45	84.65	82.99	82.61	83.06	83.25	83.71	82.04
		a*	3.12	2.45	2.16	1.66	2.13	2.00	1.61	2.58	2.38	-0.25	1.98	1.17	1.17	0.88	1.20	1.49	1.26	1.15	1.12	1.56
		b*	7.64	6.54	9.32	8.41	7.00	8.50	9.19	9.24	8.85	9.13	12.63	11.59	11.03	11.12	12.23	13.81	11.43	11.03	11.03	12.41
200-0.5-3	SCI	L*	85.85	86.58	84.79	80.81	80.27	77.66	84.36	83.99	86.41	73.69	85.38	85.38	84.24	82.60	85.16	84.61	83.66	71.28	75.33	84.37
		a*	0.61	0.16	0.16	0.61	0.33	0.13	0.06	-0.01	0.09	0.56	0.56	0.76	1.17	1.41	0.89	1.38	0.35	0.83	1.10	0.42
		b*	13.09	12.80	10.31	11.23	12.15	11.26	10.38	10.34	11.57	10.38	15.01	14.44	13.40	11.75	13.32	13.05	10.00	8.16	10.17	15.28
	-	G	63	61	63	71	73	82	68	66	59	74	64	65	64	64	65	67	57	72	73	66
	SCE	L*	84.43	85.22	83.35	79.05	78.42	75.47	82.79	82.45	85.11	71.52	83.92	83.92	82.76	81.07	83.69	83.08	82.32	69.07	73.28	82.84
		a*	0.67	0.21	0.20	0.67	0.37	0.15	0.08	0.01	0.12	0.60	0.62	0.83	1.26	1.52	0.96	1.47	0.40	0.88	1.17	0.48
		b*	13.99	13.66	11.04	12.08	13.08	12.18	11.13	11.10	12.35	11.40	16.03	15.43	14.36	12.61	14.25	13.99	10.72	9.00	11.08	16.36
200-1-1	SCI	L*	65.73	63.65	71.49	58.39	56.46	57.02	58.89	69.85	76.47	72.51	72.42	70.00	71.81	55.55	63.37	72.30	67.43	62.81	56.60	55.29
		a*	8.21	7.59	4.65	6.19	4.84	3.41	4.97	7.69	3.83	3.59	2.86	3.14	3.34	1.75	4.03	2.71	5.35	4.76	3.33	2.62
		b*	28.38	25.82	24.54	22.35	18.23	17.45	19.63	28.25	22.89	22.61	20.56	20.69	21.04	12.84	20.20	20.44	25.22	22.23	15.67	14.45
	-	G	82	85	79	84	87	88	87	80	70	71	74	78	79	88	83	75	82	84	86	86
	SCE	L*	62.79	60.47	69.09	54.74	52.43	53.05	55.17	67.26	74.56	70.37	70.19	67.51	69.04	51.83	60.21	70.04	64.64	59.58	52.62	51.17
		a*	8.97	8.34	5.00	6.92	5.45	3.79	5.54	8.32	4.10	3.86	3.07	3.39	3.60	1.94	4.43	2.92	5.83	5.24	3.74	2.95
		b*	32.78	30.05	27.29	26.73	21.92	20.89	23.33	31.93	25.01	24.99	22.71	23.11	23.38	15.47	23.31	22.60	28.69	25.79	18.75	17.41
200-1-2	SCI	L*	65.97	61.97	63.51	65.06	63.70	58.77	60.70	68.25	58.59	57.74	69.55	67.11	60.07	61.14	60.55	66.42	62.29	70.97	60.83	64.86
		a*	5.26	4.66	3.81	5.20	2.71	4.00	2.69	5.33	1.39	2.40	5.53	5.00	5.66	1.71	4.48	3.66	4.71	5.78	3.67	3.41
		b*	24.38	21.64	21.93	24.04	21.84	18.43	18.69	25.15	13.61	16.15	28.15	26.76	21.80	18.31	21.74	24.24	22.42	29.96	17.50	21.45
	-	G	79	84	79	79	80	83	82	82	86	84	81	81	80	86	85	82	84	78	84	81
	SCE	L*	63.16	58.66	60.52	62.19	60.69	55.20	57.37	65.51	54.88	54.02	66.95	64.32	56.75	57.68	57.09	63.55	58.99	68.52	57.41	61.92
		a*	5.73	5.14	4.18	5.69	2.97	4.47	2.96	5.80	1.53	2.67	5.99	5.42	6.30	1.85	4.95	3.98	5.17	6.24	4.07	3.72
		b*	27.80	25.25	25.26	27.56	25.17	21.82	21.83	28.53	16.02	19.17	31.83	30.39	25.69	21.31	25.55	27.57	25.95	33.70	20.38	24.54
200-1-3	SCI	L*	70.69	70.83	73.59	68.73	70.25	71.86	72.83	72.51	73.12	73.63	73.79	73.80	72.79	76.13	75.65	74.23	76.25	75.55	76.26	75.86
		a*	7.50	6.89	6.39	5.15	5.81	6.76	4.45	4.52	4.73	4.86	5.79	6.84	7.24	5.37	5.42	4.86	4.03	4.14	4.77	5.51
		b*	27.61	27.31	25.42	23.22	24.90	26.82	23.71	24.39	25.61	25.39	23.92	28.39	29.15	25.80	27.21	24.30	22.82	22.73	24.72	25.58
	-	G	73	74	73	76	75	72	79	83	83	86	70	77	81	70	73	72	70	72	69	72
	SCE	L*	68.41	68.54	71.44	66.24	67.88	69.65	70.48	70.00	70.65	71.10	71.75	71.55	70.38	74.20	73.62	72.16	74.32	73.54	74.35	73.86
		a*	8.10	7.43	6.85	5.57	6.27	7.27	4.80	4.88	5.10	5.25	6.20	7.35	7.79	5.74	5.80	5.20	4.32	4.43	5.09	5.89
		b*	30.90	30.56	28.07	26.08	27.84	29.85	26.33	27.23	28.58	28.36	26.38	31.56	32.57	28.28	29.93	26.75	24.92	24.90	27.05	28.07
200-2-1	SCI	L*	61.58	62.41	61.18	57.32	62.77	62.86	62.52	66.77	66.83	67.57	64.40	63.56	66.31	64.41	64.27	64.79	65.71	67.92	70.21	66.71
		a*	11.10	10.86	11.41	7.74	10.96	10.84	10.92	7.70	7.62	7.47	9.38	9.52	6.44	9.73	9.03	9.49	7.85	7.37	6.47	8.41
		b*	23.74	23.69	24.04	17.15	24.77	24.36	24.31	19.18	20.93	19.68	24.15	23.16	17.97	23.21	22.67	23.22	19.45	20.74	21.24	21.51
	-	G	84	86	88	87	87	86	86	78	80	79	79	76	82	81	76	80	77	76	74	77
	SCE	L*	58.24	59.07	57.64	53.40	59.42	59.57	59.19	64.07	64.07	64.90	61.48	60.70	63.43	61.42	61.45	61.89	62.98	65.36	67.86	64.04
		a*	12.31	12.02	12.69	8.74	12.13	11.98	12.08	8.37	8.30	8.11	10.29	10.46	7.03	10.66	9.90	10.39	8.54	7.98	6.97	9.15
		b*	27.98	27.77	28.52	20.55	29.07	28.51	28.50	21.66	23.69	22.16	27.83	26.72	20.33	26.71	26.04	26.62	22.00	23.28	23.61	24.32

Measurements After Heating:

Sample	Light	Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
200-2-2	SCI	L*	62.04	63.49	64.46	65.57	65.10	62.36	67.87	67.25	67.74	68.14	63.82	62.37	59.58	65.42	65.67	63.36	64.58	68.55	67.78	69.99
		a*	11.40	11.04	10.44	9.97	10.33	11.29	7.76	7.76	7.95	7.81	11.02	10.95	7.32	10.82	9.98	11.08	9.42	9.04	8.00	6.01
		b*	25.31	26.02	26.47	26.40	26.25	25.40	20.61	21.84	21.18	21.14	26.66	23.77	18.59	26.16	25.71	25.43	23.20	25.26	22.53	21.22
	-	G	91	88	92	86	88	92	80	82	81	80	92	84	84	84	78	87	81	77	81	78
	SCE	L*	58.43	60.14	61.06	62.47	61.90	58.75	65.17	64.45	65.01	65.45	60.38	59.09	56.07	62.40	62.89	60.05	61.59	65.98	65.05	67.52
		a*	12.70	12.21	11.54	10.95	11.36	12.57	8.43	8.46	8.64	8.48	12.21	12.12	8.19	11.84	10.90	12.24	10.33	9.79	8.70	6.49
		b*	30.12	30.57	31.04	30.55	30.52	30.17	23.25	24.76	23.93	23.84	31.44	27.89	21.94	30.20	29.54	29.81	26.69	28.54	25.48	23.71
200-2-3	SCI	L*	68.90	68.25	68.29	73.68	70.09	62.30	68.71	68.74	69.95	68.60	67.73	67.13	67.48	68.19	68.86	68.00	67.28	70.16	72.10	72.09
		a*	9.22	9.28	9.34	5.93	7.42	6.63	9.15	8.89	7.04	7.45	9.02	8.88	8.58	9.06	8.55	8.97	9.01	5.10	6.05	6.97
		b*	28.77	28.43	27.92	17.69	25.84	20.76	28.63	27.33	22.52	23.35	26.22	25.22	25.76	26.83	26.10	25.48	26.19	21.76	24.74	25.95
	-	G	84	88	85	73	82	81	80	77	78	81	80	79	79	79	78	79	80	76	76	76
	SCE	L*	66.14	65.31	65.45	71.53	67.48	59.14	66.07	66.22	67.46	65.91	65.04	64.41	64.78	65.53	66.29	65.35	64.56	67.74	69.80	69.78
		a*	10.04	10.13	10.18	6.34	8.05	7.35	9.94	9.64	7.60	8.09	9.81	9.65	9.33	9.85	9.26	9.73	9.80	5.51	6.53	7.50
		b*	33.00	32.75	32.02	19.47	29.13	24.19	32.61	30.99	25.22	26.37	29.80	28.67	29.25	30.42	29.45	28.84	29.80	24.27	27.49	28.88
250-0.5-1	SCI	L*	67.59	70.06	70.03	73.46	70.45	68.46	69.62	66.45	69.45	66.93	67.00	66.65	66.28	67.12	66.67	66.76	67.99	69.34	68.13	65.65
		a*	8.38	7.53	7.80	6.67	7.40	7.76	7.99	6.80	5.48	6.59	8.19	7.28	5.72	6.69	6.66	8.32	6.96	6.81	3.01	7.80
		b*	23.40	22.05	24.88	24.34	24.98	24.35	23.90	21.79	19.17	21.05	25.85	22.77	20.29	22.80	23.51	23.87	22.26	23.21	14.82	23.20
	-	G	78	76	78	74	76	78	77	83	79	83	87	83	81	82	85	85	77	77	82	81
	SCE	L*	64.95	67.63	67.55	71.30	68.07	65.88	67.14	63.57	66.89	64.07	64.01	63.77	63.44	64.32	63.71	63.82	65.40	66.85	65.39	62.75
		a*	9.12	8.13	8.42	7.16	7.98	8.43	8.64	7.42	5.94	7.20	8.96	7.96	6.24	7.29	7.29	9.10	7.55	7.37	3.25	8.50
		b*	26.47	24.61	27.85	26.87	27.94	27.49	26.78	24.83	21.44	23.90	29.68	25.93	23.03	25.88	26.90	27.30	25.04	26.03	16.47	26.44
250-0.5-2	SCI	L*	47.22	47.16	50.25	53.01	55.89	61.07	62.50	58.68	50.97	52.49	58.06	60.57	58.40	59.65	60.75	59.01	58.27	58.60	59.37	59.50
		a*	8.12	7.39	8.98	9.81	8.02	6.44	7.92	7.78	9.00	9.87	9.46	9.14	8.58	10.86	9.64	10.31	10.33	10.11	9.54	9.24
		b*	12.53	11.62	15.06	18.01	17.66	19.89	24.39	20.99	15.54	17.75	22.84	23.81	22.71	25.87	25.53	24.91	23.43	22.67	22.97	22.99
	-	G	89	89	88	86	84	81	80	82	87	86	84	83	85	86	85	83	85	86	83	84
	SCE	L*	41.62	41.55	45.29	48.58	51.94	57.83	59.40	55.14	46.19	48.01	54.38	57.16	54.71	56.05	57.30	55.46	54.57	54.88	55.88	55.98
		a*	9.81	8.91	10.56	11.31	9.09	7.12	8.73	8.69	10.53	11.42	10.64	10.18	9.63	12.14	10.73	11.53	11.59	11.34	10.62	10.31
		b*	16.50	15.25	19.21	22.40	21.30	23.15	28.33	24.91	19.64	22.18	27.53	28.18	27.25	31.07	30.31	29.88	28.22	27.22	27.25	27.31
250-0.5-3	SCI	L*	49.44	51.22	51.99	51.92	52.90	53.03	53.03	52.79	52.38	52.70	53.06	53.44	53.94	52.27	52.91	55.56	53.20	52.77	51.82	54.52
		a*	6.82	7.22	7.49	8.13	7.88	7.83	7.22	8.04	7.89	7.83	7.96	7.68	6.96	7.28	7.70	7.33	7.39	7.91	7.32	7.29
		b*	10.13	10.61	11.28	12.29	12.23	12.45	12.26	12.65	12.38	12.07	13.03	12.30	12.23	11.71	13.17	13.05	11.68	13.06	11.52	12.64
	-	G	90	90	90	92	89	90	90	89	90	89	87	87	87	90	92	87	89	92	89	87
	SCE	L*	44.23	46.32	47.21	46.99	48.29	48.40	48.40	48.17	47.62	48.06	48.58	49.05	49.61	47.54	48.15	51.41	48.67	48.00	47.03	50.25
		a*	8.10	8.46	8.73	9.53	9.14	9.08	8.37	9.32	9.21	9.08	9.21	8.85	8.00	8.47	8.96	8.34	8.54	9.21	8.54	8.35
		b*	13.03	13.44	14.15	15.52	15.20	15.51	15.27	15.77	15.53	15.02	16.15	15.15	15.00	14.63	16.45	15.82	14.44	16.33	14.47	15.45
250-1-1	SCI	L*	42.09	43.05	42.63	42.37	42.35	42.32	42.52	43.42	43.72	44.74	43.32	43.40	42.25	42.05	41.52	41.46	41.11	42.49	41.76	42.47
		a*	2.25	2.07	1.47	1.75	1.64	1.66	2.19	2.89	3.51	4.10	3.58	3.49	2.75	2.52	1.89	1.87	2.72	2.57	2.30	2.67
		b*	1.96	2.65	1.52	1.73	1.35	1.14	1.85	2.53	2.88	4.08	3.98	3.51	2.11	2.78	2.00	1.59	3.33	3.49	2.29	2.61
	-	G	92	91	92	95	97	96	96	97	95	97	91	91	92	92	92	92	92	91	92	92
	SCE	L*	35.02	36.06	35.72	35.10	34.52	34.93	35.25	36.33	36.82	38.03	36.65	36.80	35.20	34.94	34.30	34.19	33.73	35.58	34.57	35.51
		a*	2.80	2.52	1.76	2.13	1.98	1.99	2.72	3.63	4.39	5.12	4.43	4.36	3.45	3.16	2.32	2.32	3.47	3.18	2.88	3.31
		b*	2.98	3.84	2.35	2.64	2.12	1.83	2.79	3.67	4.12	5.66	5.61	4.95	3.18	4.09	3.03	2.47	4.92	5.01	3.42	3.82
250-1-2	SCI	L*	44.02	43.21	46.63	43.59	43.20	42.79	43.32	43.99	45.10	46.63	46.38	44.34	43.77	43.62	42.56	49.92	48.88	44.43	46.46	42.92
		a*	2.80	2.67	2.81	2.89	2.92	3.30	3.83	4.35	5.22	5.43	4.49	4.16	3.52	2.81	2.84	5.19	4.01	2.49	4.14	3.28
		b*	3.49	3.23	5.82	2.97	2.48	2.86	3.38	3.91	4.91	5.71	6.00	4.24	3.08	2.46	2.25	11.04	9.01	3.74	6.76	2.91
	-	G	92	92	91	91	93	93	94	96	95	94	91	90	90	89	90	88	89	92	92	95
	SCE	L*	37.46	36.45	40.79	37.00	36.35	35.84	36.43	37.15	38.60	40.58	40.48	38.04	37.29	37.20	35.82	44.92	43.62	37.97	40.53	35.86
		a*	3.43	3.30	3.36	3.57	3.63	4.16	4.80	5.46	6.48	6.63	5.45	5.15	4.37	3.46	3.54	6.11	4.74	3.01	5.02	4.13
		b*	4.90	4.59	7.68	4.19	3.57	4.13	4.80	5.49	6.70	7.59	8.00	5.85	4.35	3.51	3.28	14.00	11.55	5.18	8.98	4.17

Measurements After Heating:

Sample	Light	Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
250-1-3	SCI	L*	41.98	41.63	42.16	42.77	42.25	43.30	43.47	44.65	45.88	42.83	45.72	43.25	46.41	42.26	43.07	42.68	42.11	41.71	42.85	47.13
		a*	2.37	2.24	2.31	2.41	3.07	4.05	4.43	5.26	5.41	3.38	5.00	4.19	3.03	2.96	2.23	2.66	2.59	2.22	3.44	3.58
		b*	2.24	2.46	2.03	2.16	2.44	3.64	3.95	5.45	6.25	2.83	5.00	3.71	5.29	2.41	2.29	2.64	2.60	1.90	4.32	7.36
	-	G	94	93	95	94	96	96	97	94	93	96	89	91	89	92	90	91	91	92	92	90
	SCE	L*	34.66	34.31	34.83	35.73	34.90	36.22	36.40	38.07	39.72	35.65	39.85	36.62	40.64	35.25	36.41	35.86	35.12	34.50	35.96	41.45
		a*	2.99	2.79	2.87	2.98	3.90	5.14	5.62	6.57	6.64	4.28	6.12	5.26	3.63	3.74	2.73	3.32	3.23	2.74	4.30	4.28
		b*	3.31	3.63	3.04	3.17	3.60	5.17	5.61	7.52	8.40	4.10	6.69	5.22	7.01	3.55	3.31	3.82	3.81	2.89	6.09	9.63
250-2-1	SCI	L*	41.17	41.47	41.77	41.00	40.89	41.85	42.79	44.61	46.38	42.35	43.34	41.46	40.80	41.72	41.30	41.72	41.10	41.25	41.50	41.13
		a*	2.60	2.37	2.75	2.54	2.90	3.19	3.73	4.64	5.05	3.32	4.18	3.20	2.42	2.04	1.93	2.39	1.91	1.93	2.00	2.65
		b*	1.73	1.98	2.20	1.55	1.77	2.24	3.08	5.08	6.75	2.53	3.96	2.42	1.42	1.39	1.37	2.76	1.48	1.39	1.21	1.64
	-	G	93	92	92	95	95	95	97	96	93	95	93	91	92	94	93	92	93	92	94	94
	SCE	L*	33.72	34.21	34.59	33.33	33.17	34.46	35.48	37.94	40.33	35.12	36.55	34.27	3.35	34.39	33.91	34.57	33.66	33.94	34.10	33.60
		a*	3.31	2.99	3.49	3.25	3.73	4.08	4.76	5.80	6.16	4.23	5.24	4.07	3.07	2.54	2.40	2.98	2.39	2.40	2.50	3.39
		b*	2.68	2.98	3.27	2.40	2.73	3.33	4.46	7.02	9.01	3.72	5.61	3.60	2.25	2.18	2.15	4.05	2.31	2.19	1.95	2.53
250-2-2	SCI	L*	41.98	41.82	41.68	42.06	41.93	41.93	42.51	43.34	41.93	41.17	44.20	42.32	42.04	41.71	41.57	41.97	41.94	41.78	42.18	41.56
		a*	2.70	2.53	2.41	2.28	2.39	2.60	2.98	4.44	2.85	2.12	4.94	3.46	2.64	2.08	1.97	2.15	2.26	2.23	2.48	1.93
		b*	2.04	1.96	2.16	1.74	1.48	1.55	2.24	4.40	1.82	1.51	4.55	2.88	1.83	1.35	1.19	1.91	1.89	1.51	1.74	1.18
	-	G	94	95	92	93	97	97	96	92	96	93	97	96	94	96	97	94	93	97	95	96
	SCE	L*	34.67	34.41	34.47	34.88	34.35	34.36	35.18	36.59	34.48	33.70	37.30	34.99	34.74	34.19	33.87	34.65	34.76	34.13	34.86	33.93
		a*	3.41	3.19	3.04	2.85	3.03	3.29	3.78	5.58	3.62	2.66	6.24	4.40	3.33	2.60	2.45	2.66	2.79	2.80	3.12	2.40
		b*	3.03	2.95	3.23	2.62	2.26	2.37	3.34	6.18	2.76	2.32	6.33	4.18	2.73	2.06	1.85	2.83	2.81	2.25	2.58	1.83
250-2-3	SCI	L*	46.27	45.88	44.95	44.71	44.96	46.51	47.36	48.05	45.03	46.99	47.51	46.30	46.85	46.36	46.97	46.09	46.60	46.18	46.45	46.56
		a*	5.45	5.79	5.36	5.26	5.05	6.27	6.70	6.80	5.28	5.34	7.21	6.43	5.65	5.59	5.77	5.67	5.38	5.31	5.67	5.46
		b*	6.53	6.29	5.16	5.09	4.93	6.74	7.85	8.06	5.15	6.97	8.71	6.67	5.89	6.26	7.09	6.56	6.44	5.86	6.73	5.59
	-	G	89	91	92	93	91	87	90	91	91	90	96	96	91	90	90	90	90	90	90	91
	SCE	L*	40.47	39.86	38.63	38.28	38.72	40.88	41.74	42.49	38.83	41.26	41.53	39.99	41.06	40.50	41.28	40.22	40.79	40.32	40.63	40.68
		a*	6.63	7.09	6.65	6.51	6.23	7.58	8.10	8.18	6.51	6.46	8.78	7.93	6.84	6.81	6.98	6.88	6.51	6.47	6.88	6.63
		b*	8.70	8.43	7.04	7.01	6.69	8.86	10.30	10.46	6.99	9.18	11.49	8.93	7.76	8.31	9.28	8.73	8.50	7.78	8.91	7.40
300-0.5-1	SCI	L*	41.34	40.72	41.03	40.61	41.26	40.29	41.12	40.75	40.89	40.57	41.13	41.55	47.85	42.16	42.82	44.20	49.78	41.61	48.43	43.35
		a*	1.87	1.44	1.24	0.83	1.01	0.70	0.95	1.03	1.36	1.44	1.71	1.52	2.19	0.94	1.74	3.19	4.08	2.28	4.06	1.74
		b*	1.50	0.71	0.78	0.09	0.85	0.13	0.72	0.44	0.93	0.62	1.15	0.99	6.86	1.41	2.89	5.15	9.72	1.85	9.20	3.02
	-	G	94	97	95	97	94	94	94	95	93	97	95	96	89	93	92	92	88	95	87	94
	SCE	L*	33.84	32.73	33.36	32.56	33.74	32.48	33.60	32.94	33.34	32.58	33.51	33.97	42.39	34.98	35.93	37.67	44.72	34.12	43.18	36.51
		a*	2.32	1.76	1.47	0.91	1.14	0.74	1.08	1.19	1.63	1.77	2.10	1.86	2.55	1.06	2.11	3.94	4.78	2.88	4.78	2.09
		b*	2.27	1.22	1.30	0.36	1.44	0.48	1.24	0.86	1.53	1.08	1.81	1.65	8.88	2.15	4.13	7.09	12.31	2.72	11.81	4.27
300-0.5-2	SCI	L*	44.26	45.90	45.64	44.48	44.77	46.43	44.84	47.44	46.21	44.57	41.96	43.27	43.70	46.06	45.37	45.06	46.65	49.02	43.54	42.81
		a*	3.21	3.06	3.13	3.45	3.11	3.17	3.48	2.87	3.09	3.39	1.94	2.13	2.52	3.21	3.60	3.13	3.51	3.87	2.26	2.06
		b*	3.76	3.87	3.81	3.65	3.52	4.31	4.02	4.70	3.45	3.46	1.54	2.24	2.81	5.71	6.80	5.84	7.14	8.06	2.36	1.93
	-	G	89	92	92	92	92	91	91	91	90	91	90	89	90	88	86	85	86	86	89	89
	SCE	L*	37.99	39.83	39.53	38.03	38.45	40.57	38.56	41.78	40.38	38.21	35.04	36.78	37.25	40.33	39.63	39.30	41.18	43.98	37.11	36.21
		a*	3.95	3.69	3.79	4.24	3.80	3.81	4.26	3.40	3.69	4.17	2.35	2.57	3.06	3.84	4.34	3.76	4.17	4.53	2.72	2.49
		b*	5.17	5.21	5.71	5.02	4.83	5.73	5.50	6.07	4.62	4.76	2.49	3.35	4.09	7.66	9.18	7.91	9.41	10.33	3.48	2.94
300-0.5-3	SCI	L*	41.21	40.98	42.84	38.56	41.42	41.84	42.10	42.35	41.86	40.95	41.51	42.55	41.31	41.24	41.67	41.36	40.99	41.53	42.02	39.31
		a*	0.68	0.87	1.54	1.16	0.71	1.25	1.21	1.27	2.44	2.94	0.52	0.60	0.48	1.52	0.49	1.82	1.72	1.42	1.39	1.98
		b*	0.41	0.14	2.78	0.07	0.37	0.66	0.90	1.43	2.77	3.10	0.28	0.42	0.04	1.31	0.26	1.80	1.65	1.39	1.46	2.08
	-	G	97	95	94	95	96	99	98	100	94	94	97	97	98	96	98	94	94	94	95	94
	SCE	L*	33.43	33.25	35.81	29.92	33.74	34.06	34.50	34.64	34.54	33.36	33.79	35.22	33.41	33.54	33.90	33.89	33.38	34.12	34.65	31.16
		a*	0.72	0.97	1.86	1.45	0.76	1.50	1.42	1.52	3.09	3.80	0.49	0.61	0.42	1.85	0.45	2.28	2.15	1.71	1.68	2.54
		b*	0.86	0.52	4.03	0.42	0.82	1.16	1.49	2.21	4.08	4.64	0.62	0.81	0.25	2.07	0.60	2.75	2.56	2.17	2.24	3.31

Measurements After Heating:

Sample	Light	Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
300-1-1	SCI	L*	40.14	40.24	40.79	40.96	40.78	41.10	41.03	41.47	40.93	40.53	41.95	42.54	42.94	42.55	40.76	42.23	42.45	42.18	45.18	43.52
		a*	0.43	0.32	0.22	0.31	0.35	0.36	0.29	0.22	0.43	0.60	-0.01	0.10	-0.14	-0.01	0.20	0.22	0.21	0.10	0.06	-0.05
		b*	-0.28	0.32	-0.86	-0.55	-0.52	-0.13	-0.18	-0.40	-0.12	0.39	-0.82	-0.52	-1.29	-1.12	-0.53	-0.37	-0.36	-0.56	-0.43	-0.76
	-	G	96	96	97	97	96	102	100	103	103	97	101	104	104	102	93	100	101	103	103	107
	SCE	L*	32.09	32.19	32.84	33.10	32.87	32.74	32.88	33.16	32.47	32.52	33.98	34.52	35.06	34.77	33.15	34.49	34.70	34.13	38.04	35.60
		a*	0.40	0.22	0.09	0.23	0.28	0.30	0.17	0.09	0.39	0.64	-0.20	-0.09	-0.37	-0.20	0.07	0.11	0.08	-0.08	-0.11	-0.28
		b*	-0.12	-0.69	-0.92	-0.48	-0.44	0.00	-0.01	-0.33	0.06	0.81	-0.79	-0.51	-1.40	-1.18	-0.45	-0.32	-0.32	-0.60	-0.40	-0.89
300-1-2	SCI	L*	40.14	39.82	39.74	40.66	40.20	40.91	40.89	40.66	40.75	40.93	42.48	42.56	43.59	42.69	42.85	42.53	41.09	41.67	40.99	41.42
		a*	0.33	0.29	0.28	0.16	0.29	0.15	0.15	0.32	0.13	0.26	-0.04	-0.07	-0.22	-0.07	-0.13	-0.02	0.37	0.27	0.46	0.36
		b*	-0.45	-0.43	-0.43	-0.65	-0.48	-0.58	-0.54	-0.19	-0.46	-0.25	-0.86	-1.08	-1.54	-1.13	-1.26	-0.84	-0.04	-0.26	0.01	-0.04
	-	G	96	96	95	96	96	109	107	99	104	101	107	110	112	113	110	106	97	102	97	98
	SCE	L*	32.05	31.66	31.56	32.73	32.13	31.83	31.97	32.41	32.13	32.66	34.15	34.05	35.27	33.96	34.40	34.30	33.21	33.58	33.11	33.58
		a*	0.24	0.16	0.17	0.00	0.20	-0.02	-0.03	0.23	-0.04	0.13	-0.27	-0.32	-0.50	-0.30	-0.39	-0.26	0.27	0.15	0.41	0.27
		b*	-0.36	-0.33	-0.31	-0.63	-0.43	-0.71	-0.63	-0.04	-0.47	-0.14	-1.00	-1.32	-1.82	-1.36	-1.50	-0.98	0.17	-0.15	0.22	0.17
300-1-3	SCI	L*	41.93	41.89	41.10	41.25	41.12	41.70	41.38	41.16	41.70	41.32	42.67	42.29	42.96	42.73	43.22	43.09	42.83	40.36	40.48	41.24
		a*	-0.01	-0.04	0.03	-0.05	0.04	-0.01	0.04	0.60	0.41	0.68	-0.08	-0.08	-0.19	-0.05	-0.14	-0.13	-0.12	0.31	0.24	0.26
		b*	-1.03	-1.17	-0.91	-1.11	-0.88	-1.08	-0.83	0.14	-0.19	0.27	-0.80	-1.00	-1.33	-0.95	-1.01	-0.90	-0.93	-0.62	-0.66	-0.61
	-	G	95	92	97	98	94	93	95	90	91	90	102	96	93	95	103	104	101	90	90	92
	SCE	L*	34.51	34.79	33.31	33.33	33.56	34.44	33.78	33.97	34.60	34.17	34.91	34.90	36.03	35.55	35.52	35.25	35.22	32.89	33.05	33.94
		a*	-0.22	-0.25	-0.21	-0.32	-0.17	-0.21	-0.19	0.59	0.35	0.71	-0.35	-0.31	-0.45	-0.26	-0.41	-0.40	-0.37	0.19	0.10	0.14
		b*	-1.09	-1.20	-0.95	-1.27	-0.86	-1.13	-0.85	0.53	0.07	0.70	-0.89	-1.01	-1.34	-1.00	-1.16	-1.07	-1.00	-0.49	-0.55	-0.49
300-2-1	SCI	L*	41.11	41.53	40.83	41.31	41.62	41.11	41.34	39.93	40.65	40.52	41.68	41.92	41.21	40.58	41.89	40.75	41.77	42.14	41.94	42.31
		a*	0.05	-0.04	0.23	0.19	-0.02	0.03	0.00	0.82	0.58	0.52	0.07	0.00	0.54	0.54	0.11	0.55	0.15	1.61	1.74	1.48
		b*	-0.71	-0.93	-0.37	-0.37	-0.94	-0.71	-0.81	0.47	22.00	0.15	-0.88	-0.96	0.32	0.03	-0.77	-0.13	-0.76	2.04	2.14	2.12
	-	G	101	98	91	94	102	101	97	89	91	90	92	97	90	91	93	91	93	89	88	88
	SCE	L*	32.91	33.70	33.42	33.81	33.51	32.92	33.54	32.44	33.22	33.12	34.44	34.38	34.00	33.17	34.64	33.32	34.54	35.37	32.16	35.61
		a*	-0.19	-0.29	0.09	0.03	-0.26	-0.20	-0.22	0.90	0.58	0.51	-0.10	-0.20	0.53	0.51	-0.05	-0.54	-0.01	1.93	2.10	1.75
		b*	-0.78	-0.97	-0.15	-0.18	-1.01	-0.75	-0.78	1.01	0.62	0.53	-0.85	-1.00	0.77	0.39	-0.71	0.15	-0.68	3.04	3.15	3.12
300-2-2	SCI	L*	41.70	41.34	41.02	41.65	41.97	41.85	41.07	40.08	41.14	40.57	40.91	40.50	39.80	40.84	42.37	41.65	41.12	39.66	41.57	39.72
		a*	0.26	0.20	0.40	0.10	0.02	0.13	0.40	0.80	0.70	0.82	0.17	0.22	0.39	0.35	0.08	0.03	0.16	0.97	0.51	0.68
		b*	-0.50	-0.58	0.01	-0.65	-0.88	-0.77	0.04	0.31	0.07	0.31	-0.75	-0.59	-0.36	-0.43	-0.91	-1.00	-0.81	0.58	0.03	0.16
	-	G	94	92	88	99	98	101	87	88	89	88	89	88	88	89	91	90	88	88	91	88
	SCE	L*	34.30	34.05	33.97	33.81	34.33	33.86	34.11	32.71	34.08	33.37	33.75	33.28	32.42	33.66	35.47	34.61	34.07	32.19	34.39	32.28
		a*	0.12	0.06	0.33	-0.09	-0.19	-0.05	0.32	0.86	0.73	0.91	0.02	0.07	0.32	0.25	-0.09	-0.16	0.00	1.11	0.47	0.69
		b*	-0.37	-0.46	0.32	0.62	-0.87	-0.78	0.39	0.77	0.42	0.74	-0.66	-0.47	-0.16	-0.27	-0.87	-1.03	-0.76	1.14	0.37	0.57
300-2-3	SCI	L*	41.87	41.59	41.30	41.80	40.35	40.39	40.34	40.50	40.40	40.73	40.03	40.28	40.18	40.42	39.45	39.94	39.85	40.53	39.91	40.42
		a*	0.09	0.12	0.20	0.03	0.42	1.51	1.11	0.88	0.97	0.90	0.63	0.64	0.43	0.70	69.00	0.65	0.70	1.13	0.88	0.94
		b*	-0.84	-0.82	-0.55	-0.72	-0.22	1.58	0.95	0.63	0.84	0.64	-0.11	0.09	-0.20	0.27	0.01	0.09	0.13	0.74	0.45	6.00
	-	G	95	91	94	100	89	88	89	89	89	89	88	89	89	89	88	88	88	87	88	88
	SCE	L*	34.43	34.46	33.83	33.90	33.01	33.14	33.05	33.18	33.12	33.53	32.66	32.96	32.81	33.13	31.92	32.56	32.44	33.42	32.52	33.18
		a*	-0.11	-0.04	0.05	-0.19	0.35	1.85	1.27	0.98	1.11	1.00	0.63	0.66	0.36	0.73	0.71	0.65	0.75	1.30	0.97	1.07
		b*	-0.83	-0.76	-0.48	-0.82	0.04	2.50	1.66	1.18	1.48	1.19	0.20	0.45	0.07	0.70	0.38	0.45	0.51	1.34	0.93	1.12
350-0.5-1	SCI	L*	39.58	37.95	37.73	39.42	40.07	40.80	41.08	40.85	41.58	40.73	40.56	38.41	40.21	41.27	40.66	42.15	42.34	44.05	43.44	42.84
		a*	0.06	0.11	-0.03	0.28	0.07	-0.01	0.02	0.05	0.00	0.11	0.09	0.61	0.62	0.26	0.23	0.12	0.07	-0.22	-0.08	0.09
		b*	-0.78	-0.87	-1.11	-0.46	-0.73	-0.84	-0.82	-0.86	-0.85	-0.63	-0.63	-0.07	0.52	-0.34	-0.69	-0.80	-0.91	-1.28	-0.99	-0.74
	-	G	87	87	87	87	88	88	89	88	88	88	89	88	88	89	90	94	92	96	89	86
	SCE	L*	32.18	29.95	29.64	31.94	32.77	33.69	34.01	33.75	34.72	33.57	33.24	30.52	32.95	34.21	33.32	34.93	35.36	37.15	36.98	36.51
		a*	-0.13	-0.10	-0.30	0.16	-0.14	-0.23	-0.17	-0.15	-0.20	-0.05	-0.08	0.59	0.63	0.14	0.12	-0.03	-0.10	-0.46	-0.27	-0.06
		b*	-0.72	-0.87	-1.19	-0.30	-0.66	-0.81	-0.81	-0.81	-0.81	-0.54	-0.51	0.26	1.03	-0.14	-0.61	-0.73	-0.86	-1.36	-0.97	-0.66

Measurements After Heating:

Sample	Light	Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
350-0.5-2	SCI	L*	42.44	40.24	39.81	39.90	39.66	39.85	40.97	43.26	41.07	40.07	38.49	39.66	40.21	41.46	42.71	40.23	39.47	38.53	40.77	40.58
		a*	-0.05	0.18	0.39	0.45	0.73	0.22	0.08	-0.14	0.06	0.26	0.33	0.71	1.44	0.12	-0.02	0.57	0.41	0.33	0.12	0.13
		b*	-1.16	-0.73	-0.52	-0.33	0.15	-0.74	-1.06	-1.48	-0.68	-0.57	-0.42	0.42	1.79	-0.53	-0.96	0.23	-0.17	-0.42	-0.64	-0.61
	-	G	89	88	87	87	87	90	90	91	89	87	88	87	86	95	97	87	86	88	88	87
	SCE	L*	35.70	32.99	32.45	32.61	32.29	32.27	33.76	36.61	33.94	32.81	30.64	32.33	33.09	33.95	35.35	33.06	32.09	30.71	33.69	33.46
		a*	-0.23	0.04	0.29	0.39	0.76	0.08	-0.11	-0.35	-0.15	0.12	0.21	0.75	1.71	-0.06	-0.25	0.55	0.35	0.21	-0.04	-0.04
		b*	-1.20	-0.67	-0.36	-0.11	0.57	-0.65	-1.04	-1.53	-0.61	-0.42	-0.22	0.90	2.80	-0.53	-1.09	0.65	0.08	-0.21	-0.53	-0.50
350-0.5-3	SCI	L*	40.39	41.52	43.43	43.95	42.91	42.82	40.83	42.66	43.68	43.66	43.92	41.24	45.18	44.87	44.39	44.99	44.06	43.11	40.45	44.97
		a*	0.14	-0.02	-0.17	-0.28	-0.21	-0.17	-0.08	-0.18	-0.26	-0.28	-0.22	0.06	-0.50	-0.42	-0.38	-0.47	-0.28	-0.20	-0.14	-0.41
		b*	-0.40	-0.91	-1.38	-1.59	-1.27	-1.31	-1.24	-1.33	-1.45	-1.50	-1.50	-0.69	-1.79	-1.57	-1.59	-1.77	-1.60	-1.52	-1.44	-1.57
	-	G	89	95	95	104	93	92	90	90	92	92	105	93	99	98	94	94	88	86	88	94
	SCE	L*	33.07	33.97	36.52	36.39	35.96	36.92	33.56	35.94	37.07	36.98	36.27	33.80	38.43	38.11	37.78	38.55	37.80	36.83	33.27	38.52
		a*	-0.02	-0.24	-0.41	-0.55	-0.46	-0.41	-0.31	-0.39	-0.49	-0.52	-0.48	-0.16	-0.78	-0.69	-0.65	-0.73	-0.51	-0.42	-0.41	-0.66
		b*	-0.21	-0.94	-1.46	-1.84	-1.38	-1.38	-1.26	-1.34	-1.50	-1.56	-1.74	-0.67	-2.02	-1.72	-1.76	-1.98	-1.72	-1.64	-1.59	-1.72
350-1-1	SCI	L*	47.38	46.25	45.90	46.13	45.83	45.87	47.28	48.05	45.73	46.09	41.27	40.14	39.88	42.48	44.59	47.05	48.87	43.72	42.37	41.13
		a*	-0.80	-0.67	-0.65	-0.53	-0.56	-0.55	-0.69	-0.77	-0.49	-0.53	-0.11	0.06	0.01	-0.21	-0.48	-0.70	-0.49	-0.37	-0.24	-0.15
		b*	-2.03	-1.93	-2.06	-1.55	-1.58	-1.56	-1.65	-1.48	-1.41	-1.59	-1.12	-1.00	-1.43	-1.81	-2.01	-1.59	-0.01	-1.87	-1.69	-1.44
	-	G	116	105	104	105	107	102	101	101	100	106	101	98	100	96	105	109	108	102	97	101
	SCE	L*	39.92	39.26	38.89	39.10	38.62	39.06	40.85	41.80	39.00	39.01	33.11	31.83	31.27	35.18	37.19	40.01	42.36	36.29	34.90	32.89
		a*	-1.17	-1.02	-1.00	-0.86	-0.90	-0.89	-1.03	-1.10	-0.79	-0.87	-0.36	-0.16	-0.23	-0.49	-0.81	-1.05	-0.77	-0.68	-0.54	-0.45
		b*	-2.35	-2.23	-2.38	-1.82	-1.93	-1.84	-1.88	-1.64	-1.62	-1.91	-1.23	-1.07	-1.68	-2.13	-2.35	-1.90	0.01	-2.23	-2.00	-1.76
350-1-2	SCI	L*	44.07	42.98	42.78	42.65	42.71	42.59	41.88	42.83	41.56	42.69	45.30	44.56	45.27	45.09	45.36	44.93	44.55	44.92	44.51	45.17
		a*	-0.28	-0.14	-0.13	-0.14	-0.13	-0.13	-0.20	-0.32	-0.21	-0.27	-0.57	-0.47	-0.55	-0.54	-0.50	-0.45	-0.39	-0.45	-0.41	-0.45
		b*	-1.26	-0.88	-0.88	-1.00	-0.98	-0.93	-1.54	-1.69	-1.48	-1.62	-2.05	-2.06	-2.12	-1.87	-1.62	-1.63	-1.39	-1.52	-1.41	-1.59
	-	G	98	99	100	99	100	100	97	98	98	98	114	101	109	110	102	99	99	99	99	101
	SCE	L*	37.02	35.54	35.22	35.08	35.09	34.97	34.26	35.49	33.78	35.29	37.38	37.43	37.70	37.42	38.42	38.06	37.57	38.04	37.54	38.26
		a*	-0.56	-0.42	-0.41	-0.43	-0.41	-0.41	-0.51	-0.62	-0.50	-0.58	-0.90	-0.80	-0.90	-0.90	-0.83	-0.78	-0.70	-0.77	-0.71	-0.77
		b*	-1.47	-0.99	-1.00	-1.13	-1.12	-1.07	-1.79	-1.96	-1.74	-1.90	-2.50	-2.45	-2.55	-2.33	-1.90	-1.88	-1.59	-1.74	-1.64	-1.87
350-1-3	SCI	L*	43.39	42.34	43.71	42.78	43.54	42.68	42.21	41.60	40.88	41.92	43.86	42.98	43.40	43.85	45.13	44.58	44.40	44.59	45.33	43.67
		a*	-0.26	-0.11	-0.27	-0.14	-0.35	-0.29	-0.25	-0.23	-0.14	-0.26	-0.46	-0.25	-0.39	-0.46	-0.49	-0.41	-0.40	-0.40	-0.49	-0.33
		b*	-1.61	-1.11	-1.51	-1.21	-1.72	-1.72	-1.67	-1.67	-1.55	-1.69	-2.10	-1.89	-2.20	-2.26	-1.94	-1.60	-1.68	-1.61	-1.99	-1.56
	-	G	106	103	109	108	99	99	99	98	97	97	104	104	102	106	103	101	104	102	102	98
	SCE	L*	35.52	34.35	35.65	34.46	36.31	35.21	34.52	33.85	32.96	34.31	36.30	35.15	35.84	36.09	37.99	37.47	37.00	37.43	38.32	36.56
		a*	-0.59	-0.43	-0.60	-0.46	-0.66	-0.61	-0.55	-0.53	-0.43	-0.59	-0.79	-0.57	-0.71	-0.81	-0.83	-0.73	-0.72	-0.70	-0.81	-0.62
		b*	-1.95	-1.34	-1.89	-1.56	-2.03	-2.04	-2.01	-2.00	-1.85	-2.03	-2.51	-2.29	-2.68	-2.76	-2.28	-1.91	-1.98	-1.92	-2.32	-1.83
350-2-1	SCI	L*	42.14	41.60	41.64	40.09	40.99	42.94	43.35	46.39	47.20	46.76	43.43	41.93	42.91	43.15	41.88	42.80	44.85	46.18	47.23	45.88
		a*	-0.21	-0.10	-0.13	0.15	-0.03	-0.31	-0.38	-0.67	-0.76	-0.67	-0.26	-0.10	-0.22	-0.28	-0.05	-0.14	-0.53	-0.67	-0.81	-0.63
		b*	-1.72	-1.60	-1.62	-1.18	-1.47	-1.71	-1.92	-2.29	-2.00	-1.90	-1.65	-1.48	-1.76	-1.61	-1.45	-1.53	-2.14	-2.03	-2.19	-2.20
	-	G	100	98	99	97	95	98	102	102	118	107	99	98	100	98	97	97	111	120	116	119
	SCE	L*	34.40	33.83	33.79	31.91	33.26	35.57	35.81	39.71	39.56	39.79	36.12	34.24	35.36	35.83	34.32	35.51	37.01	38.03	39.71	37.73
		a*	-0.49	-0.37	-0.39	-0.03	-0.27	-0.62	-0.71	-1.01	-1.12	-1.02	-0.53	-0.35	-0.51	-0.57	-0.28	-0.37	-0.89	-1.05	-1.16	-1.01
		b*	-2.04	-1.90	-1.96	-1.36	-1.75	-2.01	-2.30	-2.70	-2.57	-2.31	-1.96	-1.76	-2.07	-1.89	-1.70	-1.79	-2.62	-2.63	-2.65	-2.77
350-2-2	SCI	L*	42.26	42.21	41.99	41.25	41.32	43.76	43.74	44.14	43.52	43.84	44.33	43.38	42.72	44.01	44.30	41.77	41.37	42.28	43.60	42.85
		a*	-0.25	-0.25	-0.26	-0.17	-0.18	-0.42	-0.39	-0.38	-0.36	-0.42	-0.47	-0.36	-0.20	-0.36	-0.45	-0.20	-0.20	-0.24	-0.35	-0.29
		b*	-1.79	-1.81	-1.79	-1.59	-1.59	-2.03	-1.94	-1.72	-1.91	-2.01	-2.23	-2.16	-1.70	-1.90	-2.14	-1.56	-1.64	-1.80	-1.81	-1.76
	-	G	98	99	98	97	97	97	108	105	99	104	105	104	98	96	99	101	94	95	97	95	96
	SCE	L*	34.68	34.59	34.38	33.43	33.54	35.82	36.03	37.11	35.88	36.18	36.94	36.13	35.47	36.92	37.12	34.39	33.80	34.85	36.67	35.66
		a*	-0.54	-0.57	-0.58	-0.49	-0.47	-0.75	-0.74	-0.69	-0.68	-0.74	-0.80	-0.67	-0.48	-0.64	-0.77	-0.48	-0.51	-0.54	-0.67	-0.58
		b*	-2.13	-2.14	-2.14	-1.89	-1.91	-2.51	-2.37	-2.02	-2.30	-2.40	-2.64	-2.55	-1.99	-2.23	-2.55	-1.85	-1.97	-2.17	-2.14	-2.10

Measurements After Heating:

Sample	Light	Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
350-2-3	SCI	L*	41.74	41.61	42.12	40.92	40.62	46.74	44.15	44.59	46.03	44.86	41.16	41.63	40.36	40.89	41.48	41.43	41.10	41.03	41.31	40.30
		a*	-0.20	-0.23	-0.29	-0.13	-0.07	-0.59	-0.33	-0.35	-0.48	-0.37	0.08	-0.13	0.03	0.03	-0.11	-0.12	-0.11	-0.06	-0.20	0.03
		b*	-1.86	-1.68	-1.60	-1.49	-1.57	-1.81	-1.62	-1.60	-1.56	-1.47	-0.98	-1.22	-1.10	-1.23	-1.46	-1.58	-1.44	-1.58	-1.60	-1.45
	-	G	96	97	98	96	96	118	114	118	124	124	98	98	96	97	97	96	95	95	95	95
	SCE	L*	34.17	33.97	34.51	33.06	32.72	38.94	35.80	36.08	37.50	35.96	33.24	33.84	32.40	32.99	33.78	33.83	33.46	33.34	33.74	32.40
		a*	-0.49	-0.51	-0.61	-0.41	-0.36	-0.94	-0.64	-0.68	-0.83	-0.74	-0.14	-0.41	-0.22	-0.23	-0.39	-0.39	-0.38	-0.32	-0.52	-0.18
		b*	-2.24	-2.01	-1.89	-1.79	-1.87	-2.22	-1.91	-1.93	-2.04	-1.90	-1.10	-1.47	-1.29	-1.42	-1.75	-1.90	-1.72	-1.88	-1.93	-1.74
400-0.5-1	SCI	L*	41.76	45.85	48.06	45.64	47.43	48.83	40.90	39.17	39.16	39.43	40.62	44.18	46.51	45.86	43.49	43.78	41.94	42.34	42.03	41.59
		a*	-0.21	-0.54	-0.68	-0.47	-0.69	-0.76	-0.08	0.17	0.24	0.11	0.11	-0.38	-0.57	-0.47	-0.33	-0.32	-0.13	-0.18	-0.14	-0.11
		b*	-1.43	-1.50	-1.16	-0.83	-1.57	-1.07	-1.59	-1.01	-0.93	-1.19	-0.81	-1.45	-1.66	-1.48	-1.38	-1.54	-1.42	-1.56	-1.38	-1.36
	-	G	97	105	115	99	108	107	97	96	96	96	97	96	99	96	96	97	95	96	95	95
	SCE	L*	34.14	38.81	40.89	38.96	40.60	42.38	33.00	30.77	30.71	31.10	32.63	37.33	40.04	39.44	36.45	36.74	34.54	35.02	34.65	34.13
		a*	-0.52	-0.88	-1.03	-0.80	-1.04	-1.10	-0.35	-0.05	0.09	-0.10	-0.10	-0.71	-0.90	-0.78	-0.64	-0.63	-0.41	-0.48	-0.41	-0.38
		b*	-1.68	-1.80	-1.52	-0.91	-1.89	-1.30	-1.93	-1.14	-1.07	-1.43	-0.91	-1.69	-1.92	-1.70	-1.64	-1.84	-1.64	-1.82	-1.61	-1.58
400-0.5-2	SCI	L*	44.63	45.33	46.29	44.92	46.93	43.19	43.75	38.93	39.88	40.31	44.75	41.11	39.55	41.72	42.51	44.47	43.73	39.47	40.96	39.42
		a*	-0.40	-0.48	-0.60	-0.49	-0.64	-0.31	-0.38	0.17	0.12	0.16	-0.56	-0.10	0.79	-0.20	-0.35	-0.57	-0.48	0.18	-0.09	0.39
		b*	-1.90	-1.92	-2.02	-2.13	-2.08	-1.68	-1.92	-1.03	-1.11	-1.09	-2.20	-1.67	0.32	-1.87	-2.19	-2.43	-2.30	-0.85	-1.55	-0.42
	-	G	106	105	124	104	117	98	101	95	94	96	105	97	95	99	102	102	105	96	98	96
	SCE	L*	37.16	38.08	37.91	37.67	39.24	35.94	36.39	30.52	31.86	32.31	37.37	33.24	31.34	33.86	34.65	37.27	36.05	31.08	32.94	31.01
		a*	-0.72	-0.79	-0.98	-0.83	-1.01	-0.62	-0.70	-0.02	-0.09	-0.01	-0.90	-0.39	0.85	-0.49	-0.67	-0.92	-0.82	0.00	-0.36	0.29
		b*	-2.29	-2.26	-2.61	-2.52	-2.61	-2.00	-2.28	-1.21	-1.30	-1.25	-2.55	-2.00	0.74	-2.20	-2.64	-2.82	-2.69	-0.95	-1.90	-0.36
400-0.5-3	SCI	L*	43.66	48.19	47.05	48.07	44.61	44.42	50.70	43.55	44.72	44.64	47.08	47.63	47.55	47.27	47.76	48.70	46.58	45.15	43.04	41.24
		a*	-0.39	-0.86	-0.68	-0.79	-0.48	-0.50	-0.94	-0.39	-0.49	-0.50	-0.50	-0.58	-0.60	-0.56	-0.47	-0.62	-0.43	-0.41	-0.22	-0.16
		b*	-2.02	-2.31	-1.79	-2.42	-1.92	-2.22	-1.38	-1.78	-1.78	-1.79	-1.51	-1.04	-1.03	-1.33	-1.34	-1.55	-1.54	-1.50	-1.60	-1.35
	-	G	102	116	102	104	105	104	127	98	100	99	113	101	102	110	108	99	109	97	94	94
	SCE	L*	36.18	40.93	40.53	41.63	37.23	37.00	43.41	36.42	37.77	37.69	39.75	41.32	41.11	40.20	40.95	42.74	39.38	38.51	36.09	33.70
		a*	-0.72	-1.21	-1.02	-1.14	-0.81	-0.83	-1.28	-0.71	-0.83	-0.83	-0.82	-0.86	-0.89	-0.89	-0.77	-0.90	-0.76	-0.71	-0.50	-0.46
		b*	-2.40	-2.73	-2.04	-2.82	-2.30	-2.63	-1.74	-2.13	-2.12	-2.14	-1.85	-1.06	-1.11	-1.53	-1.66	-1.73	-1.89	-1.72	-1.87	-1.60
400-1-1	SCI	L*	45.92	41.85	44.96	45.55	45.83	45.01	46.39	44.98	44.48	45.77	42.77	43.25	42.65	43.27	43.92	44.23	43.54	42.33	42.47	42.13
		a*	0.76	1.24	1.78	1.33	1.79	1.46	0.41	0.45	1.12	0.50	-0.03	-0.19	-0.11	0.12	0.11	0.20	0.06	0.34	0.80	0.71
		b*	-0.38	0.42	1.34	0.40	1.49	1.00	-1.12	-0.74	0.14	-0.83	-1.52	-1.99	-1.89	-1.51	-1.65	-1.48	-1.62	-0.94	0.13	-0.13
	-	G	109	95	95	99	100	97	110	98	98	101	100	107	107	116	108	101	122	96	94	95
	SCE	L*	38.54	34.42	38.40	38.83	39.14	38.37	39.12	38.18	37.57	39.01	35.22	35.19	34.41	34.48	36.06	36.99	34.33	34.96	35.29	34.83
		a*	0.88	1.44	2.12	1.57	2.15	1.72	0.42	0.42	1.29	0.49	-0.24	-0.45	-0.36	-0.01	-0.04	0.08	-0.09	0.23	0.87	0.73
		b*	-0.13	0.85	2.02	0.83	2.27	1.57	-1.08	-0.73	0.46	-0.85	-1.77	-2.39	-2.26	-1.80	-1.96	-1.70	-1.99	-0.98	0.43	0.06
400-1-2	SCI	L*	44.25	43.13	43.81	42.54	42.33	42.79	40.97	43.05	41.10	42.98	48.09	45.99	47.01	47.52	44.63	45.35	48.24	44.88	46.17	46.56
		a*	-0.36	-0.28	-0.33	-0.24	-0.22	-0.28	0.11	0.12	0.29	0.29	0.06	0.71	2.65	2.63	1.98	0.33	2.95	1.53	2.53	2.34
		b*	-2.27	-1.90	-1.83	-1.97	-1.91	-2.09	-1.17	-1.18	-0.92	-0.93	-0.87	-0.25	4.36	4.63	2.42	-0.70	5.09	0.94	3.83	3.60
	-	G	95	92	94	104	105	102	87	88	88	88	100	95	86	86	87	94	85	89	86	86
	SCE	L*	37.54	36.38	37.08	34.49	34.15	35.05	33.98	36.55	34.08	36.46	41.93	39.72	41.60	42.20	38.61	39.03	43.09	38.76	41.24	41.30
		a*	-0.60	-0.56	-0.58	-0.52	-0.53	-0.55	-0.08	0.00	0.17	0.20	-0.04	0.78	3.11	3.07	2.33	0.28	3.43	1.79	2.95	2.72
		b*	-2.58	-2.09	-1.97	-2.27	-2.28	-2.35	-1.20	-1.20	-0.85	-0.84	-0.79	0.07	5.73	6.04	3.43	-0.54	6.57	1.58	5.10	4.82
400-1-3	SCI	L*	40.79	41.63	42.42	41.09	42.76	40.74	44.50	44.01	45.62	45.84	45.74	59.21	54.84	55.60	51.40	44.37	50.97	52.42	49.05	51.16
		a*	0.44	-0.14	-0.22	0.72	1.28	0.49	1.05	0.89	1.33	1.41	1.67	2.92	2.88	2.29	1.78	1.43	2.73	2.92	2.49	2.89
		b*	-0.64	-1.69	-1.94	0.06	1.24	-0.54	1.00	0.27	1.77	1.93	2.57	9.33	7.84	7.49	4.95	1.72	5.33	6.30	4.76	5.72
	-	G	90	97	101	92	89	91	87	87	86	86	86	79	81	81	83	87	83	82	85	83
	SCE	L*	33.47	33.92	34.68	33.70	36.17	33.36	38.48	37.86	39.93	40.16	40.08	55.87	50.94	51.77	46.93	38.35	46.45	48.13	44.08	46.63
		a*	0.37	-0.39	-0.49	0.74	1.45	0.45	1.15	0.96	1.50	1.60	1.93	3.18	3.21	2.51	1.97	1.64	3.10	3.30	2.85	3.29
		b*	-0.52	-1.98	-2.20	0.38	1.95	-0.40	1.60	0.67	2.52	2.71	3.51	10.84	9.39	8.93	6.15	2.50	6.64	7.73	6.08	7.11

Measurements After Heating:

Sample	Light	Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
400-2-1	SCI	L*	61.24	60.72	59.81	60.34	61.07	61.29	57.50	55.92	57.39	54.61	61.90	61.80	61.25	61.82	61.99	61.59	53.09	49.90	53.16	50.35
		a*	2.92	3.00	2.75	2.87	3.07	3.00	3.01	2.76	2.94	2.87	2.95	3.00	3.00	3.03	2.91	2.99	3.43	2.68	3.39	2.84
		b*	9.43	9.51	8.65	8.99	9.76	9.65	7.73	6.19	7.83	6.02	7.84	7.91	8.24	7.98	7.75	7.78	7.45	5.31	7.32	5.87
	"	G	78	78	79	79	79	79	79	81	79	83	77	78	77	78	77	77	91	92	92	90
	SCE	L*	58.13	57.54	56.51	57.11	57.91	58.15	53.97	52.11	53.89	50.59	58.89	58.73	58.15	58.74	58.96	58.52	48.39	44.66	48.45	45.27
		a*	3.18	3.27	3.01	3.13	3.36	3.27	3.32	3.06	3.24	3.21	3.21	3.26	3.27	3.29	3.17	3.24	3.91	3.08	3.86	3.25
		b*	10.84	10.96	10.02	10.37	11.22	11.09	9.09	7.39	9.21	7.25	8.99	9.09	9.47	9.16	8.90	8.95	9.16	6.75	9.00	7.38
400-2-2	SCI	L*	56.27	58.01	58.70	59.73	59.07	57.85	59.11	58.96	58.77	57.45	59.54	60.12	60.13	61.60	60.24	60.81	60.04	57.08	60.20	57.94
		a*	3.36	3.32	3.28	3.18	3.18	3.17	3.19	3.04	3.24	3.13	3.26	3.19	3.12	3.20	3.16	3.11	3.25	3.18	2.57	3.27
		b*	7.56	7.68	8.30	8.80	9.29	8.60	8.60	9.59	10.06	9.01	8.97	8.86	8.84	9.68	9.27	9.37	9.35	8.20	7.44	9.23
	"	G	79	79	79	78	78	78	78	79	79	79	78	78	79	79	78	79	79	83	79	80
	SCE	L*	52.63	54.56	55.32	56.47	55.77	54.39	55.80	55.58	55.37	53.91	56.27	56.92	56.87	58.48	57.02	57.61	56.76	53.32	56.93	54.43
		a*	3.74	3.66	3.61	3.49	3.49	3.50	3.51	3.34	3.56	3.45	3.57	3.49	3.42	3.49	3.46	3.38	3.57	3.52	2.79	3.60
		b*	8.98	9.02	9.69	10.21	10.81	10.10	10.02	11.14	11.73	10.59	10.40	10.24	10.23	11.12	10.72	10.78	10.83	9.69	8.62	10.82
400-2-3	SCI	L*	49.84	51.29	51.37	49.88	49.93	48.43	51.12	51.02	48.62	51.51	48.89	50.29	51.53	49.25	47.20	47.48	49.04	51.54	49.85	45.03
		a*	3.40	3.65	3.64	3.61	3.10	3.36	3.71	3.63	3.13	3.79	3.08	3.47	3.60	3.30	3.03	2.40	3.22	3.69	3.31	2.44
		b*	5.85	6.92	7.22	6.55	5.94	5.83	7.31	6.81	4.93	7.55	5.22	6.36	7.11	6.00	4.63	2.55	5.88	7.24	5.94	3.42
	"	G	91	94	90	89	88	88	90	94	93	91	88	88	89	87	87	97	87	89	88	87
	SCE	L*	44.61	46.13	46.49	44.82	44.91	43.13	46.20	45.81	43.04	46.58	43.72	45.33	46.74	44.17	41.75	41.39	43.94	46.74	44.83	39.09
		a*	3.98	4.25	4.20	4.20	3.58	3.92	4.28	4.22	3.71	4.37	3.57	4.02	4.13	3.82	3.55	2.88	3.75	4.24	3.83	2.90
		b*	7.54	8.81	9.04	8.33	7.54	7.53	9.20	8.69	6.54	9.49	6.72	8.04	8.91	7.68	6.14	3.70	7.52	9.03	7.56	4.71

- Conventions used in numbering the samples reflect heating conditions. The first number is the target temperature, the second number is the length of exposure, the final number is an arbitrary designation to separate the three samples exposed to the same conditions. Thus, sample ‘ 100-0.5-1‘ was the first of three samples heated to 100°C for 0.5 hours.
- For the three control samples the letters following the sample number reflect the position along the humeral shaft at which the sample was taken. P = proximal, C = central and D = distal.
- Cell highlighted in yellow was an obvious transcription error and was not included in analysis.
- Data available as spreadsheet in supplemental materials.

Appendix 6 – FTIR Data from the Controlled Heating Experiment

Sample Number	Temp. (°C)	Exposure Time (hrs)	Peaks at Wavenumber (cm^{-1})									
			1650	1550	1455	1415	1250	1035	900	605	595	565
Control 1	23	N/A	0.02282677	0.0172749	0.01603486	0.01630227	0.00056169	0.02843689	0.00515396	0.0113147	0.00965653	0.02132205
Control 2	23	N/A	0.01703888	0.01112898	0.01238995	0.01359905	-0.0037254	0.03516085	0.00646062	0.01153025	0.00967283	0.02591363
Control 3	23	N/A	0.01114038	0.00646039	0.00904507	0.01036001	-0.0038254	0.04197522	0.00756468	0.01954095	0.01696943	0.03767705
100-0.5-1	100	0.5	0.01926314	0.01168676	0.01612212	0.01821785	-0.0042597	0.05293019	0.01428877	0.02238145	0.01940337	0.04237465
100-0.5-2	100	0.5	0.0146912	0.00934921	0.01267294	0.01412513	-0.0015636	0.04061207	0.01202766	0.01905815	0.01717157	0.03322218
100-0.5-3	100	0.5	0.01307102	0.00702432	0.01146845	0.01346977	-0.0050983	0.04707148	0.01282524	0.01988569	0.01687789	0.04012565
100-1-1	100	1	0.00757914	0.00478198	0.00699744	0.00803508	-0.0018427	0.0266193	0.00837299	0.01333736	0.01179093	0.02475654
100-1-2	100	1	0.01365404	0.00728248	0.01323427	0.0159982	-0.0057658	0.05807764	0.01825062	0.0281512	0.02460788	0.05451313
100-1-3	100	1	0.01077825	0.00628075	0.00952845	0.01111156	-0.0029035	0.03432615	0.01139714	0.01734517	0.01477953	0.03226035
100-2-1	100	2	0.01284614	0.00758564	0.01215111	0.01416618	-0.0034884	0.03413937	0.01341609	0.01460334	0.01358602	0.02738008
100-2-2	100	2	0.01078757	0.00627358	0.01036562	0.01216282	-0.0025911	0.03370973	0.0126867	0.01514052	0.01344568	0.02825612
100-2-3	100	2	0.01838727	0.01494051	0.01641584	0.01742123	0.00609472	0.03675591	0.01639325	0.01993151	0.0189381	0.03130529
150-0.5-1	150	0.5	0.0131896	0.00772204	0.01224657	0.01434771	-0.0035679	0.04191587	0.01574301	0.02000629	0.01795956	0.03648583
150-0.5-2	150	0.5	0.00823157	0.00476792	0.00735352	0.00861586	-0.0030482	0.02689355	0.00898448	0.01176131	0.0105174	0.02308548
150-0.5-3	150	0.5	0.00672193	0.00416146	0.00670342	0.0076849	-0.0012756	0.02360766	0.00840416	0.01287459	0.01152212	0.02183556
150-1-1	150	1	0.01785677	0.01076872	0.01600362	0.01830945	-0.0033303	0.06713466	0.01857482	0.03196551	0.02733892	0.06014976
150-1-2	150	1	0.0120231	0.00724012	0.01088868	0.0123228	-0.0027053	0.03479681	0.0120185	0.01520545	0.01348818	0.02984505
150-1-3	150	1	0.01370069	0.00813398	0.01220326	0.01415083	-0.0034617	0.04898026	0.01544777	0.02294704	0.01994907	0.04442271
150-2-1	150	2	0.01388038	0.0084889	0.01338506	0.01567891	-0.0023617	0.05575236	0.01883344	0.02884879	0.02547497	0.05254251
150-2-2	150	2	0.014181	0.00842423	0.01398706	0.016441	-0.0025703	0.05327563	0.01962542	0.02627134	0.02251632	0.04890115
150-2-3	150	2	0.01222947	0.00669336	0.01098052	0.01296453	-0.00389	0.03972017	0.01422245	0.01852115	0.0154493	0.03509653
200-0.5-1	200	0.5	0.01499675	0.0091319	0.01516577	0.0176611	-0.0023872	0.05743538	0.02018394	0.02864859	0.02553739	0.05183051
200-0.5-2	200	0.5	0.01674798	0.00946836	0.01549636	0.01831317	-0.0048831	0.06877968	0.02047223	0.03329121	0.02844523	0.06375393
200-0.5-3	200	0.5	0.01001975	0.0057901	0.00950863	0.0111699	-0.0021666	0.02866438	0.01063898	0.01290335	0.01110415	0.02312796
200-1-1	200	1	0.01796979	0.01145206	0.01619874	0.01856828	-0.002328	0.06462451	0.01986592	0.03138843	0.0268337	0.05967756
200-1-2	200	1	0.03435193	0.02400166	0.03353875	0.03583703	0.00607221	0.11620471	0.03460787	0.05578613	0.04815072	0.09802351
200-1-3	200	1	0.01580646	0.00935239	0.01513541	0.01791086	-0.0041814	0.06865967	0.02042049	0.03426393	0.02925002	0.06505631
200-2-1	200	2	0.0162199	0.00999135	0.01628189	0.01905485	-0.0030938	0.07999165	0.02014891	0.03973313	0.03273977	0.07162321
200-2-2	200	2	0.0149149	0.00917035	0.01470767	0.01739937	-0.0027034	0.07038655	0.01939128	0.03537998	0.02962114	0.06483991
200-2-3	200	2	0.01518527	0.00918502	0.0154724	0.01820903	-0.0033221	0.07508941	0.02027468	0.03739293	0.03103721	0.06921763
250-0.5-1	250	0.5	0.03258239	0.02516015	0.03286872	0.03690845	0.00910424	0.11417718	0.04325347	0.06333259	0.05551376	0.10548711
250-0.5-2	250	0.5	0.03054802	0.02227558	0.03008431	0.0333909	2.7596E-05	0.12323712	0.02564811	0.05173168	0.04230675	0.09868817
250-0.5-3	250	0.5	0.0238836	0.0145293	0.02313567	0.02659516	-0.0036961	0.11231971	0.02349969	0.05269437	0.04372086	0.09615072
250-1-1	250	1	0.02349309	0.01459714	0.02534139	0.03021449	-0.0024872	0.12329537	0.02626238	0.05546315	0.04629794	0.10418688
250-1-2	250	1	0.02401758	0.01472772	0.02481456	0.0293433	-0.0021582	0.11879028	0.02730365	0.05505259	0.0458951	0.10162313
250-1-3	250	1	0.02039811	0.01281029	0.02260694	0.02684454	-0.0023032	0.11631091	0.02526402	0.05417021	0.04439925	0.09996732
250-2-1	250	2	0.01788191	0.01142612	0.02091449	0.02522023	-0.00248	0.1073228	0.02404634	0.04966137	0.04135891	0.09009449
250-2-2	250	2	0.01735631	0.01181507	0.02092643	0.02569755	-0.0032403	0.11299779	0.0252237	0.05149374	0.04289498	0.0964529
250-2-3	250	2	0.01940505	0.01306112	0.02223421	0.02661715	-0.0022892	0.11591927	0.026528	0.05432649	0.04458446	0.10012616
300-0.5-1	300	0.5	0.01847339	0.01079756	0.02280068	0.02700198	-0.003081	0.12332854	0.0282256	0.05949451	0.04935686	0.10790632
300-0.5-2	300	0.5	0.01705859	0.00949461	0.01989037	0.02358017	-0.0032882	0.1004523	0.02401795	0.04862372	0.03989028	0.08836994
300-0.5-3	300	0.5	0.01862362	0.0113794	0.02311507	0.02746307	-0.0029109	0.11308533	0.02795249	0.0545104	0.04610096	0.09971809
300-1-1	300	1	0.0113969	0.00987157	0.02640421	0.03180993	-0.0055762	0.16023547	0.03145022	0.07397373	0.06017396	0.13267401
300-1-2	300	1	0.01104379	0.01030873	0.02491626	0.03000321	-0.0041144	0.15500089	0.03145516	0.07396716	0.05974866	0.1333128
300-1-3	300	1	0.01074148	0.01048086	0.02475401	0.02981894	-0.0052614	0.15361253	0.03169506	0.07097549	0.05753515	0.12854347
300-2-1	300	2	0.00852431	0.00842695	0.02429378	0.02952331	-0.0069331	0.17089947	0.0311978	0.07809532	0.06257745	0.14330751
300-2-2	300	2	0.00786693	0.00790241	0.02200935	0.02665479	-0.0056201	0.14030591	0.03076257	0.06624293	0.05383071	0.12155763
300-2-3	300	2	0.01102983	0.01135364	0.02454294	0.0294047	-0.0071503	0.17074438	0.02937172	0.07526377	0.06055334	0.14103659
350-0.5-1	350	0.5	0.01113097	0.01086362	0.02734712	0.03245331	-0.0053198	0.18038613	0.0328878	0.08071865	0.06489412	0.14838751
350-0.5-2	350	0.5	0.01041312	0.0103261	0.02615971	0.03046621	-0.0063394	0.17042236	0.03047325	0.07745025	0.06193163	0.14129582
350-0.5-3	350	0.5	0.00795475	0.00780984	0.02398748	0.02823121	-0.0064566	0.16466456	0.02976069	0.07583355	0.06100925	0.13840399
350-1-1	350	1	0.00147513	0.00213347	0.02258329	0.02497796	-0.0128437	0.20381256	0.02492917	0.08751296	0.06823291	0.16496417
350-1-2	350	1	0.00341921	0.00413045	0.02245521	0.02581607	-0.0089771	0.17004645	0.02872637	0.07671609	0.06102267	0.14106761
350-1-3	350	1	0.00469155	0.00539631	0.0237073	0.02754263	-0.0065985	0.16123185	0.03167373	0.07540685	0.06060388	0.13602289
350-2-1	350	2	0.00077194	0.00183601	0.02215388	0.02462202	-0.0111879	0.18388087	0.02647651	0.0811761	0.06354702	0.15176315
350-2-2	350	2	0.00247612	0.00307373	0.02347795	0.02618218	-0.0131867	0.20790237	0.02545006	0.08686694	0.06850265	0.16467804
350-2-3	350	2	0.00371274	0.00413909	0.02296752	0.02657644	-0.0113076	0.18781778	0.02779819	0.08095594	0.06425967	0.15305794
400-0.5-1	400	0.5	0.00600546	0.00636627	0.02395626	0.02799321	-0.0061911	0.15574832	0.03155849	0.07323941	0.05954199	0.13339613
400-0.5-2	400	0.5	0.00576143	0.00585656	0.02737545	0.03170196	-0.0081494	0.18734371	0.03552478	0.08665512	0.06925506	0.15864527
400-0.5-3	400	0.5	0.00551807	0.00569307	0.02500941	0.02872046	-0.006522	0.16790448	0.03250741	0.07842136	0.06251191	0.14232042
400-1-1	400	1	0.00175676	0.00277902	0.02424294	0.02662272	-0.0105723	0.1931865	0.02870555	0.08460003	0.06607754	0.15775655
400-1-2	400	1	0.00154442	0.00300333	0.02459243	0.02659615	-0.0104424	0.18401763	0.02722177	0.08315159	0.06549933	0.15072542
400-1-3	400	1	0.00685792	0.01004736	0.03019945	0.03071062	-0.000515	0.20459125	0.03404627	0.09269324	0.07427142	0.16244763
400-2-1	400	2	0.00666887	0.01069239	0.03360634	0.03525632	-0.0002138	0.22140258	0.03924227	0.10381572	0.08385347	0.18126205
400-2-2	400	2	0.00819824	0.0114408	0.03371035	0.0339525	0.00071991	0.22784326	0.03744144	0.10417983	0.08419295	0.18195864
400-2-3	400	2	0.00808081	0.01107587	0.03421436	0.03572993	0.00058026	0.21869059	0.04025245	0.10292061	0.0834491	0.17617856

Sample Number	Temp. (°C)	Exposure Time (hrs)	Ratios at Wavenumber (cm^{-1})							
			(605+565)/595	1415/1035	1650/1035	1650/1415	900/1035	1035/1415	1650/1455	1455/1415
Control 1	23	N/A	3.379758601	0.57327888	0.80271665	1.40022017	0.18124186	1.74435172	1.42357118	0.98359688
Control 2	23	N/A	3.871037764	0.38676679	0.48459822	1.25294681	0.18374479	2.58553739	1.37521847	0.91108929
Control 3	23	N/A	3.371827654	0.24681257	0.26540375	1.07532511	0.18021769	4.05165757	1.23165247	0.87307511
100-0.5-1	100	0.5	3.337362954	0.34418632	0.36393479	1.05737727	0.269955	2.9054031	1.19482659	0.88496295
100-0.5-2	100	0.5	3.044585334	0.34780618	0.36174477	1.04007572	0.29615971	2.87516452	1.15925808	0.89719084
100-0.5-3	100	0.5	3.555619526	0.28615555	0.2776844	0.9703967	0.27246313	3.49460289	1.13973736	0.85142133
100-1-1	100	1	3.230778247	0.30185156	0.28472344	0.94325649	0.31454592	3.31288666	1.08313056	0.8708613
100-1-2	100	1	3.359262266	0.27546231	0.23509975	0.85347339	0.31424514	3.63026075	1.03171814	0.82723503
100-1-3	100	1	3.356367335	0.32370534	0.31399533	0.97000355	0.33202505	3.08922926	1.13116549	0.85752577
100-2-1	100	2	3.090192503	0.41495137	0.37628507	0.90681727	0.39298004	2.40992093	1.05719897	0.85775459
100-2-2	100	2	3.227551756	0.36081031	0.32001361	0.88693034	0.37635135	2.77153946	1.04070692	0.85223834
100-2-3	100	2	2.705488121	0.4739708	0.5002534	1.05545194	0.44600305	2.10983463	1.12009321	0.94228938
150-0.5-1	150	0.5	3.145517204	0.34229787	0.31466843	0.91928246	0.37558584	2.92143213	1.07700362	0.85355558
150-0.5-2	150	0.5	3.31325264	0.32036891	0.30607969	0.9553976	0.33407554	3.12140151	1.11940615	0.85348611
150-0.5-3	150	0.5	3.012479997	0.3255258	0.28473499	0.87469253	0.35599281	3.07195312	1.00276093	0.87228421
150-1-1	150	1	3.369381982	0.27272723	0.26598432	0.97527597	0.27667996	3.66666721	1.11579565	0.87406325
150-1-2	150	1	3.339997472	0.35413585	0.34552304	0.97567937	0.34539086	2.82377512	1.1041833	0.88362084
150-1-3	150	1	3.377086295	0.28890886	0.27971857	0.96818966	0.31538761	3.46129915	1.12270697	0.86237076
150-2-1	150	2	3.194951554	0.28122409	0.24896485	0.88528989	0.33780528	3.55588309	1.03700532	0.85369851
150-2-2	150	2	3.338578282	0.30860264	0.26618172	0.86253869	0.36837514	3.24041295	1.01386534	0.85074285
150-2-3	150	2	3.470557062	0.32639656	0.30789066	0.9433024	0.35806629	3.06375779	1.11374275	0.84696615
200-0.5-1	200	0.5	3.151422733	0.30749509	0.26110651	0.84914042	0.35141992	3.25208449	0.98885507	0.85871069
200-0.5-2	200	0.5	3.411649009	0.2662585	0.2435019	0.91453196	0.29764932	3.75574869	1.08076916	0.84618621
200-0.5-3	200	0.5	3.244849877	0.38967867	0.34955407	0.89703157	0.37115696	2.56621692	1.05375296	0.85127312
200-1-1	200	1	3.393717189	0.28732564	0.27806457	0.96776803	0.30740534	3.48037165	1.10933248	0.87238772
200-1-2	200	1	3.19433723	0.30839568	0.29561566	0.95855967	0.2978181	3.24258755	1.024246	0.9358686
200-1-3	200	1	3.395561036	0.26086433	0.23021457	0.88250688	0.29741608	3.83341019	1.04433591	0.84504121
200-2-1	200	2	3.401255984	0.2382105	0.2027699	0.8512215	0.2518877	4.19796784	0.99619261	0.85447482
200-2-2	200	2	3.383390112	0.24719733	0.21189993	0.85720962	0.275497	4.04535121	1.01409051	0.84529893
200-2-3	200	2	3.434927638	0.24249801	0.20222922	0.83394179	0.27000722	4.12374519	0.98144281	0.84971002
250-0.5-1	250	0.5	3.041042744	0.3232559	0.28536694	0.88278956	0.37882766	3.09352434	0.99128889	0.89054721
250-0.5-2	250	0.5	3.555457611	0.2709484	0.24788003	0.91486064	0.20811996	3.69073964	1.0154136	0.9009734
250-0.5-3	250	0.5	3.404440905	0.23678087	0.21263946	0.89804325	0.20922146	4.22331416	1.03232799	0.86992047
250-1-1	250	1	3.448318592	0.24505782	0.19054316	0.77754367	0.21300376	4.08066958	0.927064	0.83871628
250-1-2	250	1	3.413778597	0.24701764	0.20218474	0.81850326	0.22984747	4.0482939	0.96788264	0.84566375
250-1-3	250	1	3.471624684	0.23079984	0.17537571	0.75986061	0.21721109	4.33275869	0.90229411	0.84214294
250-2-1	250	2	3.379099009	0.2349941	0.16661802	0.70903065	0.22405625	4.25542593	0.85500097	0.82927467
250-2-2	250	2	3.449043506	0.22741643	0.15359864	0.67540693	0.22322294	4.39721959	0.82939634	0.81433556
250-2-3	250	2	3.464270669	0.22961803	0.16740139	0.72904288	0.22884888	4.35505875	0.87275616	0.83533398
300-0.5-1	300	0.5	3.391642656	0.21894344	0.14979009	0.68414969	0.22886512	4.56738959	0.81021223	0.844408
300-0.5-2	300	0.5	3.43426153	0.23473995	0.16981779	0.72342943	0.23909804	4.26003324	0.85763065	0.84352096
300-0.5-3	300	0.5	3.345450403	0.24285263	0.16468641	0.67813309	0.24718053	4.11772353	0.80569165	0.84167818
300-1-1	300	1	3.434172424	0.19851991	0.07112596	0.35828123	0.19627502	5.03727801	0.43163197	0.83006186
300-1-2	300	1	3.469198508	0.19356797	0.07124984	0.36808691	0.20293534	5.16614385	0.44323612	0.83045334
300-1-3	300	1	3.467774951	0.19411787	0.06992581	0.36022348	0.20633121	5.15150931	0.43392902	0.83014379
300-2-1	300	2	3.538060731	0.17275249	0.04987907	0.28873139	0.18255058	5.78862858	0.35088425	0.82286791
300-2-2	300	2	3.488725394	0.18997625	0.05606987	0.29514147	0.21925354	5.26381574	0.35743609	0.82571818
300-2-3	300	2	3.572063041	0.17221473	0.06459852	0.37510452	0.17202159	5.80670438	0.44940958	0.83466071
350-0.5-1	350	0.5	3.530461059	0.17991022	0.06170636	0.34298422	0.18231888	5.55832802	0.40702546	0.84266036
350-0.5-2	350	0.5	3.532057402	0.17876885	0.06110186	0.34179254	0.17881016	5.59381558	0.39805965	0.85864654
350-0.5-3	350	0.5	3.511558202	0.17144677	0.0483088	0.28177143	0.18073523	5.83271417	0.33162081	0.84967958
350-1-1	350	1	3.700225089	0.12255359	0.00723766	0.05905712	0.12231422	8.15969559	0.06531937	0.90412871
350-1-2	350	1	3.568898046	0.15181773	0.02010749	0.13244491	0.16893247	6.58684596	0.15226783	0.86981547
350-1-3	350	1	3.488716362	0.17082626	0.02909818	0.17033789	0.19644834	5.85390107	0.19789493	0.86074914
350-2-1	350	2	3.665620199	0.13390202	0.00419803	0.03135152	0.14398731	7.46814738	0.03484436	0.89975871
350-2-2	350	2	3.672047287	0.12593496	0.01191001	0.09457271	0.12241352	7.94060708	0.10546576	0.89671484
350-2-3	350	2	3.641691391	0.14150121	0.01976777	0.13970038	0.14800615	7.06707718	0.16165174	0.86420584
400-0.5-1	400	0.5	3.470416988	0.17973362	0.03855875	0.21453275	0.20262493	5.56378948	0.25068433	0.85578845
400-0.5-2	400	0.5	3.541985069	0.16921819	0.03075327	0.18173737	0.18962358	5.90953015	0.21045982	0.86352526
400-0.5-3	400	0.5	3.531195857	0.17105239	0.03286434	0.19213025	0.19360654	5.84616214	0.22063971	0.87078726
400-1-1	400	1	3.667760485	0.13780839	0.00909362	0.06598739	0.14858983	7.25645247	0.07246498	0.91061075
400-1-2	400	1	3.570677631	0.14453045	0.00839276	0.05806916	0.14793024	6.91895705	0.06280048	0.92466108
400-1-3	400	1	3.435249741	0.15010722	0.03352009	0.22330764	0.16641116	6.6619049	0.22708746	0.9833552
400-2-1	400	2	3.399713528	0.15924079	0.030121	0.18915382	0.17724397	6.27979788	0.19844075	0.95320045
400-2-2	400	2	3.398603628	0.14901692	0.03598192	0.24146196	0.16432983	6.71064746	0.24319642	0.99286811
400-2-3	400	2	3.344543749	0.16338119	0.0369509	0.22616374	0.18406118	6.12065574	0.23618192	0.95758279

- Peaks and ratios used in the FTIR analysis of samples from the controlled heating experiment.
- Conventions used in numbering the samples reflect heating conditions. The first number is the target temperature, the second number is the length of exposure, the final number is an arbitrary designation to separate the three samples exposed to the same conditions. Thus, sample '100-0.5-1' was the first of three samples heated to 100°C for 0.5 hours.
- Each sample was analysed in triplicate and the results were averaged before further analysis.
- A baseline correction was conducted on the FTIR data before the peaks were isolated.
- Data available as spreadsheet in supplemental materials.

Appendix 7 – Collagen Extraction for Controlled Heating Experiment

	Isotope	Initial	0.5(M) HCl at 4°C								DI water	Mixed to	Heating Block 70°C		
Sample	Lab Labels	Dry Mass	Added	1st change	2nd change	3rd change	4th change	5th change	6th change	7th change	rinse X3	pH 3	Started	Removed	Eezee Filter
Control – 1(p)	4140	843.8	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	13/02/2019	n/a	20/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
Control – 2(c)	4141	954.9	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	13/02/2019	n/a	20/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
Control – 3(d)	4142	813.7	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	13/02/2019	n/a	20/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
100–0.5–1	4143	1037.3	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	13/02/2019	n/a	20/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
100–0.5–2	4144	1011.6	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	13/02/2019	n/a	20/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
100–0.5–3	4145	853.3	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	13/02/2019	n/a	20/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
100–1–1	4146	975.9	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	13/02/2019	n/a	20/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
100–1–2	4147	1025.6	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	n/a	n/a	13/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
100–1–3	4148	1057.9	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	13/02/2019	n/a	20/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
100–2–1	4149	1063.9	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	13/02/2019	n/a	20/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
100–2–2	4150	1004	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	13/02/2019	n/a	20/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
100–2–3	4151	1056.2	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	n/a	n/a	13/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
150–0.5–1	4152	1045.1	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	13/02/2019	n/a	20/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
150–0.5–2	4153	978.7	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	13/02/2019	n/a	20/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
150–0.5–3	4154	1169.7	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	13/02/2019	n/a	20/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
150–1–1	4155	1126.8	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	13/02/2019	n/a	20/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
150–1–2	4156	1051	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	13/02/2019	n/a	20/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
150–1–3	4157	1201.5	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	13/02/2019	n/a	20/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
150–2–1	4158	1089.9	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	13/02/2019	n/a	20/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
150–2–2	4159	1146.8	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	13/02/2019	n/a	20/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
150–2–3	4160	1044.4	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	13/02/2019	n/a	20/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
200–0.5–1	4161	1071.3	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	13/02/2019	n/a	20/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
200–0.5–2	4162	1204.3	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	13/02/2019	n/a	20/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
200–0.5–3	4163	1220	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	13/02/2019	n/a	20/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
200–1–1	4164	1171.2	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	n/a	n/a	n/a	11/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
200–1–2	4165	1049.1	30/01/2019	01/02/2019	04/02/2019	06/02/2019	n/a	n/a	n/a	n/a	08/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
200–1–3	4166	1102.7	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	n/a	n/a	13/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
200–2–1	4167	1225.1	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	n/a	n/a	n/a	11/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
200–2–2	4168	1058.6	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	n/a	n/a	n/a	11/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
200–2–3	4169	1060.4	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	n/a	n/a	n/a	11/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
250–0.5–1	4170	1128.8	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	n/a	n/a	13/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
250–0.5–2	4171	1040.6	30/01/2019	01/02/2019	04/02/2019	06/02/2019	n/a	n/a	n/a	n/a	08/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
250–0.5–3	4172	1057.3	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	n/a	n/a	n/a	11/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
250–1–1	4173	1248.7	30/01/2019	01/02/2019	04/02/2019	n/a	n/a	n/a	n/a	n/a	06/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
250–1–2	4174	1106.8	30/01/2019	01/02/2019	04/02/2019	n/a	n/a	n/a	n/a	n/a	06/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
250–1–3	4175	1034.2	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	n/a	n/a	n/a	11/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
250–2–1	4176	1344.2	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	n/a	n/a	13/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
250–2–2	4177	1286.7	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	n/a	n/a	13/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
250-2-3	4178	1213.7	30/01/2019	01/02/2019	04/02/2019	06/02/2019	n/a	n/a	n/a	n/a	08/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
300–0.5–1	4179	1266.7	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	13/02/2019	n/a	20/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
300–0.5–2	4240	1110.4	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	n/a	n/a	n/a	11/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
300–0.5–3	4241	1134.8	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	n/a	n/a	n/a	11/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
300–1–1	4242	1329.7	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	13/02/2019	n/a	20/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
300–1–2	4243	1170.8	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	13/02/2019	n/a	20/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
300–1–3	4244	1376.2	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	13/02/2019	n/a	20/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
300–2–1	4245	1093	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	13/02/2019	n/a	20/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
300–2–2	4246	1174.1	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	13/02/2019	n/a	20/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
300–2–3	4247	1429.2	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	13/02/2019	n/a	20/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
350–0.5–1	4248	1019.8	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	n/a	n/a	13/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
350–0.5–2	4249	1108.7	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	13/02/2019	n/a	20/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
350–0.5–3	4250	1154	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	13/02/2019	n/a	20/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
350–1–1	4251	1257.8	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	13/02/2019	20/02/2019	22/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
350–1–2	4252	1168.1	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	13/02/2019	n/a	20/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
350–1– 3	4253	1332.1	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	13/02/2019	n/a	20/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
350–2–1	4254	1298.9	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	13/02/2019	n/a	20/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
350–2–2	4255	1358.3	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	13/02/2019	n/a	20/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
350–2–3	4256	1253.2	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	13/02/2019	n/a	20/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
400–0.5–1	4257	1012.6	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	13/02/2019	n/a	20/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
400–0.5–2	4258	1268.2	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	13/02/2019	n/a	20/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
400–0.5–3	4259	1049.6	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	n/a	n/a	13/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
400–1–1	4260	1107.5	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	13/02/2019	n/a	20/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
400–1–2	4261	1392.3	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	13/02/2019	n/a	20/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
400–1–3	4262	1427.3	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	13/02/2019	20/02/2019	22/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
400–2–1	4263	1217.4	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	13/02/2019	n/a	20/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
400–2–2	4264	1169.4	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	n/a	n/a	13/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019
400–2–3	4265	1359.3	30/01/2019	01/02/2019	04/02/2019	06/02/2019	08/02/2019	11/02/2019	13/02/2019	n/a	20/02/2019	26/02/2019	4:00 pm 26/(	3:30 pm 28/(	28/02/2019

Sample	Isotope Lab Labels	Empty Tube Mass	Mass of Tube + Collagen	Mass of Collagen	% Collagen Yield
Control – 1(p)	4140	6711.1	6919.8	208.7	24.73
Control – 2(c)	4141	6722.3	6942.3	220	23.04
Control – 3(d)	4142	6707.1	6913.6	206.5	25.38
100–0.5–1	4143	6713.8	6952.2	238.4	22.98
100–0.5–2	4144	6700.9	6909.7	208.8	20.64
100–0.5–3	4145	6691.9	6865.1	173.2	20.30
100–1–1	4146	6728.5	6933.1	204.6	20.97
100–1–2	4147	6736.1	6911.2	175.1	17.07
100–1–3	4148	6713.8	6905.8	192	18.15
100–2–1	4149	6693.4	6926.4	233	21.90
100–2–2	4150	6715.8	6924.8	209	20.82
100–2–3	4151	6700.2	6919.4	219.2	20.75
150–0.5–1	4152	6709.2	6945.3	236.1	22.59
150–0.5–2	4153	6698.9	6925.2	226.3	23.12
150–0.5–3	4154	6709.1	6961.7	252.6	21.60
150–1–1	4155	6723.4	6954.8	231.4	20.54
150–1–2	4156	6700.8	6940.9	240.1	22.84
150–1–3	4157	6725.9	6979.2	253.3	21.08
150–2–1	4158	6714.9	6935.8	220.9	20.27
150–2–2	4159	6723.9	6937.7	213.8	18.64
150–2–3	4160	6659.1	6890.5	231.4	22.16
200–0.5–1	4161	6731.7	6961.8	230.1	21.48
200–0.5–2	4162	6764.3	7021.2	256.9	21.33
200–0.5–3	4163	6714.8	6976.5	261.7	21.45
200–1–1	4164	6720.9	6830.1	109.2	9.32
200–1–2	4165	6704.9	6781.2	76.3	7.27
200–1–3	4166	6717.1	6808.9	91.8	8.33
200–2–1	4167	6691.7	6744.3	52.6	4.29
200–2–2	4168	6701.5	6749.1	47.6	4.50
200–2–3	4169	6712.1	6769.6	57.5	5.42
250–0.5–1	4170	6705.8	6809.2	103.4	9.16
250–0.5–2	4171	6763	6831	68	6.53
250–0.5–3	4172	6699.3	6762.8	63.5	6.01
250–1–1	4173	6726.8	6777.5	50.7	4.06
250–1–2	4174	6693.4	6746.2	52.8	4.77
250–1–3	4175	6722.8	6777	54.2	5.24
250–2–1	4176	6768.9	6810.7	41.8	3.11
250–2–2	4177	6719.6	6799.5	79.9	6.21
250-2-3	4178	6711.5	6767.1	55.6	4.58
300–0.5–1	4179	6736.1	6777.2	41.1	3.24
300–0.5–2	4240	6736.8	6765.6	28.8	2.59
300–0.5–3	4241	6703.5	6737.9	34.4	3.03
300–1–1	4242	6696.5	6755.3	58.8	4.42
300–1–2	4243	6674.6	6718.2	43.6	3.72
300–1–3	4244	6718.1	6731.6	13.5	0.98
300–2–1	4245	6715.6	6726	10.4	0.95
300–2–2	4246	6684	6740.1	56.1	4.78
300–2–3	4247	6712.5	6808.5	96	6.72
350–0.5–1	4248	6686.3	6726.1	39.8	3.90
350–0.5–2	4249	6715	6723.8	8.8	0.79
350–0.5–3	4250	6728.5	6741.7	13.2	1.14
350–1–1	4251	6709.8	6719.9	10.1	0.80
350–1–2	4252	6715.8	6741.2	25.4	2.17
350–1– 3	4253	6707.3	6746.7	39.4	2.96
350–2–1	4254	6772.4	6808.6	36.2	2.79
350–2–2	4255	6687.8	6746.2	58.4	4.30
350–2–3	4256	6758.8	6807.8	49	3.91
400–0.5–1	4257	6755.4	6784.6	29.2	2.88
400–0.5–2	4258	6694.5	6736.6	42.1	3.32
400–0.5–3	4259	6699.4	6731.5	32.1	3.06
400–1–1	4260	6708.8	6729.7	20.9	1.89
400–1–2	4261	6762.2	6807.3	45.1	3.24
400–1–3	4262	6710.6	6724.5	13.9	0.97
400–2–1	4263	6758.8	6769.3	10.5	0.86
400–2–2	4264	6714.7	6745.8	31.1	2.66
400–2–3	4265	6685.4	6723.3	37.9	2.79

- Conventions used in numbering the samples reflect heating conditions. The first number is the target temperature, the second number is the length of exposure, the final number is an arbitrary designation to separate the three samples exposed to the same conditions. Thus, sample '100-0.5-1' was the first of three samples heated to 100°C for 0.5 hours.

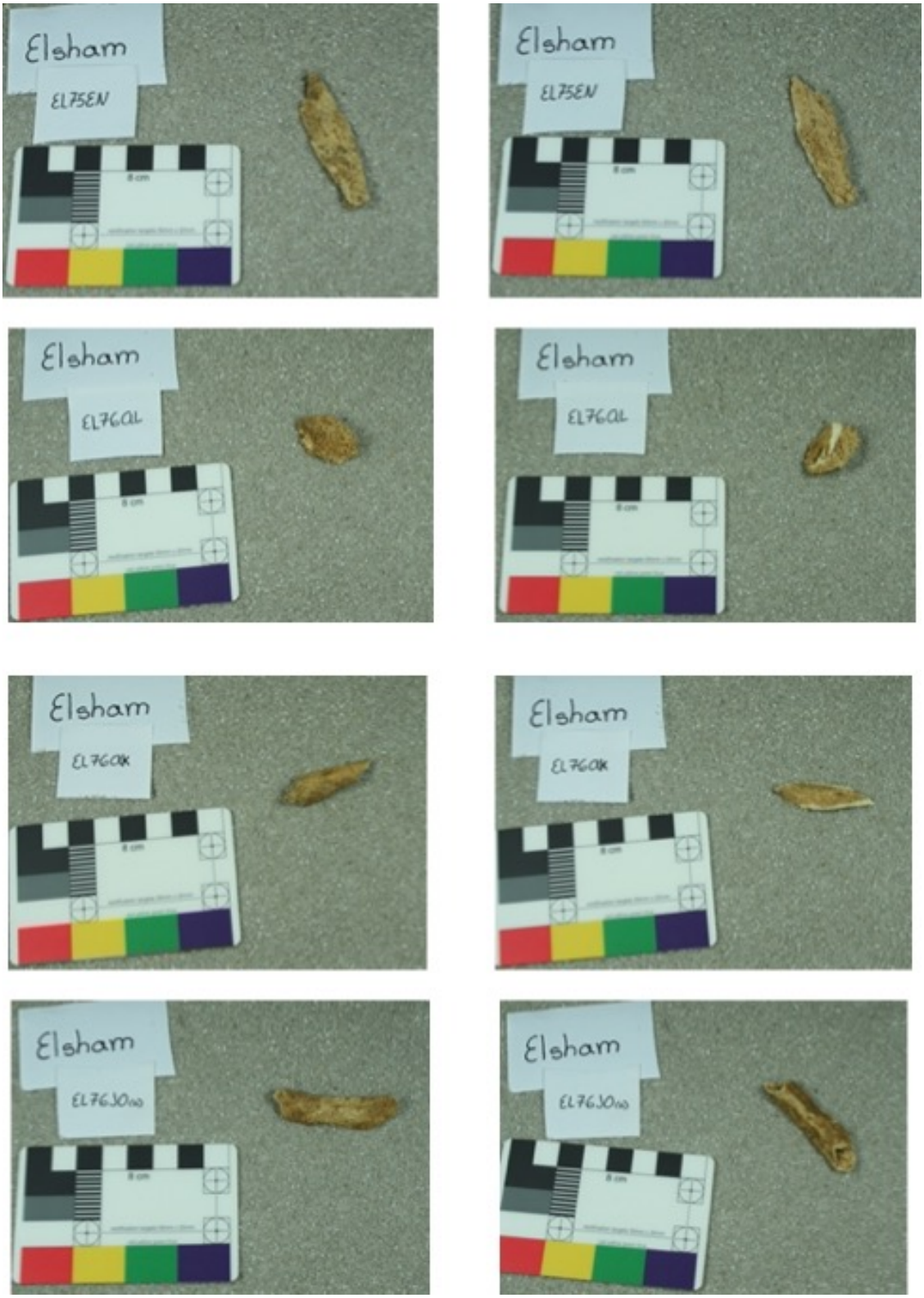
- For the three control samples the letters following the sample number reflect the position along the humeral shaft at which the sample was taken. P = proximal, C = central and D = distal.
- DI = deionised water
- Data available as spreadsheet in supplemental materials.

Appendix 8 – Stable Isotope Analysis Data from Controlled Heating Experiment

Original Labels	SIBL ID	%C	$\delta^{13}C$ (‰)	%N	$\delta^{15}N$ (‰)	C:N atomic	%S	$\delta^{34}S_{corr}$ (‰)	R: %S	R: $\delta^{34}S_{corr}$ (‰)
Control – 1(p)	4140	46.86	-23.71	16.51	6.41	3.3	0.30	4.49		
Control – 2(c)	4141	46.48	-23.66	16.12	6.62	3.4	0.33	4.52		
Control – 3(d)	4142	46.12	-23.84	16.17	6.43	3.3	0.34	4.23		
100–0.5–1	4143	44.98	-23.82	16.12	6.29	3.3	0.29	4.72		
100–0.5–2	4144	48.74	-23.91	17.24	6.25	3.3	0.20	4.45		
100–0.5–3	4145	46.34	-23.52	16.27	6.46	3.3	0.19	4.72		
100–1–1	4146	49.33	-23.88	17.34	6.72	3.3				
100–1–2	4147	46.35	-23.42	16.32	6.50	3.3				
100–1–3	4148	45.58	-23.64	15.98	6.31	3.3	0.35	4.92		
100–2–1	4149	45.40	-23.98	15.86	7.02	3.3	0.36	4.49		
100–2–2	4150	45.13	-23.97	15.69	6.76	3.4	0.31	4.36		
100–2–3	4151	46.87	-23.67	16.29	6.24	3.4	0.23	4.22		
150–0.5–1	4152	46.09	-23.71	15.72	6.75	3.4	0.34	4.35		
150–0.5–2	4153	46.94	-23.81	16.34	6.84	3.4	0.35	4.42		
150–0.5–3	4154	46.68	-23.69	16.05	6.26	3.4	0.33	4.52	0.31	4.06
150–1–1	4155	44.56	-23.71	15.44	6.42	3.4	0.33	4.09		
150–1–2	4156	47.06	-23.85	16.36	6.49	3.4	0.20	4.66		
150–1–3	4157	44.31	-23.68	15.59	6.52	3.3	0.35	4.55		
150–2–1	4158	46.78	-23.68	16.20	6.38	3.4	0.22	4.62		
150–2–2	4159	51.17	-23.88	17.36	6.68	3.4	0.33	4.69		
150–2–3	4160	49.93	-23.64	17.32	6.22	3.4	0.32	4.57		
200–0.5–1	4161	45.08	-23.58	15.70	6.47	3.3	0.34	4.65		
200–0.5–2	4162	48.94	-23.56	17.05	6.37	3.3	0.31	4.83		
200–0.5–3	4163	43.15	-23.58	14.77	6.12	3.4	0.32	4.61		
200–1–1	4164	32.43	-23.75	11.07	6.43	3.4	0.18	4.13		
200–1–2	4165	33.95	-23.75	11.66	6.71	3.4	0.25	4.78		
200–1–3	4166	39.42	-23.81	13.60	6.07	3.4	0.30	5.13		
200–2–1	4167	33.49	-23.76	11.36	6.75	3.4				
200–2–2	4168	42.45	-23.90	14.30	6.83	3.5				
200–2–3	4169	33.76	-23.70	11.66	6.61	3.4	0.20	5.42		
250–0.5–1	4170	40.55	-23.69	13.81	6.60	3.4	0.18	5.38		
250–0.5–2	4171	27.21	-24.38	8.52	6.39	3.7	0.21	4.88		
250–0.5–3	4172	32.47	-23.81	10.68	6.92	3.5	0.14	4.87		
250–1–1	4173	28.62	-23.67	9.39	8.20	3.6	0.23	6.05		
250–1–2	4174	24.88	-23.63	8.21	8.27	3.5	0.20	4.11		
250–1–3	4175	37.31	-23.61	12.26	8.33	3.6	0.19	5.68		
250–2–1	4176	33.71	-23.25	11.21	8.91	3.5	0.16	6.31		
250–2–2	4177	20.35	-23.09	7.10	9.18	3.3	0.16	7.65		
250-2-3	4178	30.39	-23.54	10.43	8.04	3.4	0.12	7.87		
300–0.5–1	4179	39.03	-23.78	11.99	8.47	3.8	0.18	6.23		
300–0.5–2	4240	21.48	-23.66	6.96	8.25	3.6	0.19	6.59		
300–0.5–3	4241	22.67	-23.85	6.91	8.23	3.8				
300–1–1	4242	6.40	-23.01	2.14	10.30	3.5	0.19	2.85		
300–1–2	4243	10.48	-23.32	3.52	10.44	3.5	0.15	3.57		
300–1–3	4244	12.06	-22.91	4.61	11.00	3.1				
300–2–1	4245	20.18	-23.32	8.76	12.94	2.7				
300–2–2	4246	8.02	-23.27	3.31	12.61	2.8				
300–2–3	4247	5.43	-22.96	2.05	11.16	3.1	0.17	4.02		
350–0.5–1	4248	15.65	-23.33	4.37	9.49	4.2	0.13	4.38		
350–0.5–2	4249	24.91	-23.26	8.24	9.89	3.5	0.16	4.36		
350–0.5–3	4250	20.81	-23.06	7.07	10.24	3.4				
350–1–1	4251	2.34	-22.85	0.91	11.72	3.0				
350–1–2	4252	5.53	-22.94	2.03	11.53	3.2				
350–1– 3	4253	4.67	-22.98	1.64	11.33	3.3	0.15	3.55		
350–2–1	4254	2.50	-22.73	0.94	12.11	3.1				
350–2–2	4255	1.44	-22.93	0.61	12.87	2.7	0.14	4.61		
350–2–3	4256	3.42	-22.89	1.38	12.72	2.9	0.15	4.84		
400–0.5–1	4257	8.27	-22.45	2.70	10.42	3.6	0.14	4.15		
400–0.5–2	4258	4.87	-23.27	1.43	10.24	4.0	0.15	4.82		
400–0.5–3	4259	6.93	-22.58	2.19	10.24	3.7	0.14	4.62		
400–1–1	4260	5.83	-22.61	1.89	11.14	3.6	0.14	4.59		
400–1–2	4261	2.19	-22.74	0.76	10.71	3.4	0.15	3.19	0.16	3.71
400–1–3	4262	2.28	-22.52	0.82	10.00	3.3	0.19	2.23	0.14	2.54
400–2–1	4263	1.71	-23.22	0.63	11.17	3.2				
400–2–2	4264	10.48	-23.49	3.42	13.72	3.6	0.22	1.32		
400–2–3	4265	5.06	-22.85	1.91	14.03	3.1	0.17	3.51	0.43	2.66

- Conventions used in numbering the samples reflect heating conditions. The first number is the target temperature, the second number is the length of exposure, the final number is an arbitrary designation to separate the three samples exposed to the same conditions. Thus, sample '100-0.5-1' was the first of three samples heated to 100°C for 0.5 hours.
- For the three control samples the letters following the sample number reflect the position along the humeral shaft at which the sample was taken. P = proximal, C = central and D = distal.
- Two samples (300-2-2 and 400-0.5-1) showed distinct colour variations in the extracted collagen, these were sampled separately for isotope analysis.
- R: %S column and R: $\delta^{34}S_{corr}$ column refer to replicate sample runs.
- %C, %N and %S measured as wt. %
- Data available as spreadsheet in supplemental materials.

Appendix 9 – Photographs of Samples taken from Burials at Elsham and Cleatham




Cleatham
Grave 10


Cleatham
Grave 10


Cleatham
Grave 11


Cleatham
Grave 11


Cleatham
Grave 18


Cleatham
Grave 18


Cleatham
Grave 19


Cleatham
Grave 19


Cleatham
Grave 25


Cleatham
Grave 25


Cleatham
Grave 29


Cleatham
Grave 29


Cleatham
Grave 31


Cleatham
Grave 31


Cleatham
Grave 37


Cleatham
Grave 37


Cleatham
Grave 38


Cleatham
Grave 38


Cleatham
Grave 40


Cleatham
Grave 40


Cleatham
Grave 45


Cleatham
Grave 45


Cleatham
Grave 48


Cleatham
Grave 48


Cleatham
Grave 49


Cleatham
Grave 49


Cleatham
Grave 50


Cleatham
Grave 50


Cleatham
Grave 54


Cleatham
Grave 54


Cleatham
Grave 57


Cleatham
Grave 57


Elsham
EL75aP
Range


Elsham
EL75aP
1


Elsham
EL75aP
1


Elsham
EL75aP
2


Elsham
EL75aP
3


Elsham
EL75aP
2


Elsham
EL75aP
3


Elsham
EL75 DW
Range


Elsham
EL75 DW
1


Elsham
EL75 DW
1


Elsham
EL75 DW
2


Elsham
EL75 DW
3


Elsham
EL75 DW
2


Elsham
EL75 DW
3


Elsham
EL75DX
Range


Elsham
EL75DX
1


Elsham
EL75DX
1


Elsham
EL75DX
2

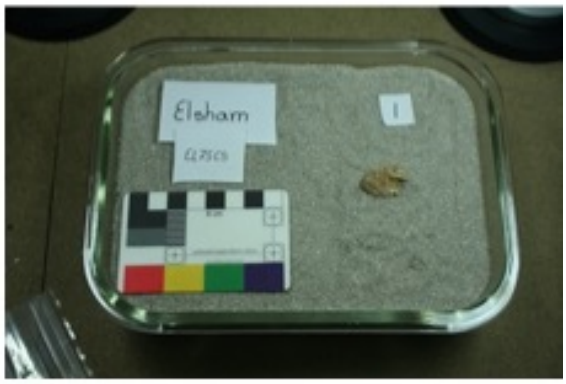

Elsham
EL75DX
3


Elsham
EL75DX
2


Elsham
EL75DX
3

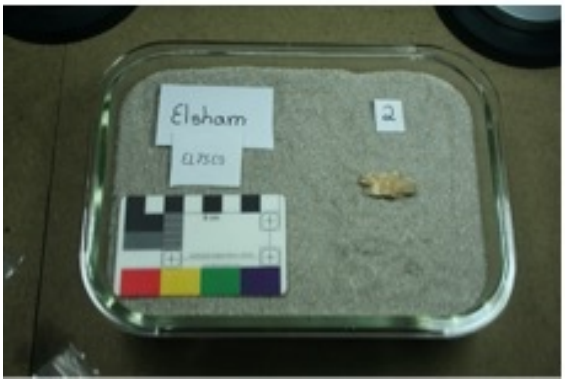

Elsham
Range


Elsham
1

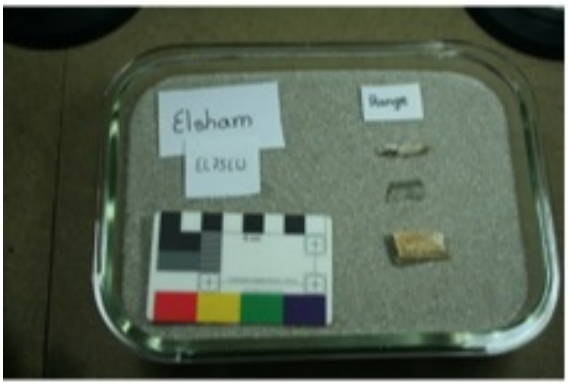

Elsham
1

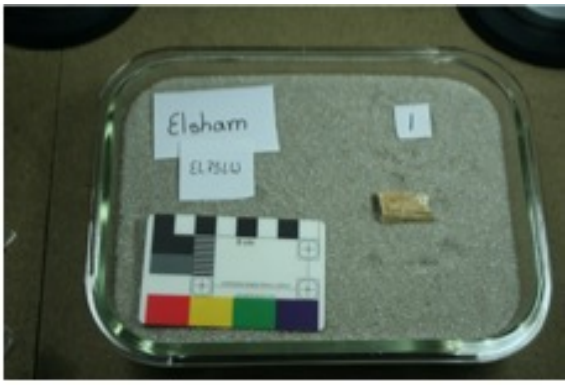

Elsham
2


Elsham
3

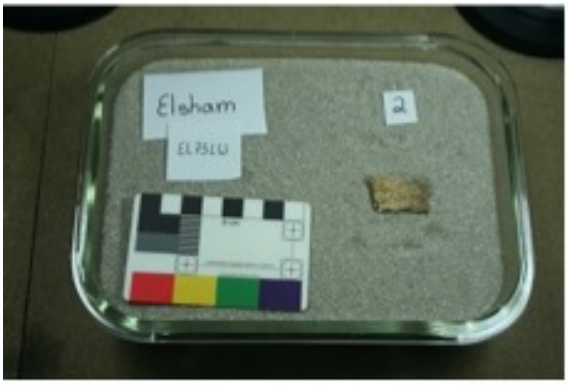

Elsham
2


Elsham
3


Elsham
EL75LU


Elsham
EL75LU
1


Elsham
EL75LU
1


Elsham
EL75LU
2


Elsham
EL75LU
3


Elsham
EL75LU
2


Elsham
EL75LU
3


Elsham


Elsham
1


Elsham
1


Elsham
2


Elsham
3


Elsham
2


Elsham
3


Elsham
EL76 MN
Range


Elsham
EL76 MN
1


Elsham
EL76 MN
1


Elsham
EL76 MN
2

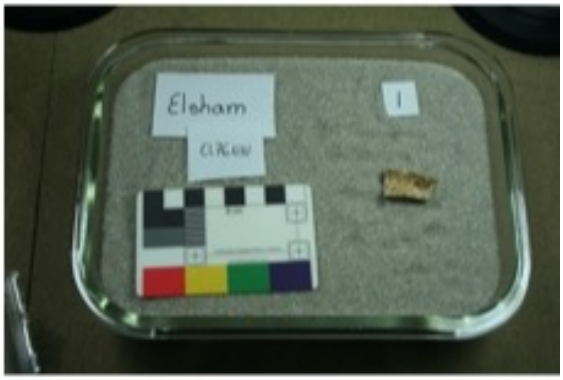

Elsham
EL76 MN
3


Elsham
EL76 MN
2


Elsham
EL76 MN
3


Elsham


Elsham
1


Elsham
1


Elsham
2


Elsham
3


Elsham
2


Elsham
3


Elsham
Range


Elsham
1


Elsham
1


Elsham
2


Elsham
3


Elsham
2


Elsham
3


Elsham


Elsham
1


Elsham
1


Elsham
2


Elsham
3


Elsham
2


Elsham
3


Cleatham
Range


Cleatham
1


Cleatham
1


Cleatham
2


Cleatham
3


Cleatham
2


Cleatham
3


Cleatham
Range


Cleatham
1


Cleatham
1


Cleatham
2


Cleatham
3


Cleatham
2


Cleatham
3


Cleatham
Range


Cleatham
1


Cleatham
1


Cleatham
2


Cleatham
3


Cleatham
2


Cleatham
3


Cleatham
Range


Cleatham
1


Cleatham
1


Cleatham
2


Cleatham
3


Cleatham
1


Cleatham
3


Cleatham
MT185.0R
Range


Cleatham
MT185.0R
1


Cleatham
MT185.0R
1


Cleatham
MT185.0R
2


Cleatham
MT185.0R
3


Cleatham
MT185.0R
2


Cleatham
MT185.0R
3


Cleatham
Range


Cleatham
1


Cleatham
1


Cleatham
2


Cleatham
3


Cleatham
2


Cleatham
3


Cleatham
Range


Cleatham
1


Cleatham
1


Cleatham
2


Cleatham
3


Cleatham
2


Cleatham
3


Cleatham
Range


Cleatham
1


Cleatham
1


Cleatham
2


Cleatham
3


Cleatham
2


Cleatham
3


Cleatham
Range


Cleatham
1


Cleatham
1


Cleatham
2


Cleatham
3


Cleatham
2


Cleatham
3


Cleatham
Range


Cleatham
1


Cleatham
1


Cleatham
2


Cleatham
3


Cleatham
2


Cleatham
3

- Sample designations from original excavations
- Three samples were selected from each cremated individual, labelled arbitrarily as 1, 2, and 3.
- Samples included in photographs to demonstrate range of colours seen in each cremation were only used in photographs and not taken for further analysis.

Appendix 10 – Colour Data from the Archaeological Application

Type	Sample	Light	Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Elsham Inhumation	EL75EN	SCI	L*	68.29	68.80	57.82	61.93	65.69	64.11	59.40	63.18	67.42	64.88	61.40	63.59	68.05	65.94	58.36	64.38	66.54	68.28	63.88	69.70
			a*	5.93	6.58	5.47	6.75	6.03	6.68	4.54	5.67	6.41	7.02	5.77	6.79	6.57	7.24	6.21	7.53	7.52	6.43	6.34	6.22
			b*	21.41	22.68	16.14	19.64	20.36	20.22	15.49	18.06	21.65	21.67	16.82	19.39	19.50	20.48	16.25	20.31	21.42	19.99	18.36	19.83
			G	92	90	90	90	91	91	92	92	94	92	96	96	94	92	94	91	92	92	96	93
		SCE	L*	65.23	65.81	53.84	58.36	62.45	60.74	55.52	59.65	64.21	61.54	57.55	59.96	64.88	62.67	54.22	61.00	63.31	65.21	60.26	66.69
			a*	6.27	6.97	6.00	7.30	6.44	7.19	4.93	6.09	6.80	7.52	6.22	7.28	6.95	7.72	6.79	8.08	8.03	6.82	6.79	6.57
			b*	23.43	24.86	18.56	22.17	22.57	22.57	17.61	20.18	23.82	24.18	18.91	21.64	21.35	22.66	18.63	22.67	23.72	21.92	20.42	21.61
Elsham Inhumation	EL76AL	SCI	L*	60.24	62.10	58.63	56.63	57.61	61.11	60.83	65.20	66.00	60.09	58.59	57.77	57.71	62.56	56.80	57.90	66.14	61.20	64.77	63.48
			a*	5.94	6.96	7.19	7.03	7.72	6.68	7.71	7.17	7.86	6.81	8.31	7.44	8.82	7.36	8.75	5.67	6.83	7.14	7.95	7.17
			b*	19.35	21.92	19.94	18.52	18.61	20.32	21.09	23.99	25.61	21.78	20.28	18.42	20.30	21.57	19.06	17.86	23.33	21.31	24.74	21.48
			G	93	94	94	94	93	94	94	96	94	91	94	93	94	95	93	92	94	94	95	94
		SCE	L*	56.39	58.39	54.55	52.30	53.42	57.31	56.97	61.72	62.64	56.30	54.49	53.64	53.51	58.86	52.52	53.84	62.81	57.40	61.29	59.93
			a*	6.47	7.52	7.88	7.79	8.50	7.24	8.38	7.66	8.39	7.43	9.10	8.20	9.71	7.94	9.67	6.24	7.30	7.75	8.53	7.73
			b*	22.12	24.88	23.05	21.69	21.63	23.16	24.11	26.85	28.66	25.12	23.50	21.41	23.68	24.40	22.37	20.75	25.98	24.32	27.82	24.20
Elsham Inhumation	EL76AK	SCI	L*	65.24	60.86	66.38	66.52	67.33	70.95	63.84	64.18	70.53	63.72	61.15	66.60	62.11	63.76	70.72	67.15	60.09	64.45	66.68	66.38
			a*	9.10	8.89	8.72	7.62	5.19	5.05	8.71	8.66	6.15	7.72	7.18	6.34	6.34	6.37	4.95	5.73	6.76	6.06	6.31	6.30
			b*	26.17	22.79	26.52	24.27	20.06	20.22	24.93	24.77	23.56	23.85	20.15	21.71	19.21	19.85	20.22	19.16	19.33	20.31	20.75	21.21
			G	97	96	97	96	94	98	95	97	96	94	97	99	95	97	96	96	98	100	96	99
		SCE	L*	61.73	56.96	62.96	63.16	64.12	67.88	60.26	60.58	67.50	60.17	58.34	63.12	58.37	60.12	67.71	63.84	55.99	60.75	63.33	62.89
			a*	9.76	9.69	9.33	8.14	5.51	5.32	9.39	9.33	6.50	8.33	7.78	6.76	6.87	6.85	5.22	6.10	7.36	6.50	6.74	6.73
			b*	29.46	26.19	29.69	27.03	22.12	21.98	28.23	28.00	25.78	26.98	22.80	24.05	21.75	22.27	22.03	21.13	22.12	22.68	22.99	23.51
Elsham Inhumation	EL76JO(a)	SCI	L*	58.84	63.94	68.61	68.50	70.96	71.04	59.91	56.82	66.57	67.12	66.44	56.61	60.27	67.06	71.43	56.29	60.99	63.62	56.30	60.09
			a*	9.10	7.51	6.82	6.83	5.67	5.81	7.64	7.01	7.18	6.97	6.63	7.95	8.08	6.86	5.52	7.05	8.74	9.03	7.32	8.36
			b*	20.33	21.53	23.14	21.93	23.03	23.13	20.13	17.59	23.96	22.21	21.34	17.43	20.33	21.77	22.06	16.85	21.12	23.12	17.39	19.93
			G	93	94	95	96	98	99	98	97	99	97	95	94	94	95	97	95	96	97	95	96
		SCE	L*	54.82	60.42	65.44	65.30	67.88	67.93	55.81	52.36	63.12	63.77	63.10	52.30	56.38	63.78	68.44	51.86	57.08	59.96	51.85	56.08
			a*	10.03	8.11	7.26	7.27	5.99	6.13	8.37	7.76	7.67	7.45	7.10	8.84	8.85	7.35	5.82	7.86	9.54	9.78	8.16	9.16
			b*	23.64	24.27	25.54	24.17	25.15	25.26	23.16	20.60	26.71	24.66	23.74	20.53	23.41	24.16	24.06	19.85	24.24	26.21	20.51	22.94

Type	Sample	Light	Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Cleatham Inhumation	Grave 10	SCI	L*	62.05	59.98	58.42	58.86	61.20	58.62	63.15	60.02	58.61	59.17	61.13	59.85	58.32	58.74	57.20	67.14	64.84	70.09	66.40	62.89
			a*	5.37	5.94	6.73	6.69	5.70	6.20	3.54	3.00	5.87	6.54	7.02	6.71	6.75	6.04	3.43	6.01	5.82	5.26	5.91	4.57
			b*	18.64	18.76	17.82	18.44	19.30	17.54	17.43	15.58	17.83	18.63	20.57	19.22	17.99	17.90	15.09	21.48	21.16	23.03	21.89	17.72
		-	G	79	82	84	84	83	84	80	83	84	83	84	83	85	85	84	77	78	76	80	84
		SCE	L*	58.94	56.57	54.77	55.25	57.85	54.97	60.12	56.58	54.96	55.61	57.76	56.37	54.61	55.08	53.39	64.49	62.00	67.67	63.61	59.68
			a*	5.91	6.60	7.55	7.47	6.31	6.93	3.87	3.31	6.56	7.30	7.78	7.46	7.56	6.75	3.84	6.53	6.37	5.68	6.43	5.02
			b*	21.58	22.05	21.18	21.87	22.51	20.81	20.03	18.20	21.15	22.04	24.07	22.65	21.40	21.23	18.00	24.34	24.25	25.79	24.90	20.42
Cleatham Inhumation	Grave 11	SCI	L*	56.14	53.74	49.96	50.63	49.64	51.30	53.35	59.33	59.02	62.47	54.97	56.03	55.65	51.66	53.89	55.78	48.82	54.05	59.81	52.03
			a*	4.87	3.97	1.99	1.23	0.91	0.60	0.52	1.97	1.45	1.52	3.88	4.61	4.63	4.57	4.85	4.82	2.42	4.66	4.03	3.58
			b*	16.49	14.25	8.74	7.76	6.63	6.39	6.11	15.42	13.87	15.31	14.34	16.07	14.97	12.51	14.08	15.34	9.58	15.04	16.52	12.42
		-	G	85	89	92	93	94	93	91	91	89	85	90	90	92	92	90	87	97	90	80	92
		SCE	L*	52.20	49.28	44.69	45.41	44.18	46.22	48.70	55.47	55.19	59.17	50.63	51.80	51.29	46.69	49.41	51.68	43.03	49.55	56.48	47.12
			a*	5.50	4.53	2.28	1.35	0.98	0.63	0.51	2.16	1.58	1.65	4.38	5.18	5.22	5.25	5.52	5.44	2.80	5.30	4.47	4.09
			b*	19.88	17.47	11.02	9.70	8.39	7.97	7.48	18.03	16.29	17.62	17.35	19.27	18.00	15.58	17.21	18.52	12.13	18.35	19.40	15.35
Cleatham Inhumation	Grave 18	SCI	L*	58.84	59.68	58.06	68.03	63.13	69.31	66.83	59.19	62.24	56.99	59.12	58.53	58.77	63.48	58.63	56.44	59.11	68.39	63.00	66.41
			a*	5.53	5.74	5.96	6.19	6.31	5.42	5.07	6.51	4.99	5.81	6.23	7.16	6.00	5.68	7.16	6.95	5.73	8.68	8.82	7.91
			b*	16.74	17.87	17.54	22.33	19.85	22.98	20.49	18.49	18.07	17.00	18.14	18.75	17.66	19.48	18.39	17.05	18.10	24.46	21.37	24.64
		-	G	86	82	84	78	80	77	78	83	82	84	84	83	84	81	83	85	83	77	80	77
		SCE	L*	55.16	56.25	54.37	65.43	60.10	66.83	64.15	55.65	59.04	53.16	55.52	54.91	55.14	60.41	55.03	52.52	55.58	65.83	59.94	63.72
			a*	6.15	6.40	6.67	6.70	6.93	5.84	5.50	7.27	5.49	6.55	6.95	8.01	6.69	6.22	8.01	7.86	6.40	9.37	9.69	8.60
			b*	19.74	21.05	20.89	25.19	22.92	25.81	23.22	21.86	20.92	20.43	21.45	22.34	20.92	22.43	21.86	20.58	21.41	27.62	24.79	28.12
Cleatham Inhumation	Grave 19	SCI	L*	71.79	75.11	69.49	75.99	68.94	73.38	73.02	75.90	70.99	75.36	65.74	67.82	70.83	69.67	69.86	70.95	68.37	68.93	69.70	65.42
			a*	8.47	7.18	8.02	6.54	8.57	8.10	7.02	6.85	8.39	6.88	6.98	6.47	6.06	6.63	5.84	6.28	7.83	6.02	5.69	7.20
			b*	27.58	28.27	25.31	27.84	26.15	28.13	26.70	28.51	27.12	27.70	22.37	21.84	22.10	23.42	22.44	23.30	23.28	23.12	22.68	21.74
		-	G	73	73	76	70	75	73	72	71	74	71	79	79	75	76	78	77	76	78	76	81
		SCE	L*	69.56	73.05	67.02	74.06	66.48	71.22	70.89	73.92	68.69	73.35	62.92	65.16	68.47	67.22	67.37	68.54	65.85	66.36	67.26	62.52
			a*	9.09	7.66	8.65	6.97	9.25	8.66	7.52	7.30	9.01	7.34	7.60	6.99	6.51	7.14	6.29	6.74	8.45	6.49	6.13	7.84
			b*	30.81	31.17	28.45	30.64	29.53	31.21	29.64	31.38	30.36	30.52	25.52	24.62	24.62	26.24	25.07	25.94	26.22	25.96	25.39	24.84
Cleatham Inhumation	Grave 25	SCI	L*	62.44	55.88	61.01	60.73	62.31	67.02	61.17	60.85	62.41	58.59	65.36	68.29	65.57	67.41	63.24	66.06	66.67	68.01	65.62	66.78
			a*	6.06	5.44	5.16	5.57	6.66	7.63	6.94	7.58	6.24	5.09	5.78	4.77	6.08	4.99	6.56	4.51	5.71	4.59	6.80	6.32
			b*	19.39	14.82	17.04	17.83	18.80	21.14	17.89	17.44	17.78	15.51	19.83	19.52	20.72	19.76	19.70	19.49	20.37	20.00	20.68	21.33
		-	G	83	86	82	83	81	80	83	82	81	83	80	79	78	79	81	78	77	76	79	80
		SCE	L*	59.23	51.85	57.72	57.34	59.17	64.29	57.84	57.52	59.27	54.99	62.49	65.65	62.80	64.72	60.17	63.31	64.02	65.47	62.82	64.03
			a*	6.66	6.17	5.70	6.17	7.33	8.30	7.68	8.40	6.88	5.70	6.30	5.16	6.63	5.40	7.20	4.89	6.21	4.97	7.41	6.84
			b*	22.46	17.92	19.89	20.84	21.80	23.99	20.87	20.39	20.59	18.37	22.62	21.94	23.63	22.27	22.73	22.15	23.09	22.53	23.58	24.17
Cleatham Inhumation	Grave 29	SCI	L*	70.98	66.16	75.09	70.11	62.33	62.16	69.00	61.65	60.70	71.39	72.21	68.22	84.20	79.45	69.05	60.13	67.68	74.31	74.31	73.50
			a*	7.47	6.75	6.49	8.37	7.98	8.36	8.79	6.94	9.39	7.92	4.92	6.23	1.94	3.12	5.35	5.35	7.51	5.32	4.16	5.63
			b*	23.88	20.55	25.39	26.78	22.37	21.84	27.06	19.68	22.20	26.41	21.34	18.82	20.27	20.99	21.20	16.77	23.42	22.59	21.07	23.02
		-	G	74	80	75	76	82	82	80	83	82	76	72	76	64	71	81	84	80	73	73	74
		SCE	L*	68.66	63.35	72.95	67.71	59.13	58.97	66.38	58.35	57.34	69.06	70.05	65.68	82.73	77.62	66.41	56.66	64.97	72.21	72.22	71.34
			a*	8.02	7.36	6.90	9.02	8.78	9.21	9.48	7.67	10.41	8.51	5.29	6.75	2.05	3.31	5.79	5.93	8.15	5.69	4.45	6.04
			b*	26.66	23.39	27.90	30.13	26.09	25.46	30.55	22.92	26.16	29.52	23.67	21.18	21.78	22.77	23.78	19.66	26.52	24.92	23.21	25.47
Cleatham Inhumation	Grave 31	SCI	L*	56.88	56.28	59.19	58.40	53.00	58.50	58.56	57.12	57.85	57.66	61.79	61.04	60.22	52.62	53.00	55.34	57.06	59.93	65.45	57.03
			a*	6.55	6.51	6.26	5.98	5.43	6.74	6.64	6.51	5.94	6.20	5.68	6.12	4.96	4.31	5.39	5.33	3.49	5.83	4.96	5.60
			b*	16.71	16.36	18.17	16.68	13.12	17.18	18.69	17.02	17.46	16.63	17.56	19.30	17.24	13.96	14.84	15.98	13.20	17.92	17.87	15.83
		-	G	84	85	82	84	88	85	84	84	84	84	82	81	83	88	87	85	85	82	79	85
		SCE	L*	53.08	52.36	55.69	54.73	48.46	54.83	54.93	53.32	54.14	53.91	58.57	57.76	56.80	48.04	48.49	51.26	53.22	56.51	62.61	53.17
			a*	7.40	7.37	6.99	6.70	6.27	7.55	7.43	7.35	6.68	6.96	6.28	6.77	5.50	4.96	6.21	6.05	3.92	6.48	5.42	6.31
			b*	20.10	19.74	21.52	19.81	16.24	20.43	22.24	20.44	20.87	19.87	20.40	22.59	20.24	17.35	18.43	19.43	15.76	21.11	20.37	18.97

Type	Sample	Light	Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Cleatham Inhumation	Grave 37	SCI	L*	58.62	64.12	59.42	59.66	57.89	60.81	61.36	59.28	59.15	58.31	57.94	58.88	61.49	57.84	57.83	57.52	57.92	61.19	63.46	62.53
			a*	6.13	7.56	6.72	7.50	7.44	7.60	7.36	7.19	6.08	6.17	5.93	6.44	6.97	6.69	6.40	6.51	5.59	6.36	4.74	5.33
			b*	18.82	22.73	19.13	20.51	19.13	21.16	21.00	19.84	18.28	18.56	17.44	19.16	20.65	18.64	18.25	18.10	17.38	19.91	18.03	18.73
		-	G	84	81	83	85	86	84	83	83	83	86	84	84	82	85	84	85	85	82	79	83
		SCE	L*	55.00	61.09	55.91	56.11	54.08	57.41	58.04	55.76	55.60	54.55	54.24	55.29	58.24	54.09	54.10	53.73	54.18	57.89	60.48	59.31
			a*	6.86	8.29	7.50	8.35	8.35	8.43	8.14	8.03	6.79	6.89	6.65	7.19	7.71	7.51	7.20	7.33	6.27	7.04	5.22	5.87
			b*	22.40	26.22	22.64	24.28	22.89	24.89	24.60	23.54	21.68	22.09	20.83	22.77	24.17	22.32	21.85	21.72	20.74	23.30	20.77	21.68
Cleatham Inhumation	Grave 38	SCI	L*	65.72	67.38	64.43	69.15	66.89	70.67	66.27	63.96	67.89	64.15	60.26	63.89	62.68	63.97	66.60	53.71	60.01	61.02	58.73	66.10
			a*	8.99	7.06	8.46	6.85	7.32	6.72	7.62	8.96	8.18	7.52	5.83	6.03	5.81	7.32	6.43	6.82	7.17	6.17	5.77	5.75
			b*	24.86	22.12	22.61	23.08	22.18	23.71	22.91	23.45	24.34	21.42	17.93	19.55	18.83	21.32	21.63	16.37	19.87	18.51	17.48	20.05
		-	G	80	76	79	79	78	76	78	82	77	79	84	77	82	80	80	87	83	82	86	79
		SCE	L*	62.88	64.79	61.53	66.58	64.21	68.29	63.53	60.92	65.29	61.21	56.80	61.00	59.52	60.98	63.81	49.36	56.57	57.72	55.03	63.31
			a*	9.80	7.68	9.27	7.40	7.98	7.24	8.32	9.83	8.88	8.25	6.48	6.63	6.39	8.04	6.98	7.83	7.98	6.85	6.43	6.27
			b*	28.50	25.09	26.04	25.92	25.21	26.50	26.18	27.13	27.58	24.67	21.02	22.50	21.77	24.54	24.53	20.27	23.43	21.60	20.69	22.77
Cleatham Inhumation	Grave 40	SCI	L*	60.54	58.11	61.41	62.29	65.94	63.16	58.31	52.84	61.63	60.61	65.74	66.47	63.11	63.10	62.46	66.67	67.47	64.23	65.18	61.87
			a*	7.56	6.66	7.52	6.62	6.97	7.64	6.33	6.22	6.91	6.28	7.27	7.90	7.70	8.32	7.78	8.50	8.06	7.76	7.33	7.62
			b*	21.10	18.80	21.76	21.12	23.41	22.70	18.93	15.74	21.15	19.99	22.91	23.28	21.49	21.96	21.07	24.01	24.02	21.97	22.10	20.53
		-	G	80	81	80	80	77	78	82	86	80	82	76	75	78	80	81	76	77	80	77	82
		SCE	L*	57.26	54.55	58.23	59.19	63.21	60.20	54.73	48.38	58.43	57.28	63.02	63.85	60.14	60.04	59.30	64.04	64.87	61.28	62.39	58.63
			a*	8.35	7.43	8.27	7.25	7.55	8.37	7.05	7.11	7.59	6.91	7.90	8.56	8.43	9.09	8.51	9.20	8.71	8.46	7.97	8.36
			b*	24.91	22.52	25.53	24.58	26.78	26.39	22.64	19.68	24.74	23.50	26.21	26.54	24.91	25.46	24.49	27.37	27.28	25.30	25.34	23.93
Cleatham Inhumation	Grave 45	SCI	L*	57.46	61.63	63.80	65.36	65.68	65.97	61.75	58.71	56.54	64.21	58.13	68.18	68.85	70.77	68.38	70.40	68.17	68.51	69.00	64.06
			a*	4.72	6.43	7.65	8.28	8.07	7.64	6.62	5.53	4.61	6.81	4.56	6.66	7.63	6.65	7.38	7.19	6.69	6.51	7.30	5.83
			b*	13.56	17.96	21.88	23.37	23.06	23.93	19.83	16.75	13.29	19.77	14.12	22.46	23.93	23.96	23.50	24.00	24.99	22.83	24.33	19.32
		-	G	82	79	78	77	75	76	79	80	83	78	80	74	75	74	75	74	76	75	74	77
		SCE	L*	53.77	58.49	60.89	62.62	63.01	63.28	58.63	55.26	52.71	61.32	54.61	65.71	66.40	68.46	65.88	68.08	65.64	66.01	66.58	61.20
			a*	5.27	7.06	8.33	8.99	8.75	8.27	7.27	6.15	5.15	7.41	5.05	7.18	8.21	7.13	7.94	7.71	7.21	7.00	7.85	6.35
			b*	16.22	20.95	25.27	26.81	26.41	27.39	23.13	19.90	15.99	22.72	16.81	25.36	27.00	26.82	26.55	26.89	28.29	25.75	27.41	22.23
Cleatham Inhumation	Grave 48	SCI	L*	68.81	64.79	65.06	63.93	66.86	69.22	55.60	61.37	69.04	64.60	64.18	61.55	64.66	59.41	58.88	63.91	56.64	57.49	65.26	58.24
			a*	6.39	5.21	6.14	6.74	5.51	5.86	6.04	6.17	5.75	6.27	7.13	7.48	7.00	6.41	6.66	6.79	6.15	7.30	6.96	6.57
			b*	21.41	18.43	19.37	19.88	20.43	22.36	16.72	18.85	21.70	20.27	20.19	20.27	19.55	18.59	18.22	20.11	17.39	18.56	21.09	17.86
		-	G	74	79	77	76	75	68	90	82	76	80	79	80	80	82	84	78	85	86	79	85
		SCE	L*	66.37	61.92	62.29	61.11	64.26	67.01	51.32	58.08	66.54	61.68	61.27	58.37	61.75	55.93	55.26	60.99	52.76	53.64	62.42	54.52
			a*	6.86	5.64	6.68	7.35	5.96	6.32	6.74	6.76	6.18	6.80	7.77	8.19	7.60	7.10	7.36	7.40	6.86	8.09	7.53	7.27
			b*	24.07	21.07	22.15	22.90	23.17	25.17	20.17	21.97	24.36	23.21	23.19	23.67	22.37	21.99	21.59	23.14	20.93	22.20	24.07	21.24
Cleatham Inhumation	Grave 49	SCI	L*	66.16	63.98	64.20	65.63	62.74	61.26	65.96	62.52	68.47	63.91	56.65	61.70	64.53	66.71	58.07	46.37	52.33	58.77	55.41	63.53
			a*	6.74	6.56	5.63	6.34	6.52	5.93	5.74	6.12	5.81	7.15	4.87	5.06	5.30	6.33	5.00	4.28	4.90	4.90	4.26	6.40
			b*	22.95	21.26	20.94	22.59	20.86	20.21	22.00	21.08	24.16	22.35	16.52	18.74	21.14	23.51	17.06	10.49	14.57	16.65	14.59	21.93
		-	G	75	77	78	76	78	79	76	78	73	77	81	77	76	77	83	89	86	80	80	77
		SCE	L*	63.51	61.10	61.33	62.94	59.72	58.09	63.28	59.49	66.06	61.04	52.93	58.65	61.74	64.06	54.44	40.60	47.80	55.33	51.60	60.64
			a*	7.30	7.16	6.14	6.88	7.14	6.52	6.21	6.70	6.26	7.79	5.44	5.55	5.76	6.84	5.54	5.09	5.59	5.43	4.80	6.99
			b*	26.21	24.53	24.11	25.87	24.23	23.68	25.11	24.52	27.32	25.84	19.94	21.88	24.33	26.79	20.33	14.12	18.25	19.78	17.79	25.40
Cleatham Inhumation	Grave 50	SCI	L*	59.09	59.59	62.42	58.40	58.88	58.36	59.36	60.78	59.26	59.76	67.38	64.50	59.03	58.10	61.09	59.62	60.51	61.02	59.76	66.37
			a*	7.96	6.55	6.21	4.80	6.25	7.54	7.39	8.07	6.40	7.60	7.36	5.51	5.14	3.62	5.88	7.11	6.83	5.46	5.34	7.71
			b*	19.17	18.44	20.06	15.77	17.51	17.96	19.26	20.37	18.45	20.16	25.55	19.59	16.59	14.97	20.02	19.76	19.91	17.54	16.08	25.17
		-	G	79	81	78	82	81	79	78	80	82	80	75	78	81	84	80	81	77	80	80	76
		SCE	L*	55.71	56.20	59.40	54.85	55.42	54.91	56.07	57.51	55.80	56.42	64.84	61.66	55.55	54.40	57.87	56.23	57.34	57.78	56.42	63.72
			a*	8.84	7.25	6.81	5.33	6.92	8.40	8.20	8.90	7.10	8.42	7.94	5.98	5.69	3.99	6.47	7.86	7.54	6.01	5.88	8.35
			b*	22.80	21.83	23.33	18.73	20.79	21.44	22.86	23.96	21.85	23.87	29.05	22.47	19.65	17.76	23.46	23.38	23.50	20.50	18.91	28.75

Type	Sample	Light	Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Cleatham Inhumation	Grave 54	SCI	L*	61.69	64.39	64.72	63.49	64.58	66.23	64.15	64.56	64.69	64.27	58.54	62.98	60.41	62.75	62.33	62.21	64.99	65.40	60.78	58.30
			a*	4.08	3.45	3.63	4.56	4.20	3.36	3.13	3.41	4.26	3.41	6.22	4.24	4.52	4.38	7.74	4.11	3.36	3.92	5.05	5.41
			b*	16.52	15.93	16.80	18.87	18.67	17.53	15.38	17.04	18.59	16.93	18.50	17.88	16.32	17.07	21.98	16.43	16.86	18.72	17.97	17.60
		-	G	78	76	77	79	78	76	77	75	79	76	81	79	79	77	77	78	76	78	81	82
		SCE	L*	58.61	61.60	61.93	60.51	61.71	63.58	61.31	61.80	61.81	61.47	55.05	59.96	57.16	59.80	59.33	59.19	62.23	62.62	57.51	54.70
			a*	4.46	3.74	3.92	4.96	4.55	3.61	3.38	3.70	4.61	3.69	6.91	4.62	4.97	4.78	8.49	4.48	3.63	4.23	5.56	6.00
			b*	19.21	18.22	19.21	21.72	21.38	19.89	17.61	19.51	21.25	19.40	22.04	20.64	19.14	19.73	25.63	19.04	19.24	21.33	21.02	20.95
Cleatham Inhumation	Grave 57	SCI	L*	59.31	64.34	65.59	69.88	57.00	66.99	63.50	64.69	65.76	62.31	68.51	63.75	63.33	64.40	62.56	64.57	62.85	63.65	63.86	62.84
			a*	8.60	8.15	7.87	5.53	7.99	7.80	9.10	8.25	7.81	8.17	6.77	8.50	8.89	8.95	7.94	7.37	7.42	9.12	8.84	9.03
			b*	21.68	23.44	23.86	21.70	20.43	24.74	24.49	23.77	23.98	22.83	23.06	24.29	23.93	24.55	23.05	23.89	22.78	24.73	24.68	23.83
		-	G	82	78	76	74	81	75	77	77	77	77	76	78	79	78	77	76	76	78	80	76
		SCE	L*	55.83	61.49	62.87	67.51	53.34	64.41	60.60	61.87	63.03	59.31	65.98	60.82	60.35	61.54	59.59	61.79	59.94	60.72	60.87	59.91
			a*	9.52	8.89	8.55	5.93	8.95	8.45	9.96	8.98	8.48	8.97	7.30	9.27	9.70	9.76	8.70	8.03	8.13	9.96	9.63	9.91
			b*	25.80	27.06	27.37	24.30	24.80	28.19	28.49	27.38	27.46	26.69	26.00	28.18	27.80	28.37	26.91	27.55	26.55	28.71	28.59	27.84

Type	Sample	Light	Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Elsham Cremation	EL75AP 1	SCI	L*	68.05	67.10	59.00	67.79	64.54	53.38	53.37	53.29	68.29	71.89	54.82	52.19	55.81	25.78	30.80	56.10	48.54	57.88	68.82	55.35
			a*	6.49	5.97	8.90	6.51	7.85	8.05	7.95	8.55	6.55	4.42	6.42	9.83	7.77	6.62	5.80	8.08	8.71	6.52	4.93	8.91
			b*	23.85	22.19	23.31	22.63	25.45	22.89	20.76	20.88	21.55	18.45	19.72	23.79	22.27	16.07	15.84	21.68	21.33	20.77	20.69	23.21
		-	G	###	###	###	###	2	2	1	###	###	###	###	###	###	5	5	2	0	0	2	0
		SCE	L*	68.26	67.37	59.12	68.02	64.47	53.29	53.35	53.45	68.41	72.21	54.90	52.48	55.98	25.05	30.31	56.02	48.57	57.92	68.75	55.36
			a*	6.52	5.99	8.91	6.54	7.85	8.05	7.96	8.57	6.56	4.45	6.44	9.87	7.81	6.60	5.78	8.08	8.72	6.52	4.92	8.92
			b*	23.83	22.18	23.30	22.63	25.36	22.82	20.71	20.88	21.51	18.45	19.71	23.85	22.32	15.90	15.74	21.62	21.31	20.73	20.59	23.17
Elsham Cremation	EL75AP 2	SCI	L*	44.37	59.85	54.13	49.14	54.81	53.85	59.26	52.21	45.76	47.21	52.94	50.39	45.84	50.15	54.17	55.18	43.71	51.66	47.09	51.64
			a*	3.83	6.22	7.61	6.06	7.57	7.10	4.11	6.40	6.48	5.74	4.38	6.75	7.31	4.48	5.03	5.53	7.31	5.17	5.54	5.57
			b*	13.21	19.07	21.62	17.83	21.42	19.75	14.74	18.93	16.71	17.18	17.38	18.16	19.12	16.04	18.07	17.14	19.37	17.40	18.51	16.95
		-	G	6	0	0	0	2	1	3	0	0	2	1	3	0	0	0	###	0	4	3	1
		SCE	L*	44.00	59.89	54.17	49.18	54.73	53.79	59.12	52.21	45.74	47.10	52.89	50.25	45.82	50.13	54.20	55.27	43.69	51.46	46.95	51.57
			a*	3.82	6.23	7.62	6.08	7.57	7.10	4.12	6.41	6.49	5.75	4.40	6.74	7.31	4.49	5.04	5.55	7.33	5.20	5.55	5.57
			b*	13.09	19.02	21.58	17.79	21.35	19.69	14.66	18.89	16.71	17.16	17.33	18.06	19.10	16.02	18.04	17.13	19.33	17.37	18.45	16.88
Elsham Cremation	EL75AP 3	SCI	L*	45.65	56.07	55.53	41.97	54.45	58.19	45.45	55.36	58.94	60.10	43.75	48.49	54.43	54.22	54.34	45.24	48.82	44.14	45.42	54.04
			a*	6.32	5.32	5.74	4.41	6.59	5.14	6.09	6.01	5.90	6.33	7.05	7.09	6.69	6.87	6.82	6.21	5.63	4.98	4.58	6.19
			b*	16.62	17.00	17.84	12.51	19.36	17.87	17.07	20.08	19.32	20.49	19.91	18.81	20.02	20.87	20.43	17.77	18.62	16.22	14.15	18.95
		-	G	3	1	1	2	###	0	3	2	0	###	2	0	###	0	0	1	0	2	2	1
		SCE	L*	45.49	56.02	55.50	41.85	54.73	58.20	45.30	55.28	58.94	60.33	43.59	48.55	54.52	54.22	54.39	45.20	48.88	44.04	45.27	53.98
			a*	6.31	5.33	5.75	4.44	6.62	5.15	6.09	6.01	5.91	6.34	7.06	7.10	6.72	6.87	6.85	6.22	5.65	5.00	4.59	6.21
			b*	16.57	16.95	17.79	12.50	19.38	17.82	17.03	20.00	19.26	20.48	19.86	18.78	20.02	20.84	20.42	17.73	18.59	16.18	14.10	18.89
Elsham Cremation	EL75DW 1	SCI	L*	48.72	51.21	49.76	53.44	52.04	53.89	53.37	48.76	49.17	53.36	43.06	40.86	44.41	49.44	42.81	47.15	41.45	44.66	43.45	45.65
			a*	5.41	3.49	3.16	2.88	3.32	3.51	3.30	3.83	5.38	3.01	3.80	3.32	4.54	2.26	3.59	3.10	3.98	4.28	3.06	2.92
			b*	16.45	14.10	12.62	13.40	13.12	15.09	13.90	12.96	16.40	13.50	12.64	11.31	14.50	10.32	12.01	11.68	12.41	14.11	11.09	10.90
		-	G	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	2	0	1	0	0
		SCE	L*	48.75	51.25	49.77	53.46	52.07	53.91	53.42	48.80	49.20	53.43	43.06	40.82	44.35	49.48	42.76	47.02	41.47	44.62	43.45	45.70
			a*	5.43	3.50	3.17	2.90	3.34	3.52	3.31	3.85	5.39	3.02	3.84	3.32	4.55	2.27	3.59	3.11	3.99	4.30	3.08	2.94
			b*	16.42	14.07	12.50	13.37	13.10	15.06	13.88	12.93	16.39	13.47	12.64	11.29	14.51	10.30	12.00	11.65	12.42	14.12	11.08	10.88
Elsham Cremation	EL75DW 2	SCI	L*	51.27	48.33	53.14	48.65	48.08	48.96	49.79	50.80	45.14	49.21	46.43	42.15	42.84	37.50	36.14	35.37	39.39	36.58	39.29	36.48
			a*	4.40	3.77	2.58	2.95	3.06	4.74	2.60	2.70	7.19	4.83	3.92	4.74	5.25	3.52	3.80	3.55	3.39	4.15	6.58	3.10
			b*	13.75	12.44	10.43	11.45	11.11	13.83	10.43	12.36	16.94	13.51	12.76	13.64	13.88	11.57	11.12	11.39	11.34	11.71	16.23	11.41
		-	G	0	0	0	0	0	0	0	0	0	0	0	0	###	0	0	0	0	0	0	2
		SCE	L*	51.32	48.37	53.16	48.68	48.12	49.02	49.79	50.86	45.17	49.26	46.50	42.24	42.94	37.54	36.18	35.39	39.41	36.63	39.37	36.35
			a*	4.42	3.77	2.60	2.97	3.08	4.75	2.61	2.72	7.20	4.84	3.94	4.75	5.26	3.51	3.80	3.55	3.40	4.16	6.60	3.11
			b*	13.74	12.43	10.41	11.45	11.10	13.81	10.41	12.34	16.93	13.49	12.73	13.65	13.87	11.58	11.15	11.40	11.35	11.73	16.26	11.40
Elsham Cremation	EL75DW 3	SCI	L*	56.15	56.80	52.01	47.21	48.02	45.99	56.14	55.26	53.29	56.55	50.07	50.05	30.83	34.15	39.53	41.89	43.55	39.33	37.40	35.98
			a*	1.07	1.26	2.97	3.08	2.93	3.20	1.36	1.25	1.30	0.68	2.44	0.56	2.01	2.12	1.31	1.89	1.34	1.68	2.80	1.99
			b*	7.16	7.78	10.74	9.96	10.42	10.62	7.59	7.26	7.46	6.80	10.33	4.72	7.99	7.69	6.80	5.92	7.81	7.59	10.29	8.62
		-	G	###	###	0	0	0	0	###	0	0	###	0	0	4	3	2	4	0	0	1	2
		SCE	L*	56.24	56.87	52.05	47.20	47.99	46.00	56.23	55.33	53.35	56.62	50.10	50.07	30.44	33.84	39.39	41.62	43.60	39.30	37.30	35.85
			a*	1.09	1.27	2.97	3.10	2.96	3.21	1.38	1.26	1.31	0.70	2.46	0.58	2.01	2.13	1.33	1.91	1.34	1.69	2.82	2.01
			b*	7.12	7.74	10.72	9.93	10.40	10.59	7.56	7.23	7.40	6.76	10.32	4.69	8.00	7.66	6.78	5.93	7.82	7.59	10.28	8.63
Elsham Cremation	EL75DX 1	SCI	L*	41.38	38.72	44.53	31.56	35.31	40.49	39.22	36.40	37.19	45.19	31.95	36.73	34.24	31.20	31.43	31.82	26.85	36.38	34.61	34.54
			a*	1.38	2.45	3.06	1.76	1.77	0.89	1.84	2.45	2.54	1.12	2.98	4.08	3.40	3.47	3.96	5.22	3.21	4.20	2.28	3.84
			b*	7.62	9.92	10.43	7.23	8.19	6.03	8.13	9.13	10.04	8.01	8.90	12.03	10.50	10.06	11.36	13.86	8.91	11.72	8.40	11.67
		-	G	4	3	###	4	4	###	###	2	3	5	0	1	0	1	2	1	1	0	0	0
		SCE	L*	41.09	38.46	44.74	31.17	34.93	40.61	39.40	36.26	36.94	44.89	31.93	36.68	34.21	31.14	31.25	31.74	26.76	36.39	34.64	34.52
			a*	1.39	2.46	3.09	1.76	1.79	0.92	1.86	2.46	2.55	1.13	3.00	4.08	3.39	3.48	3.96	5.25	3.21	4.21	2.29	3.84
			b*	7.63	9.88	10.43	7.23	8.21	6.01	8.14	9.13	10.03	7.98	8.89	12.03	10.50	10.06	11.30	13.86	8.93	11.70	8.40	11.66

Type	Sample	Light	Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Elsham Cremation	EL75DX 2	SCI	L*	44.50	43.52	46.25	49.60	45.88	44.99	44.50	46.01	46.04	45.10	44.93	44.80	38.80	39.26	42.80	41.71	40.10	39.47	43.07	39.79
			a*	2.85	3.71	3.62	2.61	3.80	2.84	4.67	3.15	3.25	4.27	4.09	4.10	4.21	4.52	3.53	2.44	4.03	5.21	4.78	4.58
			b*	9.10	9.98	9.59	8.71	10.81	9.40	13.10	10.42	11.01	11.17	13.86	13.77	13.45	13.70	12.36	10.01	12.82	14.34	14.26	14.40
		-	G	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1	0	1	1
		SCE	L*	44.47	43.51	46.27	49.61	45.89	45.02	44.47	45.98	46.02	45.09	44.98	44.71	38.72	39.29	42.77	41.73	40.06	39.48	42.98	39.74
			a*	2.86	3.71	3.64	2.63	3.82	2.85	4.70	3.16	3.27	4.29	4.10	4.13	4.22	4.53	3.54	2.46	4.06	5.22	4.80	4.60
			b*	9.11	9.97	9.56	8.68	10.80	9.39	13.10	10.41	11.00	11.16	13.86	13.75	13.47	13.70	12.34	10.00	12.83	14.32	14.22	14.39
Elsham Cremation	EL75DX 3	SCI	L*	37.57	38.96	46.22	51.92	53.66	45.64	51.71	48.05	54.26	43.23	48.05	46.86	40.89	31.37	31.02	33.25	34.20	35.20	37.80	37.56
			a*	1.40	1.78	1.47	1.21	0.85	1.62	1.36	2.08	0.59	1.55	1.77	1.06	1.59	1.21	2.05	1.25	1.66	2.14	3.25	2.58
			b*	4.36	5.00	8.27	10.95	7.87	8.00	9.20	9.48	7.13	7.50	9.61	8.91	7.88	6.54	8.08	5.92	7.79	9.65	12.43	10.64
		-	G	0	2	1	0	0	0	0	0	0	0	0	0	1	3	3	2	4	3	1	0
		SCE	L*	37.62	38.84	46.19	51.94	53.66	45.67	51.72	48.08	54.27	43.23	48.06	46.86	40.84	31.11	30.69	33.03	33.85	34.92	37.71	37.55
			a*	1.42	1.80	1.50	1.22	0.88	1.65	1.38	2.09	0.62	1.56	1.79	1.09	1.59	1.22	2.07	1.27	1.65	2.15	3.26	2.60
			b*	4.36	4.99	8.25	10.92	7.84	7.99	9.18	9.47	7.10	7.49	9.59	8.91	7.87	6.54	8.09	5.89	7.78	9.65	12.41	10.65
Elsham Cremation	EL75ES 1	SCI	L*	66.35	61.35	65.37	64.12	67.58	59.37	59.44	66.75	60.60	61.94	66.51	57.38	66.54	54.61	50.35	49.74	67.07	59.65	66.67	56.94
			a*	5.41	5.35	5.83	6.01	5.01	5.47	5.44	4.13	5.91	5.34	4.47	6.02	4.38	5.33	5.20	4.63	5.85	5.10	3.84	3.68
			b*	16.94	14.90	17.15	16.92	15.83	14.44	13.89	15.41	14.58	15.19	14.38	15.52	14.25	12.45	10.61	9.97	17.59	13.85	13.18	10.82
		-	G	80	82	79	79	76	87	83	82	82	84	80	87	80	87	89	93	75	82	79	87
		SCE	L*	63.56	58.06	62.53	61.20	64.99	55.69	55.95	63.90	57.23	58.62	63.72	53.46	63.75	50.37	45.33	44.39	64.49	56.23	63.94	52.97
			a*	5.87	5.90	6.35	6.58	5.43	6.07	6.04	4.46	6.53	5.87	4.85	6.74	4.75	6.07	6.08	5.40	6.36	5.67	4.15	4.08
			b*	19.26	17.41	19.61	19.48	17.90	17.02	16.41	17.44	17.09	17.63	16.28	18.62	16.14	15.29	13.63	12.78	19.98	16.37	14.94	12.95
Elsham Cremation	EL75ES 2	SCI	L*	65.13	65.19	66.28	80.46	79.09	68.99	67.65	71.40	69.08	58.69	58.17	61.58	66.28	57.93	58.05	63.30	63.13	66.62	58.14	56.52
			a*	6.69	6.90	7.23	2.09	3.56	6.11	6.38	5.79	5.89	6.77	6.25	3.49	5.44	6.02	4.22	6.55	6.28	5.84	5.23	4.14
			b*	18.70	18.21	19.90	14.07	18.40	19.98	18.74	20.75	18.60	16.00	14.25	14.47	15.94	13.67	12.96	16.37	15.39	16.13	12.62	12.94
		-	G	79	79	80	65	62	76	77	72	75	84	84	81	82	89	91	81	80	78	87	94
		SCE	L*	62.27	62.35	63.49	78.84	77.49	66.49	65.06	69.16	66.64	55.07	54.48	58.37	63.42	54.00	54.01	60.22	60.07	63.90	54.30	52.16
			a*	7.30	7.52	7.86	2.21	3.79	6.60	6.91	6.24	6.37	7.56	6.98	3.84	5.91	6.74	4.67	7.20	6.90	6.36	5.84	4.60
			b*	21.42	20.85	22.86	15.27	20.05	22.49	21.21	23.17	20.93	19.06	17.01	16.85	18.15	16.29	15.36	18.92	17.82	18.34	15.01	15.50
Elsham Cremation	EL75ES 3	SCI	L*	61.03	58.21	56.86	59.75	57.11	56.27	59.45	58.37	58.91	49.19	70.95	69.85	68.78	73.38	71.92	71.92	73.19	59.14	63.93	66.45
			a*	4.56	4.67	3.66	4.15	4.17	4.54	4.95	4.35	4.14	2.78	4.25	4.27	3.39	3.29	3.80	3.61	3.11	4.51	3.65	4.35
			b*	13.73	13.17	10.44	12.39	11.79	12.03	14.22	12.58	12.31	7.25	15.43	15.28	11.64	14.02	14.80	13.11	12.29	12.76	11.02	14.78
		-	G	80	85	85	83	85	85	82	83	83	94	74	75	77	70	75	72	73	82	79	77
		SCE	L*	57.79	54.50	52.98	56.30	53.26	52.32	56.00	54.74	55.34	43.65	68.64	67.46	66.26	71.31	69.63	69.73	71.03	55.67	61.01	63.78
			a*	5.04	5.20	4.09	4.60	4.68	5.11	5.51	4.85	4.58	3.20	4.57	4.60	3.64	3.51	4.06	3.87	3.32	5.02	3.98	4.72
			b*	16.07	15.70	12.55	14.60	14.16	14.56	16.83	14.97	14.57	9.34	17.22	17.10	13.05	15.50	16.44	14.56	13.59	15.13	12.68	16.78
Elsham Cremation	EL75LW 1	SCI	L*	65.42	68.97	80.78	71.93	69.45	66.52	69.97	71.57	73.00	73.69	75.04	71.39	52.77	51.71	51.14	60.62	51.73	60.06	48.64	72.97
			a*	6.83	5.84	2.12	5.16	5.61	7.10	5.71	4.82	4.18	4.76	3.74	5.20	4.08	3.75	3.95	3.13	3.05	3.53	2.85	3.44
			b*	18.84	18.06	9.68	18.81	17.86	19.80	18.22	19.02	18.40	18.87	15.98	18.80	10.69	9.85	9.97	11.02	8.00	12.55	7.42	15.01
		-	G	78	76	65	73	75	77	74	74	72	71	71	74	97	99	100	90	97	90	90	67
		SCE	L*	62.62	66.50	79.17	69.70	67.02	63.85	67.60	69.31	70.88	71.61	73.04	69.12	47.70	46.36	45.59	56.95	46.50	56.33	43.30	70.97
			a*	7.45	6.31	2.24	5.53	6.06	7.74	6.15	5.18	4.48	5.09	3.99	5.58	4.64	4.28	4.51	3.42	3.44	3.85	3.33	3.70
			b*	21.58	20.33	10.53	20.93	20.05	22.59	20.43	21.19	20.41	20.88	17.57	20.96	13.18	12.26	12.48	12.87	10.00	14.66	9.80	16.63
Elsham Cremation	EL75LW 2	SCI	L*	81.23	61.33	66.00	71.36	67.06	70.95	75.53	73.36	71.70	69.09	51.97	56.37	66.89	60.13	62.62	62.14	61.66	51.98	58.04	59.17
			a*	2.17	3.69	2.96	3.45	3.50	4.13	3.72	3.89	3.80	4.01	4.73	4.28	3.94	5.90	5.02	6.16	5.49	3.70	4.74	4.55
			b*	10.29	11.67	11.70	14.17	13.01	14.44	14.04	16.18	15.70	14.73	10.57	11.62	13.55	15.37	15.78	17.13	15.73	9.66	13.69	11.96
		-	G	63	81	78	74	77	74	70	73	74	76	88	86	77	81	81	84	84	89	87	85
		SCE	L*	79.66	58.08	63.26	69.08	64.42	68.63	73.59	71.22	69.42	66.61	47.28	52.38	64.24	56.76	59.49	58.85	58.33	47.22	54.20	55.55
			a*	2.30	4.06	3.20	3.71	3.79	4.44	3.96	4.15	4.07	4.32	5.46	4.80	4.27	6.54	5.51	6.78	6.04	4.24	5.29	5.06
			b*	11.16	13.61	13.32	15.77	14.73	16.11	15.43	17.89	17.45	16.54	13.32	14.02	15.38	18.12	18.28	19.90	18.30	12.13	16.30	14.12

Type	Sample	Light	Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Elsham Cremation	EL75LW 3	SCI	L*	74.11	60.40	65.56	68.04	69.51	73.09	74.98	70.56	65.10	73.68	52.96	48.99	55.94	53.09	52.37	47.18	46.82	51.52	53.75	49.23
			a*	5.16	5.81	6.22	5.44	5.13	5.16	4.70	5.55	6.47	5.23	4.75	4.73	4.56	4.28	3.60	4.73	5.06	4.31	5.40	4.68
			b*	20.63	18.36	17.85	17.25	17.43	20.23	19.84	18.98	17.78	19.82	10.89	9.36	11.43	10.21	8.64	8.72	9.49	10.44	12.28	9.65
		-	G	72	75	77	77	75	73	67	74	77	72	88	90	85	87	88	92	94	88	86	90
		SCE	L*	72.04	66.96	62.81	65.47	67.08	70.94	73.09	68.22	62.32	71.57	48.43	43.69	51.94	48.65	47.74	41.42	40.77	46.76	49.45	43.97
			a*	5.51	6.27	6.78	5.89	5.54	5.53	5.02	5.98	7.07	5.59	5.44	5.57	5.14	4.90	4.12	5.65	6.06	4.97	6.19	5.51
			b*	22.81	20.63	20.42	19.47	19.55	22.43	21.88	21.23	20.38	21.92	13.55	12.19	13.87	12.71	10.82	11.64	12.64	13.20	15.22	12.50
Elsham Cremation	EL76IL 1	SCI	L*	76.97	77.62	70.84	73.18	64.64	70.17	62.61	73.11	71.72	72.57	80.02	61.95	68.63	65.95	75.32	61.68	60.89	68.11	79.75	66.51
			a*	4.91	3.88	5.96	4.86	4.56	3.77	6.24	4.01	5.53	4.57	2.97	7.01	4.11	5.73	4.46	6.42	5.12	3.70	3.38	6.02
			b*	20.51	17.60	18.86	17.38	15.48	14.62	18.36	19.57	18.43	16.26	16.61	17.51	14.86	16.53	17.90	16.47	15.27	14.94	17.76	16.93
		-	G	67	69	73	71	84	78	83	73	71	72	66	81	78	79	70	81	83	82	67	77
		SCE	L*	75.14	75.77	68.57	71.07	61.57	67.68	59.42	70.93	69.55	70.42	78.34	58.77	66.04	63.16	73.34	58.45	57.52	65.37	78.03	63.84
			a*	5.22	4.12	6.41	5.21	4.97	4.05	6.86	4.29	5.93	4.90	3.15	7.74	4.42	6.24	4.76	7.08	5.66	3.99	3.59	6.54
			b*	22.47	19.21	21.07	19.24	17.71	16.33	21.34	21.68	20.52	18.03	18.05	20.44	16.69	18.82	19.66	19.22	17.86	16.84	19.29	19.24
Elsham Cremation	EL76IL 2	SCI	L*	58.35	59.56	61.86	57.99	63.84	66.66	66.82	61.53	62.45	63.23	55.77	56.70	53.97	59.35	57.13	56.97	54.32	57.87	63.47	61.36
			a*	5.12	3.49	5.52	4.95	5.47	5.46	5.35	5.78	5.38	5.76	2.37	2.42	1.36	2.01	3.11	2.98	3.01	3.53	3.03	2.72
			b*	13.38	10.21	14.19	12.60	15.95	16.72	15.81	15.37	14.25	15.91	9.68	10.22	6.75	10.06	10.48	10.43	10.03	11.16	12.54	11.36
		-	G	80	84	83	86	83	74	74	83	84	83	87	85	90	83	85	87	92	87	82	83
		SCE	L*	54.85	56.03	58.58	54.18	60.73	64.11	64.28	58.21	59.17	60.07	51.69	52.83	49.49	55.84	53.31	53.03	49.75	54.03	60.35	58.04
			a*	5.75	3.86	6.06	5.52	5.97	5.95	5.83	6.37	5.90	6.30	2.61	2.68	1.48	2.18	3.46	3.32	3.38	3.92	3.30	2.96
			b*	16.01	12.05	16.48	14.99	18.31	19.04	17.97	17.90	16.47	18.33	11.73	12.30	8.33	11.86	12.57	12.52	12.25	13.28	14.45	13.23
Elsham Cremation	EL76IL 3	SCI	L*	52.53	55.96	48.09	61.61	64.24	61.42	56.51	59.83	67.88	51.42	52.35	60.21	57.17	52.62	57.72	63.01	59.81	61.74	52.75	54.01
			a*	4.36	4.63	2.17	4.73	1.70	5.27	2.99	4.74	4.36	3.60	1.11	2.04	3.18	3.26	2.23	4.16	4.58	1.35	1.59	3.57
			b*	11.54	12.97	7.11	15.87	10.08	15.25	11.41	15.60	16.21	11.62	5.82	9.86	11.85	10.58	11.02	15.58	16.53	8.80	7.29	12.02
		-	G	88	90	92	81	81	77	88	84	76	97	89	84	91	99	91	86	81	84	89	84
		SCE	L*	47.92	51.75	42.48	58.40	61.27	58.35	52.46	56.33	65.34	46.11	47.67	56.74	53.03	47.38	53.64	59.73	56.43	58.42	48.10	49.85
			a*	5.01	5.20	2.52	5.22	1.83	5.82	3.34	5.28	4.74	4.11	1.22	2.23	3.52	3.68	2.43	4.51	5.04	1.44	1.74	4.04
			b*	14.44	15.64	9.37	18.54	11.58	17.88	13.73	18.42	18.32	14.50	7.38	11.61	14.14	13.01	13.09	17.76	19.32	10.16	8.95	14.70
Elsham Cremation	EL76MN 1	SCI	L*	59.21	75.85	57.20	50.58	49.29	53.89	45.19	60.91	56.26	54.21	56.46	56.68	58.12	55.77	59.63	52.76	45.70	50.43	47.72	62.97
			a*	5.31	3.14	4.07	2.82	3.69	4.42	3.10	3.44	4.81	4.86	4.02	3.71	3.84	4.49	3.49	2.93	3.14	3.54	3.02	5.24
			b*	17.03	17.84	13.40	9.08	10.18	12.80	7.47	13.91	13.08	12.34	14.07	11.42	11.22	14.52	15.60	9.69	7.44	10.11	8.28	16.35
		-	G	84	73	85	98	99	90	99	90	86	86	87	93	86	85	85	94	99	98	99	83
		SCE	L*	55.63	73.84	53.39	45.06	43.46	49.39	38.44	57.24	52.26	49.93	55.76	52.40	54.34	51.75	56.04	47.83	39.01	44.90	41.54	59.79
			a*	5.91	3.35	4.57	3.25	4.27	5.01	3.71	3.77	5.41	5.53	4.47	4.14	4.27	5.07	3.86	3.34	3.74	4.07	3.56	5.77
			b*	20.11	19.52	16.04	11.37	12.83	15.64	9.94	16.11	15.70	15.10	16.49	13.58	13.25	17.57	18.32	11.90	9.78	12.62	10.67	18.88
Elsham Cremation	EL76MN 2	SCI	L*	60.66	58.48	51.59	47.35	53.85	54.37	60.60	48.95	53.29	46.70	48.65	58.14	54.86	55.44	49.49	49.58	42.27	48.12	48.12	45.95
			a*	3.45	3.60	3.54	4.72	4.28	3.06	3.35	4.39	5.16	3.44	2.46	4.96	5.35	4.03	4.95	4.83	2.78	2.91	3.51	1.93
			b*	13.35	13.33	10.49	9.75	11.29	10.48	13.11	9.33	12.93	8.26	6.75	15.39	13.47	13.14	11.09	10.40	5.37	7.92	8.45	4.95
		-	G	84	86	89	94	87	88	84	90	91	92	91	83	85	86	92	89	94	89	89	90
		SCE	L*	57.24	54.76	46.76	41.44	49.48	50.05	57.16	43.63	48.64	40.83	43.25	54.52	50.73	51.37	44.17	44.43	35.05	42.69	42.80	40.02
			a*	3.80	4.01	4.07	5.59	4.87	3.45	3.69	5.15	5.88	4.11	2.84	5.55	6.09	4.54	5.79	5.67	3.45	3.43	4.14	2.28
			b*	15.58	15.73	13.12	12.74	13.82	12.76	15.30	12.03	15.87	10.95	8.71	18.29	16.40	15.92	14.17	13.35	7.69	10.33	11.01	6.73
Elsham Cremation	EL76MN 3	SCI	L*	57.54	54.18	60.05	64.47	60.29	60.35	60.44	61.63	64.31	60.56	61.55	55.05	68.61	53.50	50.09	50.85	51.93	48.81	49.60	50.77
			a*	5.80	4.57	5.04	4.31	5.48	5.08	5.05	5.24	5.21	4.49	4.50	4.71	3.26	4.39	4.37	4.68	3.97	4.65	4.15	4.04
			b*	14.32	11.54	13.14	14.25	15.11	14.66	14.07	15.20	15.10	12.59	12.81	11.41	11.35	10.59	10.48	10.34	12.07	9.76	9.23	11.62
		-	G	85	88	82	76	79	80	83	80	76	82	78	86	77	87	89	86	91	88	89	91
		SCE	L*	53.72	49.84	56.64	61.67	57.04	57.04	57.04	58.45	61.52	57.19	58.44	50.90	66.08	49.08	45.06	46.13	47.06	43.57	44.47	45.71
			a*	6.49	5.19	5.58	4.71	6.07	5.62	5.58	5.77	5.69	4.95	4.97	5.31	3.51	5.00	5.08	5.44	4.55	5.47	4.84	4.66
			b*	17.05	14.07	15.38	16.28	17.71	17.14	16.38	17.62	17.28	14.63	14.85	13.77	12.69	12.96	13.32	13.09	14.96	12.63	11.78	14.59

Type	Sample	Light	Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Elsham Cremation	EL76NN 1	SCI	L*	63.83	68.80	72.31	69.16	70.21	65.53	70.94	64.99	70.29	65.80	60.40	61.89	60.38	55.36	54.92	57.58	59.42	67.45	53.70	55.66
			a*	4.45	6.48	5.15	6.00	4.62	6.23	4.18	6.28	4.80	5.33	2.61	2.94	3.56	3.82	3.88	2.97	3.34	2.73	2.78	4.31
			b*	13.81	18.29	17.06	18.42	14.72	16.81	14.13	17.74	16.50	16.42	8.56	10.54	12.64	11.73	11.07	10.58	11.12	13.36	8.36	12.89
		-	G	76	74	72	74	72	76	75	77	73	78	84	81	85	102	102	93	90	79	92	96
		SCE	L*	60.97	66.38	70.14	66.76	67.92	62.81	68.61	62.20	67.98	63.05	56.95	58.70	56.90	50.45	49.91	53.39	55.59	64.77	49.06	51.10
			a*	4.87	6.99	5.51	6.48	4.96	6.79	4.48	6.84	5.17	5.79	2.86	3.23	3.92	4.31	4.35	3.28	3.66	2.93	3.12	4.83
			b*	15.82	20.52	18.87	20.63	16.40	19.11	15.68	20.24	18.38	18.61	9.97	12.17	14.71	13.98	13.20	12.51	12.95	15.02	10.17	15.38
Elsham Cremation	EL76NN 2	SCI	L*	72.62	75.02	67.36	77.81	64.25	70.42	59.15	58.20	62.94	59.04	64.48	54.63	66.76	59.53	50.30	52.17	48.29	50.26	52.96	56.01
			a*	2.54	1.81	5.57	2.88	3.85	4.38	6.19	4.78	4.04	4.51	4.51	4.85	3.18	2.83	3.91	4.61	4.41	4.57	4.62	5.01
			b*	13.13	9.68	17.99	13.48	14.23	17.73	16.49	13.64	14.70	13.32	15.36	12.52	13.23	11.02	9.53	11.65	9.55	10.69	11.53	13.30
		-	G	75	72	72	67	78	72	79	82	79	80	82	83	74	83	89	89	85	86	83	83
		SCE	L*	70.38	72.99	64.93	76.03	61.39	68.14	55.81	54.60	59.92	55.65	61.47	50.56	64.20	56.03	45.27	47.44	43.17	45.46	48.68	52.15
			a*	2.71	1.91	6.01	3.06	4.18	4.68	6.82	5.28	4.40	4.96	4.89	5.44	3.42	3.07	4.46	5.21	5.15	5.23	5.23	5.58
			b*	14.43	10.62	20.22	14.63	16.15	19.65	19.33	16.01	16.81	15.58	17.38	15.10	14.86	12.77	11.88	14.24	12.30	13.41	14.10	15.84
Elsham Cremation	EL76NN 3	SCI	L*	64.60	77.77	69.16	72.87	65.17	72.90	66.14	70.66	76.10	69.92	49.39	52.69	51.94	64.72	62.64	57.89	60.83	53.57	52.85	49.13
			a*	5.85	2.69	5.39	3.55	5.43	3.18	5.65	5.04	3.35	4.33	4.74	4.13	4.75	5.88	4.38	4.68	4.61	4.87	4.30	4.28
			b*	17.37	14.51	18.24	16.05	16.45	15.22	17.59	16.72	16.82	16.49	10.18	11.08	11.14	16.99	14.26	12.77	13.25	12.11	11.10	9.33
		-	G	76	68	73	71	76	75	76	69	73	75	88	87	85	77	77	80	81	86	89	88
		SCE	L*	61.85	75.95	66.79	70.75	62.44	70.66	63.47	68.48	74.07	67.54	44.31	48.15	47.42	61.92	59.69	54.35	57.57	49.21	48.27	44.00
			a*	6.35	2.86	5.79	3.79	5.89	3.39	6.10	5.40	3.56	4.65	5.46	4.67	5.40	6.37	4.76	5.18	5.05	5.48	4.84	4.95
			b*	19.76	15.75	20.33	17.66	18.63	16.72	19.83	18.53	18.29	18.30	12.84	13.49	13.71	19.27	16.33	15.02	15.30	14.68	13.48	11.78
Elsham Cremation	EL76PY 1	SCI	L*	68.89	70.45	72.34	66.67	66.85	67.08	69.45	79.95	75.40	80.68	56.79	53.36	56.07	58.03	52.54	47.37	50.65	49.90	48.94	48.25
			a*	5.47	5.90	5.03	5.79	2.94	4.24	4.44	3.19	4.35	2.25	4.82	4.30	4.90	4.18	3.73	3.47	3.69	3.21	3.83	3.72
			b*	18.26	17.72	16.29	16.75	12.41	15.83	15.00	15.42	14.98	10.38	12.14	10.26	12.14	13.13	10.69	7.72	9.33	8.31	8.25	8.48
		-	G	71	69	68	74	76	74	70	63	64	61	81	81	80	77	81	84	82	82	83	82
		SCE	L*	66.58	68.27	70.29	64.11	64.23	64.54	67.20	78.36	73.60	79.16	53.12	49.25	52.35	54.66	48.33	42.14	46.14	45.23	44.07	43.30
			a*	5.89	6.33	5.38	6.26	3.16	4.57	4.76	3.37	4.63	2.38	5.35	4.84	5.48	4.63	4.21	4.05	4.23	3.68	4.44	4.35
			b*	20.38	19.66	17.95	18.83	13.92	17.76	16.67	16.66	16.39	11.23	14.40	12.52	14.50	15.47	13.16	10.10	11.72	10.53	10.57	10.99
Elsham Cremation	EL76PY 2	SCI	L*	69.13	65.01	66.48	70.45	72.23	64.09	68.27	68.29	64.50	55.47	58.97	65.06	54.21	49.66	48.97	51.04	55.75	56.44	56.87	50.93
			a*	5.00	6.25	6.78	5.70	5.37	6.29	5.28	6.02	5.25	3.99	4.97	5.14	4.74	4.69	4.48	4.05	3.53	4.61	5.89	4.15
			b*	16.82	17.81	18.44	17.36	18.85	17.18	17.11	18.38	15.27	11.22	13.17	15.57	11.15	10.14	9.89	10.79	9.45	12.03	14.25	10.29
		-	G	72	75	73	71	69	76	73	73	77	84	80	75	82	87	89	90	79	81	80	82
		SCE	L*	66.78	62.29	63.95	68.21	70.14	61.29	65.84	65.86	61.69	51.50	55.56	62.36	50.19	44.65	43.69	46.10	52.05	52.70	53.24	46.41
			a*	5.37	6.78	7.34	6.10	5.73	6.84	5.68	6.47	5.68	4.44	5.48	5.56	5.32	5.39	5.15	4.60	3.93	5.13	6.55	4.75
			b*	18.74	20.21	20.78	19.25	20.79	19.56	19.12	20.56	17.33	13.40	15.41	17.63	13.51	12.75	12.46	13.28	11.34	14.31	16.92	12.86
Elsham Cremation	EL76PY 3	SCI	L*	60.99	57.05	62.32	57.92	59.35	62.79	53.31	58.34	45.73	61.84	58.27	50.10	53.82	54.41	54.20	54.08	48.13	50.56	50.09	59.69
			a*	4.82	5.62	5.70	4.85	5.55	5.40	4.23	5.56	3.46	5.08	5.75	3.65	3.39	2.85	4.31	3.08	3.28	3.00	3.07	4.41
			b*	12.75	12.90	14.31	13.30	13.83	16.96	11.82	13.99	7.24	14.99	15.56	8.86	10.13	9.04	11.85	9.90	8.73	7.69	9.05	13.20
		-	G	76	79	77	79	78	81	80	78	89	75	82	83	80	80	81	80	88	81	83	81
		SCE	L*	57.91	53.50	59.32	54.46	56.04	59.70	49.25	54.93	39.83	58.90	54.67	45.40	49.82	50.48	50.20	50.11	42.77	46.05	45.43	56.28
			a*	5.29	6.26	6.23	5.37	6.12	5.86	4.79	6.17	4.07	5.57	6.34	4.19	3.81	3.17	4.84	3.44	3.78	3.42	3.50	4.83
			b*	14.73	15.32	16.41	15.67	16.15	19.36	14.48	16.45	9.56	17.25	18.22	11.20	12.34	10.94	14.35	11.99	11.15	9.67	11.39	15.30
Elsham Cremation	EL76PZ 1	SCI	L*	64.84	59.01	60.03	57.06	74.14	57.71	55.85	72.84	73.49	65.53	65.62	59.75	56.52	60.35	56.68	58.73	61.19	63.01	61.56	57.41
			a*	7.11	6.31	5.80	6.65	4.20	5.03	5.96	4.71	5.41	6.27	4.59	6.21	4.93	4.08	4.68	5.61	5.50	5.54	5.78	6.09
			b*	18.86	15.06	15.50	14.84	18.16	13.65	13.54	19.27	19.35	17.67	13.94	15.95	13.13	12.91	13.06	15.05	16.60	16.89	17.59	15.44
		-	G	75	80	79	79	68	81	83	74	71	76	74	79	82	82	84	80	78	78	80	82
		SCE	L*	62.13	55.59	56.74	53.51	72.16	54.12	51.98	70.64	71.42	62.82	62.98	56.46	52.74	56.98	52.85	55.30	58.08	60.05	58.41	53.73
			a*	7.70	6.96	6.37	7.41	4.47	5.56	6.65	5.01	5.77	6.79	4.97	6.83	5.49	4.47	5.21	6.20	6.03	6.03	6.33	6.76
			b*	21.42	17.60	18.02	17.63	19.89	16.08	16.16	21.18	21.24	19.98	15.75	18.57	15.60	14.95	15.49	17.66	19.19	19.33	20.30	18.24

Type	Sample	Light	Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Elsham Cremation	EL76PZ 2	SCI	L*	54.02	53.97	58.05	58.75	52.76	53.71	53.61	53.57	52.27	55.64	56.29	55.59	50.25	49.42	54.45	54.65	55.06	52.18	56.04	53.52
			a*	5.71	5.37	5.51	4.65	3.05	4.93	5.54	5.67	5.02	6.34	6.82	6.11	5.24	4.79	5.19	5.50	3.88	6.03	5.77	6.04
			b*	11.26	11.28	12.21	10.97	7.14	10.77	12.55	12.66	11.67	15.62	15.80	14.52	10.25	9.71	12.47	13.61	12.69	11.97	13.39	12.68
		-	G	80	80	79	79	81	80	80	80	83	79	80	80	83	84	81	82	85	84	81	81
		SCE	L*	50.08	50.01	54.60	55.37	48.59	49.73	49.62	49.55	47.91	51.92	52.57	51.82	45.60	44.60	50.51	50.65	50.96	47.78	52.28	49.44
			a*	6.46	6.08	6.11	5.13	3.45	5.58	6.27	6.43	5.71	7.08	7.60	6.84	6.05	5.55	5.85	6.17	4.30	6.86	6.44	6.84
			b*	13.70	13.73	14.38	12.85	8.81	13.12	15.32	15.48	14.37	18.78	18.85	17.43	12.90	12.33	15.09	16.41	15.12	14.73	15.99	15.47
Elsham Cremation	EL76PZ 3	SCI	L*	61.71	60.76	59.72	61.53	57.01	56.70	57.84	55.01	47.55	63.86	51.49	50.86	50.45	48.47	50.26	47.64	53.29	53.87	46.46	49.50
			a*	5.97	6.99	6.71	6.45	6.52	6.74	6.87	4.84	3.85	4.06	4.34	4.26	3.81	4.77	4.94	3.89	4.77	5.59	4.72	4.53
			b*	13.50	16.45	15.79	14.93	14.45	14.67	15.46	11.30	7.75	18.66	11.31	9.89	10.27	9.43	10.70	8.37	11.25	12.65	8.10	9.13
		-	G	76	76	77	77	78	79	78	81	86	77	81	82	82	83	83	85	83	82	86	84
		SCE	L*	58.70	57.66	56.49	58.49	53.47	53.09	54.40	51.13	42.21	61.01	47.13	46.38	45.90	43.50	45.61	42.41	49.09	49.80	40.92	44.68
			a*	6.54	7.68	7.40	7.06	7.27	7.53	7.65	5.43	4.47	4.38	4.95	4.91	4.36	5.56	5.71	4.56	5.38	6.31	5.57	5.25
			b*	15.56	19.10	18.44	17.23	17.17	17.47	18.29	13.59	10.02	21.27	14.08	12.39	12.94	12.15	13.47	10.87	13.72	15.40	10.64	11.60

Type	Sample	Light	Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Cleatham Cremation	MT84FT 1	SCI	L*	47.42	47.84	41.61	44.97	43.06	59.28	65.23	60.21	60.80	60.59	62.47	60.24	43.84	44.87	44.37	46.78	48.29	44.22	61.49	61.29
			a*	1.20	1.34	0.31	1.29	0.27	7.17	6.51	6.97	5.12	5.26	7.04	6.93	0.76	1.23	0.92	1.43	2.15	0.98	5.37	6.57
			b*	4.76	5.34	0.31	3.30	1.21	16.15	17.88	17.13	14.80	15.40	17.81	16.16	3.28	4.86	4.47	4.27	6.58	4.19	16.21	16.08
		-	G	83	83	85	86	85	78	75	77	78	78	76	78	85	85	87	84	84	85	77	77
		SCE	L*	42.27	42.78	34.98	39.13	36.85	55.97	62.55	57.03	57.64	57.40	59.51	57.03	37.81	39.05	38.35	41.45	43.26	38.26	58.42	58.22
			a*	1.32	1.51	0.24	1.48	0.18	7.92	7.06	7.68	5.61	5.77	7.69	7.64	0.81	1.39	0.98	1.60	2.44	1.08	5.88	7.21
			b*	6.32	7.02	0.95	4.69	2.08	18.89	20.26	19.95	17.12	17.86	20.46	18.80	4.75	6.68	6.21	5.76	8.52	5.87	18.70	18.59
Cleatham Cremation	MT84FT 2	SCI	L*	54.27	53.67	54.98	50.37	52.87	55.55	55.06	54.40	55.53	56.53	55.95	53.98	55.74	52.58	53.39	60.99	57.08	54.27	59.66	53.90
			a*	0.25	0.40	0.96	0.75	0.82	0.49	0.50	0.77	0.83	0.85	1.13	1.28	2.10	2.47	1.20	0.98	1.74	1.92	1.28	2.31
			b*	2.86	2.73	4.48	3.03	4.17	3.48	3.28	5.27	4.60	4.67	5.23	4.73	7.44	7.61	5.55	7.14	7.55	6.43	7.38	7.35
		-	G	80	81	79	82	81	80	80	81	80	79	80	81	81	81	81	77	79	80	77	82
		SCE	L*	50.32	49.63	51.17	45.78	48.68	51.76	51.21	50.45	51.76	52.90	52.23	49.94	51.92	48.37	49.31	57.89	53.53	50.35	56.44	49.79
			a*	0.20	0.38	1.02	0.79	0.87	0.48	0.48	0.80	0.86	0.88	1.21	1.39	2.31	2.77	1.30	1.03	1.89	2.12	1.37	2.58
			b*	3.65	3.51	5.51	4.01	5.25	4.31	4.12	6.48	5.63	5.69	6.35	5.85	8.95	9.38	6.87	8.31	9.00	7.84	8.65	8.97
Cleatham Cremation	MT84FT 3	SCI	L*	52.49	53.43	53.65	54.07	54.82	53.65	54.77	55.97	54.64	54.04	53.37	52.45	54.31	54.42	53.77	47.91	51.99	50.78	49.53	49.84
			a*	1.09	1.50	2.52	0.94	2.48	1.70	2.60	1.26	1.50	1.47	2.03	2.40	1.92	2.60	1.63	1.68	2.45	2.52	3.08	3.02
			b*	5.31	6.81	9.27	5.50	8.75	7.09	9.94	6.86	6.56	6.05	7.01	7.08	6.05	9.68	7.28	5.63	8.41	7.93	8.69	9.08
		-	G	81	81	80	80	80	81	80	79	79	80	81	81	80	80	80	83	82	82	83	84
		SCE	L*	48.29	49.34	49.64	50.12	50.97	49.61	50.91	52.30	50.78	50.06	49.26	48.23	50.39	50.49	49.75	42.83	47.67	46.27	44.77	45.04
			a*	1.17	1.65	2.80	1.01	2.75	1.87	2.90	1.37	1.64	1.61	2.26	2.69	2.12	2.89	1.81	1.90	2.77	2.86	3.53	3.46
			b*	6.64	8.34	11.27	6.76	10.57	8.67	11.98	8.24	7.96	7.41	8.59	8.76	7.39	11.71	8.89	7.37	10.42	9.97	11.06	11.47
Cleatham Cremation	MT84IT 1	SCI	L*	50.61	55.38	50.83	51.98	50.74	50.66	51.56	52.00	45.07	46.26	48.14	49.70	46.61	41.58	45.08	49.15	47.03	49.34	51.89	47.75
			a*	0.68	0.91	0.62	0.49	0.38	0.56	0.50	0.70	0.36	0.36	0.10	1.05	0.93	0.15	0.11	1.22	0.94	0.63	0.63	0.91
			b*	3.77	5.13	3.05	3.00	3.03	3.34	3.05	3.58	2.24	2.16	1.68	4.16	3.53	0.60	0.41	5.47	4.82	3.24	4.31	4.05
		-	G	84	83	86	83	85	84	85	85	87	86	85	84	85	88	85	84	87	86	85	86
		SCE	L*	45.93	51.42	46.10	47.59	46.07	45.99	47.01	47.47	39.17	40.67	42.99	44.90	41.19	34.68	39.34	44.23	41.55	44.37	47.37	42.45
			a*	0.69	0.96	0.63	0.48	0.36	0.56	0.49	0.72	0.32	0.32	0.00	1.15	1.01	0.03	-0.02	1.35	1.04	0.64	0.63	0.98
			b*	4.92	6.30	4.05	3.92	4.01	4.39	4.00	4.63	3.30	3.15	2.46	5.45	4.86	1.33	1.00	7.13	6.46	4.33	5.46	5.43
Cleatham Cremation	MT84IT 2	SCI	L*	54.45	55.00	53.40	54.36	54.97	55.59	53.04	52.30	52.31	54.08	50.53	51.72	52.32	51.73	53.32	51.02	52.47	52.15	49.41	48.21
			a*	2.31	2.90	2.48	2.05	2.16	1.94	2.60	2.60	3.57	3.27	1.65	2.06	1.60	2.15	2.17	2.33	1.55	1.41	2.07	2.09
			b*	7.92	8.09	7.78	7.29	7.25	7.55	7.83	7.75	9.33	9.34	5.45	5.84	5.70	6.62	7.04	7.78	5.01	5.21	5.91	5.56
		-	G	82	82	83	83	83	82	84	84	84	82	85	85	83	84	83	84	84	84	85	85
		SCE	L*	50.42	51.07	49.22	50.30	50.99	51.73	48.76	47.92	47.92	50.00	45.82	47.19	47.96	47.26	49.12	46.42	48.11	47.70	44.51	43.11
			a*	2.58	3.24	2.77	2.28	2.39	2.13	2.92	2.94	4.05	3.68	1.84	2.31	1.77	2.42	2.42	2.65	1.72	1.55	2.37	2.42
			b*	9.64	9.82	9.60	8.90	8.80	9.13	9.65	9.62	11.57	11.38	6.96	7.34	7.15	8.31	8.69	9.80	6.30	6.54	7.61	7.29
Cleatham Cremation	MT84IT 3	SCI	L*	56.05	55.68	54.68	55.22	57.57	55.94	53.78	57.51	61.43	58.74	58.42	57.22	52.50	57.37	54.44	53.75	48.63	44.49	50.10	45.79
			a*	4.36	5.12	3.59	3.60	4.76	3.36	3.45	4.17	3.57	4.61	4.40	4.15	3.53	3.36	3.29	3.30	3.47	2.59	3.65	2.66
			b*	8.93	10.86	7.55	8.12	10.71	7.50	7.45	11.44	10.83	12.17	10.88	10.10	9.00	9.11	7.89	8.89	8.15	5.81	8.37	5.49
		-	G	81	82	81	84	80	81	82	81	78	79	80	81	84	81	83	81	86	91	84	89
		SCE	L*	52.26	51.79	50.73	51.22	54.01	52.14	49.68	53.87	58.32	55.32	54.96	53.58	48.13	53.73	50.38	49.69	43.48	38.14	45.33	39.89
			a*	4.89	5.77	4.05	4.03	5.31	3.75	3.90	4.64	3.90	5.10	4.87	4.63	4.02	3.71	3.69	3.73	4.04	3.08	4.24	3.14
			b*	10.71	13.04	9.19	9.78	12.70	9.02	9.13	13.57	12.52	14.31	12.83	12.01	11.13	10.82	9.59	10.88	10.49	7.89	10.64	7.37
Cleatham Cremation	MT84KJ 1	SCI	L*	59.27	58.68	59.23	56.66	58.58	56.58	57.17	57.98	58.11	56.76	54.22	54.66	55.31	54.39	52.25	52.75	55.18	52.65	49.97	49.20
			a*	0.98	1.05	0.40	-0.03	0.53	0.82	1.70	1.19	0.98	1.01	0.34	0.31	0.88	1.25	1.29	1.77	1.24	0.47	0.94	0.86
			b*	7.34	7.39	5.83	4.20	6.38	8.11	9.89	7.97	7.99	8.66	4.74	5.43	5.72	7.50	7.35	8.33	7.08	5.25	3.79	3.95
		-	G	80	80	80	82	81	83	83	82	82	83	81	83	82	83	85	85	85	87	89	89
		SCE	L*	55.88	55.23	55.85	52.93	55.09	52.78	53.42	54.37	54.54	52.99	50.25	50.63	51.38	50.34	47.77	48.34	51.10	48.09	44.90	44.01
			a*	1.04	1.12	0.39	-0.11	0.54	0.87	1.86	1.29	1.04	1.08	0.32	0.29	0.93	1.36	1.43	1.96	1.34	0.48	1.00	0.89
			b*	8.65	8.74	6.91	5.15	7.58	9.70	11.74	9.45	9.46	10.34	5.89	6.67	6.97	9.16	9.12	10.28	8.57	6.55	4.93	5.16

Type	Sample	Light	Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Cleatham Cremation	MT84KJ 2	SCI	L*	60.28	61.78	60.07	59.81	56.66	57.92	62.52	58.62	55.88	59.31	57.77	57.17	54.66	52.40	55.23	55.86	53.79	47.42	50.92	48.47
			a*	2.13	1.15	2.39	1.92	1.23	0.63	0.47	2.50	4.35	3.14	1.71	1.47	2.74	1.13	2.96	3.09	2.94	2.46	4.01	1.76
			b*	11.20	8.39	11.50	10.16	7.41	5.15	7.71	11.94	11.76	11.71	9.93	8.00	9.77	6.19	11.56	10.81	10.18	8.18	10.90	6.44
		-	G	80	79	81	79	81	81	79	80	82	79	81	81	83	84	82	82	85	86	84	88
		SCE	L*	56.99	58.66	56.73	56.49	52.97	54.35	59.45	55.16	52.04	55.95	54.17	53.53	50.62	48.00	51.29	52.00	49.54	42.07	46.29	43.23
			a*	2.33	1.23	2.61	2.10	1.33	0.65	0.48	2.75	4.89	3.46	1.86	1.60	3.07	1.24	3.32	3.45	3.31	2.89	4.63	2.00
			b*	13.03	9.71	13.39	11.87	8.88	6.22	8.90	14.06	14.12	13.71	11.77	9.55	11.84	7.71	13.96	12.94	12.39	10.73	13.74	8.33
Cleatham Cremation	MT84KJ 3	SCI	L*	57.23	57.86	56.98	57.21	55.72	58.13	55.21	58.96	57.91	58.08	58.87	64.84	59.22	60.05	61.67	62.48	60.97	62.07	58.85	62.53
			a*	-0.45	-0.74	-0.47	-0.05	-0.56	-0.38	-0.36	-0.41	-0.20	0.18	0.08	-0.53	0.87	-0.03	-0.13	-0.49	-0.56	-0.38	0.16	-0.36
			b*	2.17	4.81	3.26	5.42	3.27	2.77	1.60	3.05	4.93	6.64	5.88	5.21	7.78	4.89	4.74	4.20	3.38	3.81	4.98	4.44
		-	G	81	82	81	81	82	81	82	80	81	81	80	78	81	81	78	78	80	79	81	78
		SCE	L*	53.60	54.22	53.29	53.57	51.85	54.60	51.30	55.56	54.33	54.55	55.47	62.02	55.80	56.71	58.57	59.45	57.76	59.00	55.38	59.51
			a*	-0.59	-0.90	-0.60	-0.13	-0.72	-0.49	-0.49	-0.51	-0.29	0.14	0.04	-0.62	0.92	-0.09	-0.19	-0.58	-0.68	-0.46	0.12	-0.45
			b*	2.78	5.80	4.04	6.53	4.09	3.44	2.16	3.75	5.93	7.89	6.99	6.02	9.15	5.79	5.58	4.95	4.07	4.52	5.93	5.22
Cleatham Cremation	MT85AQ 1	SCI	L*	69.43	60.62	66.69	67.27	64.33	60.87	57.26	64.53	57.85	68.30	64.05	56.61	62.55	68.43	61.53	66.03	62.23	49.65	75.10	68.91
			a*	6.14	6.71	6.19	5.47	6.14	6.44	6.38	5.81	4.52	5.41	5.40	5.46	5.87	5.16	6.22	4.39	5.24	4.40	3.91	5.66
			b*	21.06	18.51	19.47	18.96	19.07	18.07	16.22	17.86	13.69	18.48	17.95	15.24	18.43	18.44	18.30	16.98	18.57	10.75	20.20	20.52
		-	G	75	81	73	78	80	78	83	78	84	75	79	84	78	76	83	76	75	89	67	73
		SCE	L*	67.00	57.32	64.16	64.61	61.40	57.70	53.55	61.68	54.15	65.80	61.14	52.77	59.55	65.91	58.22	63.37	59.31	44.50	73.21	66.50
			a*	6.60	7.40	6.71	5.90	6.68	7.11	7.13	6.32	5.02	5.83	5.89	6.12	6.42	5.56	6.83	4.77	5.77	5.10	4.18	6.11
			b*	23.52	21.58	22.03	21.31	21.77	21.07	19.34	20.37	16.17	20.69	20.50	18.21	21.27	20.65	21.16	19.23	21.55	13.57	22.16	22.98
Cleatham Cremation	MT85AQ 2	SCI	L*	56.31	56.08	52.19	60.01	45.13	58.41	61.45	58.48	64.38	59.11	64.86	63.99	53.45	48.29	67.87	49.68	65.71	62.10	64.17	53.60
			a*	5.64	5.16	5.57	4.49	2.77	3.22	5.00	5.19	4.75	4.24	4.06	3.12	3.53	3.37	4.52	3.57	2.80	3.32	3.55	4.95
			b*	16.47	15.88	13.97	16.47	7.49	13.21	18.23	17.42	17.10	15.70	16.83	15.42	12.60	9.88	17.40	11.33	15.00	12.77	13.89	13.10
		-	G	81	80	84	79	93	83	79	79	74	79	76	76	86	90	76	90	74	82	79	82
		SCE	L*	52.57	52.35	47.75	56.74	38.79	54.82	58.30	55.05	61.66	55.76	62.10	61.18	49.09	42.83	65.31	44.52	63.09	58.90	61.24	49.47
			a*	6.34	5.78	6.40	4.94	3.24	3.53	5.48	5.77	5.16	4.70	4.41	3.39	3.99	3.92	4.86	4.10	3.02	3.62	3.85	5.63
			b*	19.79	19.12	17.38	19.23	9.92	15.49	21.13	20.62	19.52	18.46	19.14	17.61	15.38	12.65	19.51	14.29	16.99	14.68	15.81	16.07
Cleatham Cremation	MT85AQ 3	SCI	L*	61.23	58.36	58.02	58.23	53.31	46.99	55.56	68.60	66.28	52.99	68.40	72.82	65.95	63.60	63.56	44.99	46.55	61.78	52.35	57.89
			a*	4.83	5.60	5.37	5.00	3.87	3.73	5.34	5.07	5.74	4.65	3.66	4.11	4.00	5.77	5.16	3.24	3.53	6.07	4.37	4.67
			b*	15.28	16.08	15.18	14.36	11.13	8.66	14.44	17.10	18.43	12.61	15.28	18.21	17.71	18.52	17.77	7.62	8.63	18.26	12.29	13.93
		-	G	79	82	82	81	86	88	83	73	75	85	74	72	82	82	76	89	91	80	83	81
		SCE	L*	58.08	54.81	54.43	54.68	48.92	41.40	51.63	66.19	63.67	48.65	65.93	70.67	63.05	60.50	60.69	38.89	40.71	58.62	47.99	54.33
			a*	5.32	6.22	5.97	5.54	4.40	4.42	6.00	5.46	6.23	5.29	3.93	4.39	4.31	6.28	5.63	3.89	4.16	6.67	5.00	5.19
			b*	17.71	18.99	17.97	16.95	13.63	11.37	17.42	19.15	20.87	15.55	17.08	20.07	19.96	21.16	20.42	10.30	11.32	21.15	15.27	16.51
Cleatham Cremation	MT85AR 1	SCI	L*	63.46	66.11	70.66	76.45	77.07	77.01	73.81	68.40	66.13	63.62	49.90	49.34	47.49	48.44	49.38	55.99	48.59	49.21	50.32	49.60
			a*	-1.74	-1.05	-1.56	-1.27	-1.17	-1.16	-1.71	-1.83	-1.05	-0.59	-0.16	0.09	-0.22	-0.36	-0.45	-0.96	-0.42	-0.12	-0.18	-0.15
			b*	0.65	2.17	-0.93	0.93	1.49	3.46	3.57	2.12	3.81	2.94	1.57	2.59	0.45	-0.48	0.11	-1.79	-1.41	1.33	1.65	1.48
		-	G	78	77	73	69	68	67	70	74	75	76	86	86	87	86	85	83	86	86	86	86
		SCE	L*	60.50	63.40	68.37	74.57	75.23	75.20	71.77	65.96	63.49	60.76	45.01	44.36	42.11	43.33	44.44	52.10	43.51	44.18	45.50	44.66
			a*	-1.98	-1.19	-1.73	-1.38	-1.26	-1.25	-1.86	-2.04	-1.19	-0.72	-0.32	0.00	-0.41	-0.57	-0.65	-1.19	-0.64	-0.27	-0.33	-0.31
			b*	0.97	2.64	-0.76	1.20	1.79	3.91	4.05	2.55	4.44	3.53	2.30	3.56	0.98	-0.16	0.55	-1.72	-1.27	2.02	2.36	2.18
Cleatham Cremation	MT85AR 2	SCI	L*	56.43	56.94	55.08	54.13	56.01	49.78	55.69	53.34	48.12	49.47	55.93	55.28	56.67	54.37	52.31	52.51	49.87	48.57	45.83	51.15
			a*	0.62	0.93	0.43	0.58	0.53	3.18	1.83	1.78	0.63	2.93	0.96	0.74	0.65	0.45	0.22	3.61	2.42	2.85	2.89	1.02
			b*	5.76	6.60	4.93	5.32	5.60	7.91	7.40	7.63	4.29	7.82	7.00	5.80	5.84	5.08	3.90	8.62	7.51	7.66	7.12	4.83
		-	G	83	82	84	87	84	86	84	84	87	86	86	84	82	85	88	83	90	88	90	85
		SCE	L*	52.62	53.23	51.02	49.80	52.08	44.84	51.75	49.09	42.84	44.49	51.90	51.27	52.92	50.17	47.70	48.20	44.72	43.33	39.85	46.51
			a*	0.61	0.97	0.41	0.57	0.51	3.68	1.99	1.98	0.64	3.39	1.01	0.75	0.65	0.43	0.15	4.11	2.74	3.28	3.41	1.10
			b*	6.99	7.95	6.07	6.56	6.80	10.12	8.94	9.45	5.73	10.06	8.45	7.10	7.05	6.27	4.97	10.70	9.51	9.89	9.55	6.21

Type	Sample	Light	Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Cleatham Cremation	MT85AR 3	SCI	L*	61.35	62.00	63.14	60.55	61.91	61.32	53.98	51.79	55.43	57.31	58.71	59.47	55.96	52.03	53.97	59.52	51.74	55.91	59.08	58.88
			a*	1.80	1.48	1.69	1.43	1.33	1.15	2.00	2.50	2.17	1.13	2.28	2.47	1.70	1.48	1.66	2.04	1.51	1.44	1.69	1.52
			b*	10.26	10.11	10.02	9.08	9.61	8.36	7.81	8.47	9.33	6.35	9.67	11.39	7.25	6.03	6.78	7.99	5.98	6.60	10.26	7.28
		-	G	79	78	78	79	78	80	81	85	81	82	80	80	84	85	82	82	85	86	79	80
		SCE	L*	58.21	58.93	60.19	57.31	58.83	58.10	49.94	47.24	51.57	53.65	55.26	56.10	52.05	47.55	49.89	56.05	47.22	51.88	55.70	55.43
			a*	1.95	1.60	1.81	1.54	1.41	1.22	2.23	2.83	2.39	1.19	2.49	2.71	1.83	1.63	1.83	2.22	1.68	1.56	1.83	1.63
			b*	11.93	11.70	11.52	10.62	11.14	9.72	9.62	10.58	11.29	7.63	11.44	13.37	8.75	7.58	8.35	9.38	7.54	7.94	12.06	8.61
Cleatham Cremation	MT85BH 1	SCI	L*	58.92	75.56	50.97	63.06	62.20	66.69	71.77	66.75	66.06	61.70	63.29	68.79	59.07	63.07	59.76	62.91	59.37	57.15	56.47	53.10
			a*	4.76	3.91	3.78	3.51	5.35	4.25	3.44	3.34	3.41	4.82	3.79	4.18	2.85	3.75	5.06	3.65	4.19	3.48	3.75	2.99
			b*	15.16	20.94	11.11	16.89	18.94	18.40	16.83	13.41	13.42	15.90	13.12	18.12	11.83	14.81	16.85	16.60	14.87	11.57	13.06	11.16
		-	G	89	72	88	76	80	79	73	76	79	78	77	74	86	77	80	78	87	85	84	89
		SCE	L*	55.08	73.55	46.11	60.18	59.09	63.95	69.55	64.12	63.29	58.61	60.38	66.35	55.41	60.15	56.42	59.93	55.70	53.30	52.60	48.51
			a*	5.25	4.16	4.32	3.83	5.86	4.60	3.67	3.60	3.69	5.29	4.12	4.49	3.11	4.09	5.58	3.97	4.61	3.84	4.17	3.35
			b*	17.77	22.97	13.91	19.48	21.95	20.79	18.65	15.15	15.18	18.45	15.07	20.29	13.82	17.06	19.80	19.12	17.40	13.72	15.62	13.66
Cleatham Cremation	MT85BH 2	SCI	L*	64.52	63.44	63.88	56.33	54.09	53.05	57.07	55.93	62.43	55.76	70.17	68.06	67.77	68.30	66.77	59.29	59.87	53.59	52.66	57.37
			a*	4.50	4.70	5.19	4.17	4.66	4.42	4.86	4.76	5.30	4.30	4.59	5.43	5.16	4.80	4.29	4.92	5.02	4.34	4.43	5.19
			b*	17.02	16.08	17.12	13.88	13.12	12.26	14.76	14.30	17.71	13.99	18.72	20.05	18.95	17.89	16.51	15.00	15.94	12.98	12.23	15.17
		-	G	77	80	77	82	85	85	82	85	75	81	70	75	76	72	80	80	82	88	83	80
		SCE	L*	61.69	60.43	61.02	52.54	49.86	48.70	53.34	51.94	59.52	51.94	67.95	65.54	65.22	65.89	64.01	55.92	56.46	49.13	48.33	53.80
			a*	4.90	5.13	5.66	4.68	5.27	5.03	5.43	5.32	5.81	4.84	4.96	5.86	5.58	5.17	4.62	5.45	5.54	4.89	5.06	5.80
			b*	19.48	18.46	19.63	16.68	16.00	15.13	17.64	17.22	20.53	16.92	20.93	22.59	21.34	20.12	18.60	17.65	18.68	15.88	15.21	18.13
Cleatham Cremation	MT85BH 3	SCI	L*	63.87	62.80	62.08	64.99	62.39	65.96	63.23	51.02	60.72	55.91	56.11	47.02	53.72	55.87	55.62	54.84	57.30	56.88	54.15	59.24
			a*	6.14	5.61	5.78	5.59	5.42	3.80	5.49	4.82	4.46	4.68	3.80	3.63	3.75	4.44	4.36	4.78	4.32	4.17	4.22	4.53
			b*	18.28	17.69	17.60	18.23	16.52	15.35	17.67	12.66	14.22	13.44	11.79	8.88	11.26	12.37	12.33	12.96	13.07	12.84	11.32	13.55
		-	G	80	78	78	75	78	77	75	86	79	85	85	88	87	86	82	83	83	81	83	81
		SCE	L*	60.90	59.81	59.01	62.26	59.37	63.24	60.41	46.33	57.53	51.95	52.13	41.48	49.35	51.85	51.75	50.82	53.57	53.18	50.04	55.79
			a*	6.70	6.13	6.34	6.08	5.93	4.11	6.01	5.55	4.92	5.23	4.22	4.29	4.21	4.96	4.90	5.39	4.80	4.65	4.76	5.02
			b*	20.97	20.42	20.42	20.82	19.10	17.38	20.38	15.99	16.58	16.17	14.10	11.75	13.74	14.82	14.90	15.72	15.54	15.34	13.83	15.92
Cleatham Cremation	MT86TR 1	SCI	L*	53.94	54.91	57.88	64.19	56.23	56.43	56.06	54.77	54.10	53.72	57.73	53.73	54.13	53.65	58.54	58.19	54.19	58.89	51.71	53.75
			a*	2.15	2.54	1.17	-0.14	1.05	1.98	3.28	2.17	2.15	1.21	-0.19	0.19	1.20	-0.96	-0.69	-0.19	2.91	2.09	2.20	1.26
			b*	8.91	10.00	7.04	2.95	6.48	9.00	12.21	9.27	8.65	6.50	3.88	5.00	6.34	2.00	0.52	2.57	9.19	9.26	8.30	7.18
		-	G	84	83	82	78	83	82	82	84	83	85	82	84	84	85	84	80	83	82	85	85
		SCE	L*	49.78	50.92	54.26	61.30	52.38	52.67	52.22	50.72	49.98	49.46	54.09	49.51	49.98	49.39	54.90	54.68	50.12	55.39	47.14	49.49
			a*	2.38	2.83	1.25	-0.20	1.12	2.18	3.65	2.41	2.39	1.32	-0.29	0.13	1.31	-1.21	-0.86	-0.28	3.25	2.29	2.47	1.37
			b*	10.92	12.15	8.42	3.52	7.86	10.82	14.69	11.27	10.59	8.01	4.75	6.23	7.81	2.70	0.89	3.23	11.23	10.89	10.39	8.81
Cleatham Cremation	MT86TR 2	SCI	L*	60.22	57.82	56.39	59.01	55.08	59.05	56.04	58.66	57.88	62.53	57.23	60.80	56.14	61.37	52.32	53.91	55.73	57.37	55.41	56.95
			a*	1.41	1.91	2.43	2.91	1.90	2.44	1.88	3.83	1.84	2.10	4.57	3.46	3.94	2.84	1.70	1.34	3.28	3.18	3.65	3.41
			b*	8.30	8.48	9.74	11.42	8.27	10.49	8.66	13.66	10.20	11.61	14.66	13.59	13.19	12.54	7.66	7.27	11.08	12.12	12.01	12.22
		-	G	80	81	83	81	82	80	82	80	82	79	81	80	83	80	83	84	81	81	81	84
		SCE	L*	56.92	54.24	52.58	55.57	51.13	55.62	52.23	55.20	54.26	59.47	53.57	57.54	52.28	58.17	47.97	49.75	51.91	53.75	51.54	53.14
			a*	1.51	2.08	2.67	3.20	2.08	2.66	2.06	4.24	2.00	2.26	5.09	3.80	4.39	3.10	1.89	1.46	3.66	3.53	4.09	3.78
			b*	9.73	10.08	11.69	13.44	10.04	12.34	10.44	16.14	12.09	13.36	17.49	15.80	15.84	14.52	9.55	8.91	13.37	14.43	14.55	14.54
Cleatham Cremation	MT86TR 3	SCI	L*	80.04	72.97	79.51	75.54	76.83	81.22	75.66	76.40	48.67	49.89	51.16	50.49	48.38	49.45	50.95	48.91	67.34	66.15	50.35	50.63
			a*	1.11	2.87	1.08	1.87	2.21	1.17	2.50	2.29	2.12	1.94	2.08	3.05	2.13	1.56	2.45	1.36	2.17	1.83	2.39	1.34
			b*	10.21	14.20	10.56	12.29	12.98	10.88	13.02	13.22	7.19	6.77	7.62	9.40	7.54	6.53	8.09	6.41	10.84	9.61	8.39	6.15
		-	G	63	69	66	67	67	62	66	68	86	84	85	85	87	85	85	86	77	78	85	86
		SCE	L*	78.45	70.92	77.84	73.67	75.00	79.69	73.81	74.53	43.55	45.10	46.53	45.76	43.17	44.53	46.30	43.85	64.72	63.41	45.58	45.87
			a*	1.18	3.06	1.14	1.99	2.34	1.23	2.66	2.44	2.44	2.20	2.35	3.50	2.44	1.76	2.79	1.52	2.32	1.95	2.71	1.47
			b*	11.09	15.66	11.48	13.48	14.15	11.77	14.28	14.45	9.35	8.70	9.62	11.93	9.83	8.42	10.23	8.34	12.21	10.89	10.68	7.83

Type	Sample	Light	Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Cleatham Cremation	MT88AAA 1	SCI	L*	58.45	59.26	56.29	59.99	49.46	59.70	57.18	54.66	53.84	48.81	48.08	56.40	57.78	54.42	56.15	53.74	61.86	49.71	44.57	51.58
			a*	1.94	1.87	3.27	2.71	2.80	2.14	2.62	2.55	1.45	2.21	2.43	1.84	2.60	2.63	2.48	1.86	4.86	1.44	0.08	1.84
			b*	9.53	9.68	11.89	11.70	8.46	10.12	10.88	10.32	8.01	8.04	7.70	8.79	10.49	9.68	9.41	8.33	17.51	6.65	1.59	7.58
		-	G	81	83	81	83	87	81	81	84	83	88	91	82	83	85	83	84	78	88	90	85
		SCE	L*	54.92	55.75	52.54	56.56	44.43	56.31	53.53	50.56	49.68	43.62	42.56	52.61	54.09	50.27	52.27	49.53	58.79	44.66	38.34	47.00
			a*	2.10	2.02	3.64	2.94	3.22	2.34	2.90	2.83	1.59	2.55	2.81	2.01	2.85	2.93	2.73	2.06	5.33	1.58	-0.06	2.05
			b*	11.22	11.34	14.28	13.64	10.81	11.82	12.97	12.51	9.82	10.35	9.97	10.54	12.42	11.75	11.25	10.21	20.32	8.47	2.46	9.47
Cleatham Cremation	MT88AAA 2	SCI	L*	60.19	60.11	60.17	59.25	56.81	61.01	65.15	67.13	62.26	63.94	51.80	47.40	51.44	46.62	55.01	48.95	47.95	47.49	46.94	45.21
			a*	4.47	3.37	2.75	3.64	3.73	3.76	2.81	2.53	4.03	2.66	2.15	2.36	1.96	3.45	3.95	3.90	3.61	3.01	3.85	2.68
			b*	14.57	12.71	11.53	13.32	12.29	13.16	11.81	11.35	14.86	11.74	7.91	7.64	7.13	8.25	11.32	10.08	9.13	7.73	9.23	6.68
		-	G	78	79	79	82	83	81	77	74	76	79	85	87	86	90	84	87	87	87	87	93
		SCE	L*	56.98	56.85	56.90	55.78	53.03	57.75	62.36	64.58	59.30	61.02	47.27	41.99	46.76	40.82	50.98	43.86	42.63	42.08	41.43	38.93
			a*	4.93	3.70	3.00	4.01	4.16	4.11	3.03	2.71	4.41	2.87	2.41	2.75	2.18	4.07	4.44	4.54	4.23	3.52	4.58	3.15
			b*	17.06	14.85	13.45	15.63	14.67	15.29	13.41	12.81	17.20	13.42	9.87	10.08	8.95	10.91	13.74	13.00	11.90	10.16	12.25	8.95
Cleatham Cremation	MT88AAA 3	SCI	L*	51.82	55.62	61.31	57.79	50.53	43.02	45.47	47.25	42.25	42.29	43.63	44.88	49.21	49.41	48.60	46.11	44.04	39.20	50.01	42.76
			a*	3.31	2.77	1.24	3.04	2.02	0.81	1.78	1.21	1.30	0.47	1.24	0.74	2.26	1.53	2.01	1.49	1.57	0.63	2.42	2.18
			b*	10.79	10.77	8.33	12.85	7.93	3.03	5.64	4.79	3.48	2.31	4.10	3.44	7.06	6.26	6.61	5.27	4.29	1.09	8.15	5.06
		-	G	87	84	79	83	87	90	89	87	90	90	89	89	88	87	86	88	88	91	88	90
		SCE	L*	47.16	51.67	58.14	54.12	45.67	36.38	39.48	41.79	35.42	35.43	37.19	38.80	44.10	44.38	43.47	40.40	37.80	31.29	45.04	36.04
			a*	3.75	3.07	1.32	3.35	2.27	0.86	2.09	1.35	1.50	0.42	1.42	0.76	2.59	1.71	2.31	1.69	1.83	0.64	2.75	2.64
			b*	13.41	12.98	9.68	15.22	10.02	4.47	7.65	6.41	5.19	3.59	5.85	4.83	9.07	8.08	8.62	7.13	6.08	2.09	10.37	7.23
Cleatham Cremation	MT88ALD 1	SCI	L*	50.12	51.42	52.78	49.28	50.19	49.77	50.61	49.72	49.11	52.52	56.21	57.94	59.81	58.65	58.16	55.78	58.85	60.57	59.83	59.08
			a*	0.72	0.52	0.43	-0.01	0.17	0.41	0.24	0.13	0.39	0.60	0.29	0.05	-0.07	0.05	-0.08	-0.31	0.10	0.38	0.13	0.05
			b*	3.25	2.92	3.37	1.63	2.10	2.54	2.34	2.53	2.39	4.13	4.34	3.24	3.47	3.67	3.14	1.49	3.95	5.34	5.23	4.42
		-	G	85	85	84	86	86	85	85	86	85	84	82	78	77	78	78	80	78	77	78	78
		SCE	L*	45.30	46.84	48.44	44.29	45.37	44.90	45.87	44.82	44.16	48.15	52.40	54.51	56.59	55.30	54.75	52.04	55.53	57.43	56.58	55.77
			a*	0.74	0.50	0.42	-0.14	0.09	0.37	0.18	0.04	0.35	0.60	0.25	-0.01	-0.14	-0.02	-0.16	-0.42	0.04	0.37	0.08	0.00
			b*	4.32	3.85	4.31	2.37	2.91	3.46	3.19	3.44	3.31	5.25	5.33	3.95	4.17	4.42	3.83	1.99	4.73	6.25	6.13	5.24
Cleatham Cremation	MT88ALD 2	SCI	L*	59.03	55.80	56.97	58.58	58.17	61.57	58.48	46.62	51.65	55.75	47.43	49.28	49.49	52.14	55.50	54.27	47.62	49.58	44.87	51.11
			a*	-1.45	0.48	0.45	1.17	1.35	-0.64	1.22	1.03	1.51	1.57	-0.37	-0.03	-0.39	0.63	0.93	1.52	-0.21	-0.21	1.54	0.93
			b*	3.09	4.97	4.72	7.68	8.52	3.95	7.80	4.31	6.97	7.85	1.68	2.46	1.34	3.77	5.03	6.94	1.42	2.17	4.29	4.59
		-	G	80	80	79	78	79	77	79	86	83	80	84	83	84	81	79	80	84	83	89	84
		SCE	L*	55.64	52.03	53.39	55.20	54.73	58.53	55.07	41.11	47.22	51.97	42.21	44.45	44.67	47.86	51.79	50.36	42.47	44.81	38.77	46.54
			a*	-1.68	0.47	0.43	1.26	1.47	-0.75	1.31	1.11	1.66	1.70	-0.57	-0.15	-0.57	0.63	0.98	1.65	-0.36	-0.36	1.75	0.99
			b*	3.76	6.01	5.68	9.00	9.99	4.67	9.16	5.72	8.64	9.37	2.45	3.30	1.96	4.76	6.09	8.42	2.11	2.96	5.77	5.77
Cleatham Cremation	MT88ALD 3	SCI	L*	58.33	56.94	58.18	57.96	59.89	60.68	57.71	56.73	58.35	57.38	45.06	50.19	50.25	49.62	51.55	49.71	48.62	49.87	49.25	50.56
			a*	4.43	2.86	2.78	2.55	3.69	3.53	4.26	3.23	4.52	4.11	0.11	0.27	-0.04	1.80	2.11	-0.13	-0.22	0.27	-0.48	0.07
			b*	14.05	10.32	10.81	9.40	12.66	12.59	13.00	11.11	13.90	13.56	1.29	4.38	3.04	6.89	8.07	3.04	2.08	4.12	1.34	3.61
		-	G	80	78	78	77	77	76	79	79	79	79	84	81	82	86	84	83	83	82	82	83
		SCE	L*	54.87	53.40	54.77	54.55	56.71	57.57	54.22	53.11	54.89	53.85	39.41	45.63	45.63	44.69	47.05	44.99	43.71	45.42	44.50	45.98
			a*	4.89	3.16	3.06	2.80	4.05	3.87	4.71	3.58	4.99	4.55	0.01	0.21	-0.13	2.02	2.36	-0.28	-0.36	0.22	-0.67	-0.02
			b*	16.47	12.22	12.69	11.05	14.69	14.54	15.32	13.16	16.28	16.01	2.03	5.61	3.98	8.65	9.95	4.00	2.88	5.31	1.97	4.66
Cleatham Cremation	MT89BBT 1	SCI	L*	43.99	42.16	41.56	43.74	44.05	45.18	41.13	44.02	44.45	44.53	43.96	43.31	43.13	43.73	43.13	48.61	46.38	44.17	44.11	49.92
			a*	1.25	0.89	1.01	1.08	1.92	2.44	1.46	2.13	2.13	2.77	1.65	0.23	0.78	1.01	0.70	3.75	2.58	2.22	2.01	4.16
			b*	4.23	2.70	2.66	3.53	5.32	6.70	3.35	5.20	5.73	6.77	4.32	0.78	2.12	2.68	2.31	9.25	6.94	5.62	5.29	9.91
		-	G	85	87	86	86	85	85	87	85	85	85	85	88	87	86	87	85	86	88	88	85
		SCE	L*	38.03	35.51	34.87	37.65	38.06	39.43	34.21	38.01	38.60	38.63	37.93	36.93	36.79	37.58	36.75	43.53	40.82	38.01	37.94	45.11
			a*	1.44	0.97	1.12	1.22	2.25	2.87	1.70	2.52	2.51	3.31	1.92	0.14	0.84	1.11	0.73	4.39	3.05	2.63	2.37	4.83
			b*	5.87	3.92	3.98	4.95	7.27	8.97	4.95	7.17	7.78	9.15	5.97	1.25	2.99	3.65	3.22	11.66	8.95	7.49	7.06	12.33

Type	Sample	Light	Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Cleatham Cremation	MT89BBT 2	SCI	L*	54.03	58.16	56.09	56.26	54.72	56.15	56.14	57.04	58.98	58.37	50.09	47.25	49.51	47.96	49.51	48.17	46.11	47.91	51.47	45.73
			a*	3.47	2.51	2.89	2.95	2.20	1.91	3.09	2.70	2.96	3.87	3.24	2.77	4.47	4.64	4.64	2.62	1.95	3.46	2.85	2.79
			b*	10.00	8.77	8.85	8.60	8.59	7.56	10.14	9.07	10.72	12.13	8.54	6.99	10.39	9.73	10.76	7.38	5.85	8.59	8.79	6.78
		-	G	84	78	79	79	83	82	81	79	82	82	84	85	84	85	84	86	87	85	84	86
		SCE	L*	49.88	54.75	52.44	52.63	50.72	52.32	52.40	53.49	55.50	54.80	45.37	41.96	44.65	42.77	44.66	42.98	40.40	42.76	46.95	40.06
			a*	3.91	2.77	3.24	3.29	2.44	2.10	3.43	3.00	3.25	4.27	3.75	3.26	5.22	5.46	5.41	3.05	2.28	4.08	3.26	3.32
			b*	11.95	10.20	10.46	10.17	10.22	8.89	11.97	10.64	12.40	14.09	10.60	8.98	13.02	12.36	13.48	9.32	7.57	10.94	10.75	8.87
Cleatham Cremation	MT89BBT 3	SCI	L*	66.11	64.25	64.36	60.72	62.90	64.12	62.18	63.29	59.92	60.47	52.50	51.62	53.18	55.35	54.39	54.70	53.83	56.60	55.79	52.87
			a*	5.06	6.24	5.84	6.34	5.68	6.25	5.34	5.71	6.20	5.92	4.30	4.34	4.68	4.34	4.55	4.31	4.27	4.46	4.59	4.07
			b*	14.53	16.24	15.61	16.03	15.12	16.77	14.57	15.08	15.76	14.73	11.85	11.58	12.54	12.20	12.09	12.70	11.75	12.75	13.03	11.01
		-	G	76	76	76	76	77	77	80	77	78	76	84	85	84	83	82	86	84	80	81	82
		SCE	L*	63.45	61.44	61.55	57.63	59.96	61.28	59.07	60.38	56.66	57.37	48.12	47.08	48.91	51.41	50.35	50.50	49.62	52.92	52.02	48.66
			a*	5.49	6.80	6.37	7.01	6.22	6.81	5.84	6.23	6.85	6.54	4.91	4.97	5.31	4.87	5.13	4.83	4.83	4.99	5.15	4.64
			b*	16.28	18.40	17.63	18.53	17.19	18.98	16.58	17.10	18.24	16.98	14.36	14.18	15.14	14.45	14.48	15.06	14.09	15.03	125.47	13.37

- Sample designations taken from original excavations.
- Data available as spreadsheet in supplemental materials.

Appendix 11 – FTIR Data from the Archaeological Application

Sample Number	Site	Funerary Rite	Peaks at Wavenumber (cm^{-1})									
			1650	1550	1455	1415	1250	1035	900	605	595	565
EL75EN	Elsham	Inhumation	0.001894	0.00210756	0.01002188	0.01166854	-0.0012275	0.05607586	0.01424286	0.03259368	0.02368656	0.05163157
EL76AL	Elsham	Inhumation	0.00149721	0.00122497	0.00946567	0.01053901	-0.0005105	0.05529039	0.01790048	0.02799651	0.02093832	0.0481481
EL76AK	Elsham	Inhumation	0.00171602	0.00180242	0.00651586	0.00700027	0.0027069	0.03375308	0.005981	0.01427373	0.00745951	0.02570276
EL76JO(a)	Elsham	Inhumation	0.00246268	0.00237683	0.01180544	0.0136674	0.00536665	0.0656014	0.0171027	0.03811707	0.02784752	0.0592566
Grave 10	Cleatham	Inhumation	0.00027158	-0.0004881	0.00485544	0.0053541	0.00381244	0.05675807	0.02168243	0.02430921	0.0193234	0.04256507
Grave 11	Cleatham	Inhumation	0.00159683	0.00176727	0.00554365	0.00550542	0.01108839	0.0284206	0.00817151	0.01999868	0.01362815	0.02948609
Grave 18	Cleatham	Inhumation	0.00276243	0.0029451	0.0111924	0.01204024	0.01139666	0.05649177	0.01872963	0.03383816	0.02488056	0.05241093
Grave 19	Cleatham	Inhumation	0.00488527	0.0044052	0.01441007	0.01505707	0.0133666	0.06225279	0.03220048	0.02439716	0.02256143	0.04798703
Grave 25	Cleatham	Inhumation	0.00170082	0.00202957	0.01091551	0.01048949	0.0134686	0.02605203	0.0082936	0.01305134	0.01107993	0.02216428
Grave 29	Cleatham	Inhumation	0.00372278	0.00467697	0.02022113	0.02245264	0.01586317	0.11304379	0.02644424	0.06211128	0.04520407	0.0968778
Grave 31	Cleatham	Inhumation	-0.0007996	-0.0016858	0.00944399	0.00983553	0.01104447	0.05152122	0.02152079	0.01478041	0.01295174	0.04146753
Grave 37	Cleatham	Inhumation	0.00169909	0.0018875	0.00801794	0.00776177	0.0200006	0.04476428	0.01348917	0.02347983	0.01821201	0.03846889
Grave 38	Cleatham	Inhumation	0.00284506	0.00324845	0.00896587	0.00869977	0.01815033	0.03575532	0.01128391	0.02365928	0.01640277	0.03471668
Grave 40	Cleatham	Inhumation	0.00333945	0.00414567	0.01695881	0.01839191	0.01376155	0.09465467	0.02580445	0.05659051	0.04173064	0.08952045
Grave 45	Cleatham	Inhumation	0.0023595	0.00257618	0.01068586	0.01088695	0.01616941	0.04542686	0.01435929	0.02487824	0.01831031	0.03954463
Grave 48	Cleatham	Inhumation	0.0018393	0.00187317	0.00507829	0.00535428	0.00237047	0.0240556	0.00882961	0.01488485	0.01041596	0.02300037
Grave 49	Cleatham	Inhumation	0.00045277	-0.0001235	0.01205468	0.01291443	0.00061292	0.06961551	0.0199225	0.03088016	0.02304297	0.05522435
Grave 50	Cleatham	Inhumation	0.00324823	0.00270195	0.00764886	0.00824221	0.00749497	0.04821372	0.01830971	0.02677477	0.02188674	0.04194385
Grave 54	Cleatham	Inhumation	0.00389031	0.00297422	0.01185393	0.01304504	0.01142684	0.08242821	0.02955694	0.04145481	0.03363169	0.0682442
Grave 57	Cleatham	Inhumation	0.00310982	0.00332992	0.0090759	0.00962493	0.01328192	0.04320779	0.01367796	0.02847716	0.02139647	0.04280049
EL75AP 1	Elsham	Cremation	8.1245E-05	-2.377E-05	0.01226442	0.00767797	0.01045662	0.16901776	0.0697919	0.10873078	0.05594014	0.16081495
EL75AP 2	Elsham	Cremation	0.00402243	0.00360312	0.01122434	0.00950146	0.01684152	0.09973419	0.04516225	0.05807096	0.03174433	0.08389984
EL75AP 3	Elsham	Cremation	0.00424054	0.00363128	0.01455144	0.01222532	0.01550896	0.13178627	0.06098287	0.07261047	0.04049101	0.10666409
EL75DW 1	Elsham	Cremation	0.00784352	0.00861023	0.02815261	0.03092362	0.01933598	0.18482039	0.03947423	0.09475781	0.05886651	0.1493856
EL75DW 2	Elsham	Cremation	0.00631393	0.00683913	0.02875147	0.03221427	0.00185166	0.25019865	0.04509317	0.11388198	0.06556995	0.18612857
EL75DW 3	Elsham	Cremation	0.00446782	0.00521154	0.0208761	0.02226752	0.0041205	0.14160241	0.0329829	0.07379564	0.04676977	0.11789664
EL75DX 1	Elsham	Cremation	0.00341302	0.00249244	0.01153487	0.01182957	0.00434166	0.12518959	0.0434867	0.05685878	0.03307399	0.08917458
EL75DX 2	Elsham	Cremation	0.00567403	0.00657196	0.02984846	0.03174553	0.00512624	0.23643542	0.05677193	0.11365401	0.06949541	0.18691362
EL75DX 3	Elsham	Cremation	0.00048058	0.00054635	0.01211723	0.01358504	0.00448574	0.09862731	0.02233869	0.054118	0.03151393	0.08676572
EL75ES 1	Elsham	Cremation	0.00252051	0.00259727	0.01110375	0.00858475	0.01526422	0.1924915	0.07284412	0.12268818	0.05806038	0.17171499
EL75ES 2	Elsham	Cremation	0.00139776	0.00135765	0.00784484	0.00629298	0.01152186	0.11595807	0.04187262	0.07292353	0.03396958	0.10465658
EL75ES 3	Elsham	Cremation	0.00041892	-0.0002458	0.003943	0.00249515	0.00797047	0.06048383	0.02061362	0.02241949	0.01000703	0.0428164
EL75LW 1	Elsham	Cremation	0.00046594	0.00055714	0.00571808	0.00459767	-0.0003837	0.07506544	0.03271533	0.05983976	0.02971684	0.07955489
EL75LW 2	Elsham	Cremation	0.00052412	0.00088381	0.00856866	0.00561239	0.00381326	0.11611592	0.04820988	0.08411426	0.04150808	0.11600011
EL75LW 3	Elsham	Cremation	-0.0001628	0.000326	0.01185998	0.00993728	0.0087406	0.08928134	0.03486232	0.0645338	0.03009118	0.09105685
EL76IL 1	Elsham	Cremation	0.00192851	0.00259326	0.01329625	0.00995246	0.01522471	0.09549652	0.03591547	0.07106274	0.03420934	0.09835087
EL76IL 2	Elsham	Cremation	0.00157508	0.00222591	0.01391563	0.01035098	0.01611358	0.11083997	0.03715997	0.0662082	0.03117596	0.09796447
EL76IL 3	Elsham	Cremation	0.00180418	0.00261316	0.01843276	0.01360003	0.02002861	0.17811656	0.05928661	0.09749777	0.04680622	0.15719275
EL76MN 1	Elsham	Cremation	0.0016133	0.00238397	0.01379709	0.00878204	0.01810775	0.15661642	0.05549724	0.08842164	0.04334712	0.14076268
EL76MN 2	Elsham	Cremation	0.00533051	0.00541998	0.01568254	0.01273329	0.02160316	0.11671284	0.04468803	0.05513849	0.02921986	0.08756632
EL76MN 3	Elsham	Cremation	0.00204679	0.00254291	0.01437968	0.0113785	0.01834028	0.08425857	0.03145015	0.05041969	0.02645664	0.07728963
EL76NN 1	Elsham	Cremation	0.00240337	0.00348363	0.0128802	0.00895408	0.01373639	0.2012338	0.06605662	0.13283107	0.055662	0.18999007
EL76NN 2	Elsham	Cremation	0.00278651	0.00265015	0.01149102	0.00760838	0.0163084	0.12612852	0.05272158	0.08170217	0.03834755	0.12164582
EL76NN 3	Elsham	Cremation	0.00154414	0.0017218	0.01601172	0.01005578	0.01719804	0.23942648	0.09458331	0.14894946	0.06498138	0.22600456
EL76PY 1	Elsham	Cremation	0.00664103	0.00699611	0.02044832	0.01618859	0.02404906	0.17542228	0.07999891	0.10237038	0.05563864	0.14958061
EL76PY 2	Elsham	Cremation	0.00285705	0.00422527	0.0160028	0.01253081	0.02211246	0.11869939	0.04741358	0.0811828	0.03964404	0.11757774
EL76PY 3	Elsham	Cremation	0.00756424	0.00609004	0.01449638	0.01126576	0.02106112	0.15619947	0.07764667	0.07228033	0.04295262	0.11385137
EL76PZ 1	Elsham	Cremation	0.00346945	0.00438907	0.0284864	0.0196124	0.01958054	0.26848466	0.11132208	0.17237696	0.08789893	0.25900588
EL76PZ 2	Elsham	Cremation	0.0024309	0.0029305	0.01677461	0.01147769	0.01799755	0.15697477	0.06610447	0.10277978	0.05272977	0.15107216
EL76PZ 3	Elsham	Cremation	0.00316728	0.00414521	0.01375889	0.00999208	0.01698507	0.1117479	0.04571524	0.07743998	0.03968796	0.1091697
MT84FT 1	Cleatham	Cremation	0.0083668	0.00971812	0.02537104	0.0284946	0.01725964	0.10102737	0.02501502	0.04327559	0.02795614	0.07549443
MT84FT 2	Cleatham	Cremation	0.00056549	0.00032344	0.0094839	0.01094094	-0.0037518	0.08608849	0.01887044	0.04743165	0.02882533	0.07693824
MT84FT 3	Cleatham	Cremation	0.00210771	0.00186058	0.01210249	0.01328945	0.00045824	0.08942343	0.02036808	0.05057605	0.0318101	0.07774898
MT84IT 1	Cleatham	Cremation	0.00315698	0.00305249	0.01488102	0.01565447	0.00661918	0.09860253	0.02641485	0.0569142	0.03595983	0.08874797
MT84IT 2	Cleatham	Cremation	0.0029116	0.00275875	0.01320956	0.01321065	0.00931423	0.10980898	0.02878431	0.06106022	0.03490206	0.09481415
MT84IT 3	Cleatham	Cremation	0.00378095	0.00418705	0.01718591	0.01817175	0.01237685	0.14736639	0.02914368	0.07116859	0.04089933	0.11033945
MT84KJ 1	Cleatham	Cremation	0.00174061	0.00207103	0.01344422	0.01370252	0.00884529	0.12327145	0.02720365	0.05894078	0.0342919	0.09485361
MT84KJ 2	Cleatham	Cremation	0.00502346	0.00567956	0.01633192	0.01630134	0.01525912	0.13261026	0.03122458	0.06305189	0.03562091	0.09732599
MT84KJ 3	Cleatham	Cremation	0.00396484	0.00462344	0.02474684	0.02531273	0.00945193	0.20720363	0.0419371	0.10163165	0.06025866	0.16253824
MT85AQ 1	Cleatham	Cremation	0.00385944	0.00351068	0.0092929	0.00621202	0.01135448	0.33246169	0.10802583	0.17284651	0.06650167	0.25646241
MT85AQ 2	Cleatham	Cremation	0.00158833	0.00175907	0.00946754	0.00576012	0.01350824	0.12411028	0.05258916	0.08389561	0.04329482	0.12172049
MT85AQ 3	Cleatham	Cremation	0.00204626	-0.000584	-0.0013126	-0.0018531	0.00370847	0.07783941	0.04617848	0.021132	0.01554715	0.05332547
MT85AR 1	Cleatham	Cremation	0.00107497	0.00133388	0.00855215	0.00882357	0.00126912	0.0867153	0.02020656	0.04557119	0.02352151	0.06911794
MT85AR 2	Cleatham	Cremation	0.00330129	0.00336011	0.01714075	0.01711064	0.00189813	0.21366498	0.04089458	0.09641472	0.04712872	0.15080163
MT85AR 3	Cleatham	Cremation	0.00375227	0.00407465	0.01721661	0.01869581	0.00366422	0.13838347	0.03094412	0.07525485	0.04616038	0.11862738
MT85BH 1	Cleatham	Cremation	0.00307018	0.00192805	0.00398673	0.00296122	0.00521909	0.07961145	0.03748313	0.02303914	0.01236372	0.04534171
MT85BH 2	Cleatham	Cremation	0.00270001	0.00110718	0.00509272	0.00338778	0.00408051	0.12917191	0.06061031	0.06398712	0.03561761	0.09640341
MT85BH 3	Cleatham	Cremation	0.00321293	0.00105976	0.0057733	0.00372353	0.00677754	0.19506116	0.08417125	0.08541578	0.04769097	0.14157246
MT86TR 1	Cleatham	Cremation	0.00375185	0.00403463	0.02070385	0.01991063	0.00166119	0.25996986	0.0624651	0.12872257	0.05741907	0.1943373
MT86TR 2	Cleatham	Cremation	0.00292234	0.00266715	0.01595374	0.01783964	0.0025707	0.12852708	0.02833546	0.06859741	0.04071516	0.10714014
MT86TR 3	Cleatham	Cremation	0.00235141	0.00242446	0.01379643	0.01381943	0.00949222	0.12145967	0.02712576	0.06900231	0.03574586	0.10018459
MT88AAA 1	Cleatham	Cremation	-0.000747	3.8215E-05	0.01584177	0.01319042	0.01047587	0.22376225	0.07723534	0.12960166	0.05376513	0.18248621
MT88AAA 2	Cleatham	Cremation	0.00538488	0.00515724	0.01801998	0.01477456	0.01968079	0.16872257	0.07328562	0.10280789	0.05674548	0.14412816
MT88AAA 3	Cleatham	Cremation	0.00385001	0.00455614	0.02086075	0.02222834	0.01897335	0.13138512	0.03846989	0.06720173	0.04784937	0.10790048
MT88ALD 1	Cleatham	Cremation	0.00299875	0.00286574	0.01361488	0.01325965	-7.405E-05	0.18478882	0.03593214	0.0897266	0.04360486	0.13735571
MT88ALD 2	Cleatham	Cremation	0.00328718	0.00261366	0.01533184	0.01600132	-0.0002434	0.19516819	0.03866891	0.08734453	0.04439257	0.14302318
MT88ALD 3	Cleatham	Cremation	0.00369351	0.00311544	0.01598248	0.01812228	0.00019626	0.17196469	0.02957696	0.07957007	0.04414223	0.13110434
MT89BBT 1	Cleatham	Cremation	0.00370292	0.00228804	0.00287617	0.00332252	0.0048396	0.0571346	0.03421658	0.02071116	0.02004771	0.04758606
MT89BBT 2	Cleatham	Cremation	0.00483501	0.00429593	0.01504479	0.01702178	0.00223957	0.13643493	0.04001533	0.07061946	0.04885854	0.11180342
MT89BBT 3	Cleatham	Cremation	0.00225326	0.00052315	0.0061477	0.00466347	0.00479696	0.1228409	0.05472762	0.06255052	0.03728207	0.09222837

Sample Number	Site	Funerary Rite	Ratios at Wavenumber (cm^{-1})							
			(605+565)/5	1415/1035	1650/1035	1650/1415	900/1035	1035/1415	1650/1455	1455/1415
EL75EN	Elsham	Inhumation	3.5558238	0.20808488	0.03377563	0.16231661	0.25399275	4.8057313	0.1889863	0.85888027
EL76AL	Elsham	Inhumation	3.63661483	0.19061198	0.02707903	0.14206364	0.32375383	5.24626008	0.15817269	0.89815528
EL76AK	Elsham	Inhumation	5.35912809	0.20739643	0.05084041	0.24513635	0.17719853	4.82168367	0.26336039	0.93080193
EL76JO(a)	Elsham	Inhumation	3.49667246	0.20834008	0.03754002	0.18018626	0.26070634	4.79984445	0.20860536	0.86376619
Grave 10	Cleatham	Inhumation	3.4607917	0.09433189	0.0047849	0.05072408	0.38201492	10.6008691	0.05593349	0.90686418
Grave 11	Cleatham	Inhumation	3.63106868	0.19371238	0.05618576	0.29004731	0.28752067	5.16229263	0.28804726	1.0069435
Grave 18	Cleatham	Inhumation	3.4665252	0.21313258	0.04889967	0.2294331	0.33154611	4.6919153	0.2468129	0.92958313
Grave 19	Cleatham	Inhumation	3.20831621	0.24186977	0.0784747	0.3244502	0.51725351	4.13445634	0.33901761	0.95703053
Grave 25	Cleatham	Inhumation	3.17832447	0.40263616	0.06528556	0.16214531	0.31834767	2.48363189	0.15581692	1.0406143
Grave 29	Cleatham	Inhumation	3.51714089	0.19861897	0.03293218	0.16580581	0.23392917	5.0347659	0.18410338	0.90061251
Grave 31	Cleatham	Inhumation	4.34288582	0.19090261	-0.0155202	-0.0812992	0.41770728	5.23827293	-0.0846699	0.96019101
Grave 37	Cleatham	Inhumation	3.40153064	0.17339214	0.03795636	0.21890475	0.30133774	5.76727396	0.21191086	1.03300393
Grave 38	Cleatham	Inhumation	3.55890829	0.24331403	0.07957033	0.32702731	0.31558694	4.10991514	0.31732136	1.03058714
Grave 40	Cleatham	Inhumation	3.501287	0.19430532	0.03528037	0.18157183	0.27261682	5.14653937	0.1969155	0.92207993
Grave 45	Cleatham	Inhumation	3.51839379	0.23965895	0.05194057	0.21672703	0.31609686	4.17259614	0.22080545	0.98152936
Grave 48	Cleatham	Inhumation	3.63722745	0.22257941	0.07646041	0.34351969	0.36705017	4.49277855	0.36218871	0.948455
Grave 49	Cleatham	Inhumation	3.73669298	0.18551078	0.00650387	0.03505928	0.286179	5.39052243	0.03755972	0.93342762
Grave 50	Cleatham	Inhumation	3.13973763	0.17095156	0.06737156	0.39409736	0.37976146	5.84961018	0.42466896	0.92801076
Grave 54	Cleatham	Inhumation	3.26177533	0.15825942	0.04719631	0.29822118	0.35857794	6.31873901	0.32818715	0.90869242
Grave 57	Cleatham	Inhumation	3.33128149	0.22275918	0.07197355	0.32310026	0.3165623	4.48915274	0.34264558	0.94295759
EL75AP 1	Elsham	Cremation	4.81846708	0.045427	0.00048069	0.01058159	0.4129264	22.0133379	0.00662446	1.59735208
EL75AP 2	Elsham	Cremation	4.47232048	0.09526781	0.04033151	0.42334879	0.45282619	10.4967248	0.35836671	1.18132846
EL75AP 3	Elsham	Cremation	4.42751473	0.09276626	0.03217742	0.34686558	0.46274071	10.7797812	0.29141731	1.19027105
EL75DW 1	Elsham	Cremation	4.14740733	0.16731714	0.04243862	0.25364178	0.21358158	5.97667409	0.27860723	0.91039194
EL75DW 2	Elsham	Cremation	4.57542741	0.12875477	0.02523566	0.19599783	0.18022948	7.76670264	0.2196036	0.89250738
EL75DW 3	Elsham	Cremation	4.0986366	0.1572538	0.03155184	0.2006428	0.2329261	6.35914694	0.2140159	0.93751356
EL75DX 1	Elsham	Cremation	4.4153535	0.09449324	0.02726282	0.28851606	0.34736673	10.5827677	0.29588737	0.97508746
EL75DX 2	Elsham	Cremation	4.32500002	0.13426724	0.02399821	0.17873466	0.240116	7.44783319	0.19009446	0.94024131
EL75DX 3	Elsham	Cremation	4.47052202	0.13774113	0.0048727	0.0353758	0.22649599	7.25999571	0.03966102	0.89195393
EL75ES 1	Elsham	Cremation	5.0706383	0.04459809	0.01309411	0.29360259	0.37842775	22.4224857	0.22699583	1.29342725
EL75ES 2	Elsham	Cremation	5.22762124	0.05426943	0.01205405	0.22211496	0.36110139	18.4265791	0.17817636	1.24660176
EL75ES 3	Elsham	Cremation	6.5190055	0.04125325	0.00692609	0.167892	0.34081213	24.2405149	0.1062431	1.58026262
EL75LW 1	Elsham	Cremation	4.69076347	0.06124876	0.00620715	0.1013433	0.43582413	16.3268615	0.08148584	1.24369212
EL75LW 2	Elsham	Cremation	4.82109386	0.04833437	0.00451377	0.09338635	0.41518751	20.6892105	0.06116715	1.52674027
EL75LW 3	Elsham	Cremation	5.17063904	0.11130298	-0.0018232	-0.0163805	0.39047715	8.98448564	-0.013725	1.19348318
EL76IL 1	Elsham	Cremation	4.95226184	0.10421808	0.02019451	0.19377164	0.37609191	9.59526449	0.14504133	1.33597526
EL76IL 2	Elsham	Cremation	5.26600144	0.09338668	0.01421041	0.15216745	0.33525784	10.7081649	0.11318798	1.34437815
EL76IL 3	Elsham	Cremation	5.44138234	0.07635466	0.01012923	0.13266032	0.33285288	13.096778	0.0978792	1.35534737
EL76MN 1	Elsham	Cremation	5.28718638	0.05607353	0.01030095	0.18370437	0.35435137	17.8337273	0.11693032	1.57105846
EL76MN 2	Elsham	Cremation	4.88382927	0.10909928	0.04567205	0.41862828	0.38288875	9.16596296	0.33990111	1.23161785
EL76MN 3	Elsham	Cremation	4.82711828	0.13504262	0.02429172	0.17988191	0.3732576	7.40506958	0.14233881	1.26375868
EL76NN 1	Elsham	Cremation	5.79966789	0.04449591	0.01194318	0.26841086	0.32825809	22.4739774	0.18659428	1.43847313
EL76NN 2	Elsham	Cremation	5.3027637	0.06032242	0.02209261	0.36624209	0.4179989	16.5775856	0.24249434	1.51031191
EL76NN 3	Elsham	Cremation	5.77017635	0.04199943	0.00644933	0.15355767	0.39504115	23.8098466	0.0964382	1.59229093
EL76PY 1	Elsham	Cremation	4.52834571	0.09228352	0.03785739	0.41022911	0.45603622	10.8361708	0.32477135	1.26313208
EL76PY 2	Elsham	Cremation	5.01363023	0.10556758	0.02406965	0.22800228	0.39944246	9.47260546	0.17853454	1.2770766
EL76PY 3	Elsham	Cremation	4.33341866	0.07212417	0.04842678	0.67143622	0.49709945	13.8649771	0.52180198	1.28676442
EL76PZ 1	Elsham	Cremation	4.90771452	0.07304848	0.01292233	0.17690074	0.41463108	13.6895387	0.12179312	1.45246907
EL76PZ 2	Elsham	Cremation	4.81420515	0.07311803	0.01548593	0.21179364	0.42111523	13.6765173	0.14491553	1.46149711
EL76PZ 3	Elsham	Cremation	4.70192145	0.08941631	0.02834312	0.31697936	0.40909258	11.183642	0.2301992	1.37697854
MT84FT 1	Cleatham	Cremation	4.24844161	0.28204829	0.08281718	0.29362766	0.24760638	3.54549217	0.32977772	0.89038055
MT84FT 2	Cleatham	Cremation	4.31460471	0.12708942	0.00656875	0.05168604	0.21919813	7.86847534	0.05962669	0.86682712
MT84FT 3	Cleatham	Cremation	4.03409661	0.1486126	0.02356994	0.1585999	0.22777119	6.72890437	0.17415463	0.91068438
MT84IT 1	Cleatham	Cremation	4.05069172	0.15876338	0.03201724	0.2016664	0.26789222	6.29868172	0.21214817	0.95059223
MT84IT 2	Cleatham	Cremation	4.46605063	0.12030576	0.02651518	0.22039826	0.26213074	8.31215387	0.2204165	0.99991727
MT84IT 3	Cleatham	Cremation	4.43792192	0.12331	0.0256568	0.20806743	0.19776344	8.10964237	0.22000286	0.94574878
MT84KJ 1	Cleatham	Cremation	4.48486086	0.11115732	0.01412014	0.12702839	0.2206809	8.99625874	0.12946895	0.98114942
MT84KJ 2	Cleatham	Cremation	4.50235254	0.12292666	0.03788139	0.30816252	0.23546123	8.13493203	0.30758547	1.00187607
MT84KJ 3	Cleatham	Cremation	4.38393237	0.12216353	0.01913499	0.15663421	0.2023956	8.18574924	0.16021595	0.97764426
MT85AQ 1	Cleatham	Cremation	6.45561144	0.01868493	0.01160866	0.62128469	0.32492715	53.5190653	0.41530993	1.49595432
MT85AQ 2	Cleatham	Cremation	4.74920767	0.04641134	0.01279773	0.27574569	0.42372927	21.5464565	0.16776583	1.64363441
MT85AQ 3	Cleatham	Cremation	4.78914077	-0.0238063	0.02628825	-1.1042551	0.59325318	-42.005649	-1.5588913	0.70835929
MT85AR 1	Cleatham	Cremation	4.87592594	0.10175333	0.01239653	0.12182921	0.23302181	9.82768854	0.12569577	0.96923871
MT85AR 2	Cleatham	Cremation	5.24555564	0.08008163	0.01545078	0.19293789	0.19139578	12.4872587	0.19259901	1.00175952
MT85AR 3	Cleatham	Cremation	4.20018724	0.13510147	0.02711499	0.20070092	0.22361141	7.4018437	0.21794458	0.92088056
MT85BH 1	Cleatham	Cremation	5.53076559	0.03719586	0.03856458	1.03679765	0.47082592	26.8847121	0.77010006	1.34631551
MT85BH 2	Cleatham	Cremation	4.50312466	0.02622693	0.02090242	0.79698321	0.46922205	38.1287523	0.53017005	1.5032596
MT85BH 3	Cleatham	Cremation	4.75956474	0.01908906	0.0164714	0.86287158	0.43151209	52.3860389	0.55651589	1.55048868
MT86TR 1	Cleatham	Cremation	5.62635118	0.07658822	0.01443186	0.18843445	0.24027824	13.0568376	0.18121505	1.03983886
MT86TR 2	Cleatham	Cremation	4.31626858	0.13880061	0.02273712	0.16381139	0.22046293	7.20457939	0.18317558	0.89428618
MT86TR 3	Cleatham	Cremation	4.73304827	0.11377796	0.01935963	0.17015275	0.22333137	8.78904871	0.17043651	0.99833514
MT88AAA 1	Cleatham	Cremation	5.8046523	0.05894836	-0.0033383	-0.0566305	0.34516698	16.9640006	-0.0471526	1.20100599
MT88AAA 2	Cleatham	Cremation	4.35164235	0.08756719	0.03191556	0.36446943	0.43435578	11.4198028	0.29882804	1.21966276
MT88AAA 3	Cleatham	Cremation	3.65944645	0.1691846	0.02930322	0.17320266	0.29280251	5.91070359	0.18455747	0.9384755
MT88ALD 1	Cleatham	Cremation	5.20772972	0.07175569	0.01622796	0.22615576	0.19444976	13.9361769	0.22025513	1.02678998
MT88ALD 2	Cleatham	Cremation	5.1893299	0.08198736	0.01684282	0.20543196	0.19813122	12.1970021	0.21440242	0.95816065
MT88ALD 3	Cleatham	Cremation	4.77262719	0.10538375	0.02147831	0.20381049	0.17199438	9.4891289	0.23109757	0.88192397
MT89BBT 1	Cleatham	Cremation	3.40673356	0.0581525	0.06481042	1.11449065	0.59887669	17.1961648	1.28744741	0.86565917
MT89BBT 2	Cleatham	Cremation	3.73369459	0.12476117	0.03543819	0.28404827	0.29329238	8.01531416	0.32137419	0.88385526
MT89BBT 3	Cleatham	Cremation	4.15156376	0.03796346	0.0183429	0.48317254	0.44551628	26.3411186	0.36652042	1.3182691

- Peaks and ratios used in the FTIR analysis of archaeological samples.
- Each bone sample was measured in triplicate and the results were averaged prior to further analysis.
- Samples were named using the original excavation labels.
- For cremated individuals three samples were selected from each individual and numbered 1-3.
- A baseline correction was conducted on the FTIR data before the peaks were isolated.
- Data available as spreadsheet in supplemental materials.

Appendix 12: Collagen Extraction from Samples taken from Inhumed Individuals at Elsham and Cleatham

Sample	Site	Burial Type	Isotope Lab Labels	Initial Dry Mass	0.5(M) HCl at 4°C					DI water rinse X3	Mixed to pH 3	Heating Block 70°C		Eezee Filter
					Added	1st Change	2nd Change	3rd Change	4th Change			Start	Finished	
EL75EN	Elsham	Inhumation	7260	450	24/02/2020	26/02/2020	n/a	n/a	n/a	28/02/2020	09/03/2020	09/03/2020	9-11/03/202	11/03/2020
EL76AL	Elsham	Inhumation	7261	404.2	24/02/2020	26/02/2020	28/02/2020	n/a	n/a	02/03/2020	09/03/2020	09/03/2020	9-11/03/202	11/03/2020
EL76AK	Elsham	Inhumation	7262	368.2	24/02/2020	26/02/2020	n/a	n/a	n/a	28/02/2020	09/03/2020	09/03/2020	9-11/03/202	11/03/2020
EL76JO(a)	Elsham	Inhumation	7263	389.6	24/02/2020	26/02/2020	n/a	n/a	n/a	28/02/2020	09/03/2020	09/03/2020	9-11/03/202	11/03/2020
G 10	Cleatham	Inhumation	7264	440.2	24/02/2020	26/02/2020	28/02/2020	n/a	n/a	02/03/2020	09/03/2020	09/03/2020	9-11/03/202	11/03/2020
G 11	Cleatham	Inhumation	7265	431.5	24/02/2020	26/02/2020	28/02/2020	02/03/2020	n/a	04/03/2020	09/03/2020	09/03/2020	9-11/03/202	11/03/2020
G 18	Cleatham	Inhumation	7266	353.9	24/02/2020	26/02/2020	28/02/2020	n/a	n/a	02/03/2020	09/03/2020	09/03/2020	9-11/03/202	11/03/2020
G 19	Cleatham	Inhumation	7267	398.1	24/02/2020	26/02/2020	28/02/2020	n/a	n/a	02/03/2020	09/03/2020	09/03/2020	9-11/03/202	11/03/2020
G 25	Cleatham	Inhumation	7268	411.6	24/02/2020	26/02/2020	n/a	n/a	n/a	28/02/2020	09/03/2020	09/03/2020	9-11/03/202	11/03/2020
G 29	Cleatham	Inhumation	7269	384.8	24/02/2020	26/02/2020	n/a	n/a	n/a	28/02/2020	09/03/2020	09/03/2020	9-11/03/202	11/03/2020
G 31	Cleatham	Inhumation	7270	352	24/02/2020	26/02/2020	n/a	n/a	n/a	28/02/2020	09/03/2020	09/03/2020	9-11/03/202	11/03/2020
G 37	Cleatham	Inhumation	7271	500.4	24/02/2020	26/02/2020	28/02/2020	n/a	n/a	02/03/2020	09/03/2020	09/03/2020	9-11/03/202	11/03/2020
G 38	Cleatham	Inhumation	7272	554.1	24/02/2020	26/02/2020	28/02/2020	02/03/2020	04/03/2020	06/03/2020	09/03/2020	09/03/2020	9-11/03/202	11/03/2020
G 40	Cleatham	Inhumation	7273	409.3	24/02/2020	26/02/2020	28/02/2020	n/a	n/a	02/03/2020	09/03/2020	09/03/2020	9-11/03/202	11/03/2020
G 45	Cleatham	Inhumation	7274	507.8	24/02/2020	26/02/2020	28/02/2020	02/03/2020	n/a	04/03/2020	09/03/2020	09/03/2020	9-11/03/202	11/03/2020
G 48	Cleatham	Inhumation	7275	401.7	24/02/2020	26/02/2020	28/02/2020	n/a	n/a	02/03/2020	09/03/2020	09/03/2020	9-11/03/202	11/03/2020
G 49	Cleatham	Inhumation	7276	474.7	24/02/2020	26/02/2020	28/02/2020	n/a	n/a	02/03/2020	09/03/2020	09/03/2020	9-11/03/202	11/03/2020
G 50	Cleatham	Inhumation	7277	335.7	24/02/2020	26/02/2020	n/a	n/a	n/a	28/02/2020	09/03/2020	09/03/2020	9-11/03/202	11/03/2020
G 54	Cleatham	Inhumation	7278	362.7	24/02/2020	26/02/2020	n/a	n/a	n/a	28/02/2020	09/03/2020	09/03/2020	9-11/03/202	11/03/2020
G 57	Cleatham	Inhumation	7279	312.1	24/02/2020	26/02/2020	28/02/2020	02/03/2020	n/a	04/03/2020	09/03/2020	09/03/2020	9-11/03/202	11/03/2020

Sample	Site	Burial Type	Empty Tube Mass	Mass of Tube +	Mass of Collagen	% Collagen yield
EL75EN	Elsham	Inhumation	6759.5	6774.9	15.4	3.42222222
EL76AL	Elsham	Inhumation	6707.6	6739.4	31.8	7.86739238
EL76AK	Elsham	Inhumation	6731.7	6751.7	20	5.43183053
EL76JO(a)	Elsham	Inhumation	6707.4	6740.5	33.1	8.49589322
G 10	Cleatham	Inhumation	6700.1	6758.7	58.6	13.3121308
G 11	Cleatham	Inhumation	6706.2	6793.1	86.9	20.1390498
G 18	Cleatham	Inhumation	6720.8	6785.9	65.1	18.3950268
G 19	Cleatham	Inhumation	6738.6	6807.7	69.1	17.3574479
G 25	Cleatham	Inhumation	6719.2	6763.1	43.9	10.6656948
G 29	Cleatham	Inhumation	6722.3	6745.5	23.2	6.02910603
G 31	Cleatham	Inhumation	6722.0	6748.7	26.7	7.58522727
G 37	Cleatham	Inhumation	6684.5	6733.9	49.4	9.87210232
G 38	Cleatham	Inhumation	6794.9	6765.4	96.2	17.3614871
G 40	Cleatham	Inhumation	6697.2	6720.4	23.2	5.66821402
G 45	Cleatham	Inhumation	6727.3	6810	82.7	16.2859393
G 48	Cleatham	Inhumation	6723.3	6773.9	50.6	12.596465
G 49	Cleatham	Inhumation	6718.7	6766.8	48.1	10.1327154
G 50	Cleatham	Inhumation	6708.9	6740.9	32	9.53232052
G 54	Cleatham	Inhumation	6728.0	6750.1	22.1	6.09318996
G 57	Cleatham	Inhumation	6723.1	6780.7	57.6	18.4556232

- Sample numbers refer to original excavation context.
- EL76JO(a) was a double burial of an adult and a non-adult, only the adult was sampled.
- DI water = deionised water
- Data available as spreadsheet in supplemental materials.

Appendix 13: Collagen Extraction from Samples taken from Cremated Individuals at Elsham and Cleatham

Sample	Site	Burial Type	Isotope Lab Labels	Initial Dry Mass (mg)	0.5(M) HCl at 4°C							DI water rinse X3	Mixed to pH 3	Heating Block 70°C		Eezee Filter
					Added	1st Change	2nd Change	3rd Change	4th Change	5th Change	6th Change			Started	Finished	
EL75AP 1	Elsham	Cremation	8220	419.7	28/09/2020	30/09/2020	02/10/2020	05/10/2020	n/a	n/a	n/a	07/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
EL75AP 2	Elsham	Cremation	8221	662.6	28/09/2020	30/09/2020	02/10/2020	05/10/2020	07/10/2020	09/10/2020	n/a	12/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
EL75AP 3	Elsham	Cremation	8222	580.6	28/09/2020	30/09/2020	02/10/2020	05/10/2020	07/10/2020	n/a	n/a	09/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
EL75DW 1	Elsham	Cremation	8223	517.2	28/09/2020	30/09/2020	02/10/2020	05/10/2020	07/10/2020	n/a	n/a	09/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
EL75DW 2	Elsham	Cremation	8224	440.4	28/09/2020	30/09/2020	02/10/2020	05/10/2020	n/a	n/a	n/a	07/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
EL75DW 3	Elsham	Cremation	8225	670.0	28/09/2020	30/09/2020	02/10/2020	05/10/2020	07/10/2020	09/10/2020	n/a	12/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
EL75DX 1	Elsham	Cremation	8226	544.6	28/09/2020	30/09/2020	02/10/2020	05/10/2020	n/a	n/a	n/a	07/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
EL75DX 2	Elsham	Cremation	8227	375.2	28/09/2020	30/09/2020	02/10/2020	05/10/2020	n/a	n/a	n/a	07/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
EL75DX 3	Elsham	Cremation	8228	663.7	28/09/2020	30/09/2020	02/10/2020	05/10/2020	07/10/2020	09/10/2020	n/a	12/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
EL75ES 1	Elsham	Cremation	8229	419.3	28/09/2020	30/09/2020	02/10/2020	05/10/2020	n/a	n/a	n/a	07/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
EL75ES 2	Elsham	Cremation	8230	443.8	28/09/2020	30/09/2020	02/10/2020	05/10/2020	07/10/2020	n/a	n/a	09/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
EL75ES 3	Elsham	Cremation	8231	515.2	28/09/2020	30/09/2020	02/10/2020	05/10/2020	07/10/2020	n/a	n/a	09/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
EL75LW 1	Elsham	Cremation	8232	503.5	28/09/2020	30/09/2020	02/10/2020	05/10/2020	07/10/2020	n/a	n/a	09/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
EL75LW 2	Elsham	Cremation	8233	542.1	28/09/2020	30/09/2020	02/10/2020	05/10/2020	07/10/2020	n/a	n/a	09/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
EL75LW 3	Elsham	Cremation	8234	389.0	28/09/2020	30/09/2020	02/10/2020	05/10/2020	07/10/2020	n/a	n/a	09/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
EL76IL 1	Elsham	Cremation	8235	345.1	28/09/2020	30/09/2020	02/10/2020	05/10/2020	07/10/2020	n/a	n/a	09/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
EL76IL 2	Elsham	Cremation	8236	515.1	28/09/2020	30/09/2020	02/10/2020	05/10/2020	07/10/2020	n/a	n/a	09/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
EL76IL 3	Elsham	Cremation	8237	394.2	28/09/2020	30/09/2020	02/10/2020	05/10/2020	n/a	n/a	n/a	07/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
EL76MN 1	Elsham	Cremation	8238	364.6	28/09/2020	30/09/2020	02/10/2020	05/10/2020	n/a	n/a	n/a	07/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
EL76MN 2	Elsham	Cremation	8239	475.8	28/09/2020	30/09/2020	02/10/2020	n/a	n/a	n/a	n/a	05/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
EL76MN 3	Elsham	Cremation	8240	322.8	28/09/2020	30/09/2020	02/10/2020	05/10/2020	n/a	n/a	n/a	07/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
EL76NN 1	Elsham	Cremation	8241	519.7	28/09/2020	30/09/2020	02/10/2020	05/10/2020	07/10/2020	09/10/2020	n/a	12/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
EL76NN 2	Elsham	Cremation	8242	548.5	28/09/2020	30/09/2020	02/10/2020	05/10/2020	07/10/2020	n/a	n/a	09/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
EL76NN 3	Elsham	Cremation	8243	410.7	28/09/2020	30/09/2020	02/10/2020	05/10/2020	07/10/2020	n/a	n/a	09/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
EL76PY 1	Elsham	Cremation	8244	491.9	28/09/2020	30/09/2020	02/10/2020	05/10/2020	n/a	n/a	n/a	07/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
EL76PY 2	Elsham	Cremation	8245	510.0	28/09/2020	30/09/2020	02/10/2020	05/10/2020	07/10/2020	09/10/2020	n/a	12/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
EL76PY 3	Elsham	Cremation	8246	551.7	28/09/2020	30/09/2020	02/10/2020	05/10/2020	n/a	n/a	n/a	07/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
EL76PZ 1	Elsham	Cremation	8247	764.6	28/09/2020	30/09/2020	02/10/2020	05/10/2020	07/10/2020	09/10/2020	12/10/2020	14/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
EL76PZ 2	Elsham	Cremation	8248	509.0	28/09/2020	30/09/2020	02/10/2020	05/10/2020	07/10/2020	09/10/2020	n/a	12/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
EL76PZ 3	Elsham	Cremation	8249	493.6	28/09/2020	30/09/2020	02/10/2020	05/10/2020	07/10/2020	09/10/2020	n/a	12/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
MT84FT 1	Cleatham	Cremation	8250	360.5	28/09/2020	30/09/2020	02/10/2020	05/10/2020	n/a	n/a	n/a	07/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
MT84FT 2	Cleatham	Cremation	8251	541.3	28/09/2020	30/09/2020	02/10/2020	05/10/2020	07/10/2020	n/a	n/a	09/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
MT84FT 3	Cleatham	Cremation	8252	785.5	28/09/2020	30/09/2020	02/10/2020	05/10/2020	07/10/2020	09/10/2020	12/10/2020	14/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
MT84IT 1	Cleatham	Cremation	8253	563.3	28/09/2020	30/09/2020	02/10/2020	05/10/2020	07/10/2020	09/10/2020	n/a	12/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
MT84IT 2	Cleatham	Cremation	8254	384.8	28/09/2020	30/09/2020	02/10/2020	05/10/2020	n/a	n/a	n/a	07/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
MT84IT 3	Cleatham	Cremation	8255	505.7	28/09/2020	30/09/2020	02/10/2020	05/10/2020	07/10/2020	n/a	n/a	09/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
MT84KJ 1	Cleatham	Cremation	8256	477.2	28/09/2020	30/09/2020	02/10/2020	05/10/2020	n/a	n/a	n/a	07/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
MT84KJ 2	Cleatham	Cremation	8257	302.8	28/09/2020	30/09/2020	02/10/2020	n/a	n/a	n/a	n/a	05/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
MT84KJ 3	Cleatham	Cremation	8258	393.7	28/09/2020	30/09/2020	02/10/2020	05/10/2020	n/a	n/a	n/a	07/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
MT85AQ 1	Cleatham	Cremation	8259	773.0	28/09/2020	30/09/2020	02/10/2020	05/10/2020	07/10/2020	n/a	n/a	09/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
MT85AQ 2	Cleatham	Cremation	8260	1019.0	28/09/2020	30/09/2020	02/10/2020	05/10/2020	n/a	n/a	n/a	07/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
MT85AQ 3	Cleatham	Cremation	8261	964.2	28/09/2020	30/09/2020	02/10/2020	05/10/2020	07/10/2020	n/a	n/a	09/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
MT85AR 1	Cleatham	Cremation	8262	535.1	28/09/2020	30/09/2020	02/10/2020	05/10/2020	07/10/2020	n/a	n/a	09/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
MT85AR 2	Cleatham	Cremation	8263	555.3	28/09/2020	30/09/2020	02/10/2020	05/10/2020	07/10/2020	n/a	n/a	09/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
MT85AR 3	Cleatham	Cremation	8264	728.4	28/09/2020	30/09/2020	02/10/2020	05/10/2020	07/10/2020	09/10/2020	n/a	12/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
MT85BH 1	Cleatham	Cremation	8265	636.7	28/09/2020	30/09/2020	02/10/2020	n/a	n/a	n/a	n/a	05/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
MT85BH 2	Cleatham	Cremation	8266	632.1	28/09/2020	30/09/2020	02/10/2020	05/10/2020	07/10/2020	n/a	n/a	09/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
MT85BH 3	Cleatham	Cremation	8267	669.8	28/09/2020	30/09/2020	02/10/2020	05/10/2020	n/a	n/a	n/a	07/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
MT86TR 1	Cleatham	Cremation	8268	538.1	28/09/2020	30/09/2020	02/10/2020	05/10/2020	07/10/2020	09/10/2020	n/a	12/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
MT86TR 2	Cleatham	Cremation	8269	567.0	28/09/2020	30/09/2020	02/10/2020	05/10/2020	07/10/2020	n/a	n/a	09/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
MT86TR 3	Cleatham	Cremation	8270	557.0	28/09/2020	30/09/2020	02/10/2020	05/10/2020	07/10/2020	09/10/2020	n/a	12/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
MT88AAA 1	Cleatham	Cremation	8271	894.2	28/09/2020	30/09/2020	02/10/2020	05/10/2020	07/10/2020	n/a	n/a	09/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
MT88AAA 2	Cleatham	Cremation	8272	838.0	28/09/2020	30/09/2020	02/10/2020	05/10/2020	07/10/2020	09/10/2020	12/10/2020	14/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
MT88AAA 3	Cleatham	Cremation	8273	499.1	28/09/2020	30/09/2020	02/10/2020	n/a	n/a	n/a	n/a	05/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
MT88ALD 1	Cleatham	Cremation	8274	516.2	28/09/2020	30/09/2020	02/10/2020	05/10/2020	07/10/2020	n/a	n/a	09/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
MT88ALD 2	Cleatham	Cremation	8275	670.2	28/09/2020	30/09/2020	02/10/2020	05/10/2020	07/10/2020	09/10/2020	n/a	12/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
MT88ALD 3	Cleatham	Cremation	8276	502.6	28/09/2020	30/09/2020	02/10/2020	05/10/2020	n/a	n/a	n/a	07/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
MT89BBT 1	Cleatham	Cremation	8277	660.5	28/09/2020	30/09/2020	02/10/2020	n/a	n/a	n/a	n/a	05/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
MT89BBT 2	Cleatham	Cremation	8278	568.0	28/09/2020	30/09/2020	02/10/2020	05/10/2020	n/a	n/a	n/a	07/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020
MT89BBT 3	Cleatham	Cremation	8279	801.4	28/09/2020	30/09/2020	02/10/2020	05/10/2020	07/10/2020	09/10/2020	n/a	12/10/2020	14/10/2020	14/10/2020	16/10/2020	16/10/2020

Sample	Site	Burial Type	Isotope Lab Labels	Empty Tube Mass	Mass of Tube + Collagen	Mass of Collagen	% Collagen yield
EL75AP 1	Elsham	Cremation	8220	6704.8	6708.8	4	0.95306171
EL75AP 2	Elsham	Cremation	8221	6689.3	6697.6	8.3	1.25264111
EL75AP 3	Elsham	Cremation	8222	6674.4	6679.9	5.5	0.9472959
EL75DW 1	Elsham	Cremation	8223	6657.3	6660.2	2.9	0.56071152
EL75DW 2	Elsham	Cremation	8224	6680.4	6684.1	3.7	0.84014532
EL75DW 3	Elsham	Cremation	8225	6664.8	6683.1	18.3	2.73134328
EL75DX 1	Elsham	Cremation	8226	6669.1	6689.6	20.5	3.76423063
EL75DX 2	Elsham	Cremation	8227	6732.3	6733.8	1.5	0.39978678
EL75DX 3	Elsham	Cremation	8228	6680.1	6693.4	13.3	2.00391743
EL75ES 1	Elsham	Cremation	8229	6671.3	6677.1	5.8	1.38325781
EL75ES 2	Elsham	Cremation	8230	6670.5	6671.9	1.4	0.31545741
EL75ES 3	Elsham	Cremation	8231	6694.8	6701.6	6.8	1.31987578
EL75LW 1	Elsham	Cremation	8232	6741.2	6752.3	11.1	2.20456802
EL75LW 2	Elsham	Cremation	8233	6697.4	6712.5	15.1	2.78546394
EL75LW 3	Elsham	Cremation	8234	6673.4	6674.7	1.3	0.33419023
EL76IL 1	Elsham	Cremation	8235	6681.0	6682	1	0.28977108
EL76IL 2	Elsham	Cremation	8236	6660.3	6669.9	9.6	1.86371578
EL76IL 3	Elsham	Cremation	8237	6725.1	6727	1.9	0.48198884
EL76MN 1	Elsham	Cremation	8238	6678.9	6681	2.1	0.57597367
EL76MN 2	Elsham	Cremation	8239	6670.1	6678.4	8.3	1.74443043
EL76MN 3	Elsham	Cremation	8240	6679.0	6682	3	0.92936803
EL76NN 1	Elsham	Cremation	8241	6640.3	6641	0.7	0.13469309
EL76NN 2	Elsham	Cremation	8242	6698.9	6712.1	13.2	2.40656335
EL76NN 3	Elsham	Cremation	8243	6663.7	6665.4	1.7	0.41392744
EL76PY 1	Elsham	Cremation	8244	6682.5	6692.6	10.1	2.05326286
EL76PY 2	Elsham	Cremation	8245	6680.7	6682.2	1.5	0.29411765
EL76PY 3	Elsham	Cremation	8246	6691.3	6705.7	14.4	2.61011419
EL76PZ 1	Elsham	Cremation	8247	6668.2	6682.3	14.1	1.84410149
EL76PZ 2	Elsham	Cremation	8248	6665.8	6671	5.2	1.021611
EL76PZ 3	Elsham	Cremation	8249	6676.5	6682.5	6	1.21555916
MT84FT 1	Cleatham	Cremation	8250	6663.2	6666.2	3	0.83217753
MT84FT 2	Cleatham	Cremation	8251	6676.0	6685.1	9.1	1.681138
MT84FT 3	Cleatham	Cremation	8252	6668.0	6677.5	9.5	1.20942075
MT84IT 1	Cleatham	Cremation	8253	6687.3	6690.6	3.3	0.58583348
MT84IT 2	Cleatham	Cremation	8254	6745.5	6746.3	0.8	0.20790021
MT84IT 3	Cleatham	Cremation	8255	6728.8	6732.4	3.6	0.71188452
MT84KJ 1	Cleatham	Cremation	8256	6710.5	6713.4	2.9	0.60771165
MT84KJ 2	Cleatham	Cremation	8257	6656.8	6658.2	1.4	0.46235139
MT84KJ 3	Cleatham	Cremation	8258	6696.3	6697.4	1.1	0.27940056
MT85AQ 1	Cleatham	Cremation	8259	6681.1	6693.3	12.2	1.57826649
MT85AQ 2	Cleatham	Cremation	8260	6691.3	6704	12.7	1.24631992
MT85AQ 3	Cleatham	Cremation	8261	6746.3	6765.8	19.5	2.02240199
MT85AR 1	Cleatham	Cremation	8262	6671.3	6679.7	8.4	1.56980004
MT85AR 2	Cleatham	Cremation	8263	6691.8	6708.7	16.9	3.04339996
MT85AR 3	Cleatham	Cremation	8264	6667.3	6673.9	6.6	0.90609555
MT85BH 1	Cleatham	Cremation	8265	6687.1	6695.2	8.1	1.2721847
MT85BH 2	Cleatham	Cremation	8266	6644.7	6651.5	6.8	1.07577915
MT85BH 3	Cleatham	Cremation	8267	6687.6	6696.6	9	1.34368468
MT86TR 1	Cleatham	Cremation	8268	6664.3	6668.6	4.3	0.79910797
MT86TR 2	Cleatham	Cremation	8269	6670.1	6683.6	13.5	2.38095238
MT86TR 3	Cleatham	Cremation	8270	6689.1	6697.5	8.4	1.50807899
MT88AAA 1	Cleatham	Cremation	8271	6691.7	6708.4	16.7	1.86759114
MT88AAA 2	Cleatham	Cremation	8272	6691.7	6721.7	30	3.57995227
MT88AAA 3	Cleatham	Cremation	8273	6673.8	6682	8.2	1.64295732
MT88ALD 1	Cleatham	Cremation	8274	6692.2	6698.6	6.4	1.23982952
MT88ALD 2	Cleatham	Cremation	8275	6691.5	6698.2	6.7	0.99970158
MT88ALD 3	Cleatham	Cremation	8276	6672.4	6690.4	18	3.58137684
MT89BBT 1	Cleatham	Cremation	8277	6680.7	6691.5	10.8	1.63512491
MT89BBT 2	Cleatham	Cremation	8278	6688.8	6698.7	9.9	1.74295775
MT89BBT 3	Cleatham	Cremation	8279	6631.1	6640.8	9.7	1.21038183

- Sample numbers refer to original excavation context, three samples were selected from each cremated individual for analysis.
- DI water = deionised water
- Data available as spreadsheet in supplemental materials.

SIBL ID	Site	Burial Number	Sex	Age	%C	$\delta^{13}C$ (‰)	%N	$\delta^{15}N$ (‰)	C:Natomic	% S	$\delta^{34}S_{corr}$ (‰)	R: % S	R: $\delta^{34}S_{corr}$ (‰)
7260	Elsham	EL75EN	Female	19-25	29.73	-23.23	10.42	11.18	3.3	0.19	-2.8		
7261	Elsham	EL76AL	Male	31-40	39.57	-21.40	14.28	9.68	3.2	0.24	5.22		
7262	Elsham	EL76AK	?	19+	27.65	-22.43	10.33	9.40	3.1	0.17	-4.14		
7263	Elsham	EL76JO(a)	Female	31-40	41.16	-22.59	14.36	11.41	3.3	0.2	4.69		
7264	Cleatham	Grave 10	Male	26-40	37.49	-22.63	13.66	11.37	3.2	0.27	4.63		
7265	Cleatham	Grave 11	Female	19-25	42.81	-21.86	15.70	10.69	3.2	0.22	9.18		
7266	Cleatham	Grave 18	Male	19-25	41.73	-21.39	15.48	11.07	3.1	0.23	1.75		
7267	Cleatham	Grave 19	Female	19+	40.56	-23.17	15.08	10.66	3.1	0.2	-1.5	0.21	-1.83
7268	Cleatham	Grave 25	Male	19+	39.22	-21.62	14.10	10.21	3.2	0.3	-2.54		
7269	Cleatham	Grave 29	Male	41+	34.58	-20.40	12.44	11.61	3.2	0.19	8.73		
7270	Cleatham	Grave 31	Male	19+	34.14	-21.75	12.37	10.83	3.2	0.23	1.67		
7271	Cleatham	Grave 37	Male	19-25	32.24	-22.19	11.65	10.37	3.2	0.19	-2.3		
7272	Cleatham	Grave 38	Female	19-25	41.33	-22.08	15.05	11.60	3.2	0.21	-2.57	0.22	-2.23
7273	Cleatham	Grave 40	Male	19+	35.12	-23.16	12.46	10.42	3.3	0.23	-2		
7274	Cleatham	Grave 45	Male	19-25	40.96	-22.72	15.06	10.56	3.2	0.23	-1.77		
7275	Cleatham	Grave 48	Female	19-25	40.04	-21.67	14.44	10.49	3.2	0.23	-4.95		
7276	Cleatham	Grave 49	Male	19-25	40.34	-23.40	14.46	10.37	3.3				
7277	Cleatham	Grave 50	Female	19-25	39.33	-23.85	14.02	11.48	3.3	0.22	4.44		
7278	Cleatham	Grave 54	Female	19-25	35.60	-23.49	12.42	11.09	3.3	0.2	1.05		
7279	Cleatham	Grave 57	Female	19-25	43.03	-22.64	15.61	11.08	3.2	0.31	1.09		

- Samples in this table are from inhumation burials
- Sample designations taken from original excavations
- R: %S column and R: $\delta^{34}S_{corr}$ refer to replicate samples
- %C, %N and %S measured as wt. %
- Sex and age data for Elsham samples from Squires, 2011 and for Cleatham from Leahy, 2007
- Data available as spreadsheet in supplemental materials.

ID #	Site	Burial Number	0.3-0.5 mg Samples		Re-run with 3-5 mg Samples				
			%C	$\delta^{13}C$ (‰)	%C	$\delta^{13}C$ (‰)	%N	$\delta^{15}N$ (‰)	C:Natomic
8279	Cleatham	MT89BBT 3	2.76	-24.90	2.52	-25.36	0.33	6.54	8.8
8278	Cleatham	MT89BBT 2	5.17	-25.23	4.80	-25.27	0.51	7.54	11.0
8277	Cleatham	MT89BBT 1	5.85	-24.25	5.53	-24.09	0.89	9.60	7.3
8276	Cleatham	MT88ALD 3	1.54	-26.60	1.20	-26.70			9.7
8275	Cleatham	MT88ALD 2	4.48	-26.20					
8274	Cleatham	MT88ALD 1	6.72	-26.11					
8273	Cleatham	MT88AAA 3	7.23	-24.92					
8272	Cleatham	MT88AAA 2							
8271	Cleatham	MT88AAA 1							
8270	Cleatham	MT86TR 3	8.39	-26.60					
8269	Cleatham	MT86TR 2	3.16	-26.39	1.91	-26.45			10.2
8267	Cleatham	MT85BH 3	4.31	-25.03					
8266	Cleatham	MT85BH 2	3.87	-25.01					
8265	Cleatham	MT85BH 1	3.75	-25.28					
8264	Cleatham	MT85AR 3	7.32	-26.17					
8263	Cleatham	MT85AR 2	3.56	-25.47	2.70	-25.63	0.30	7.28	10.3
8262	Cleatham	MT85AR 1	3.15	-26.02					
8261	Cleatham	MT85AQ 3	2.65	-24.91	2.52	-24.90	0.34	7.27	8.7
8260	Cleatham	MT85AQ 2	2.51	-25.11	2.13	-25.06	0.30	6.74	8.3
8259	Cleatham	MT85AQ 1	2.37	-25.41	2.17	-25.33	0.27	6.13	9.5
8256	Cleatham	MT84KJ 1	5.36	-25.37					
8252	Cleatham	MT84FT 3	7.08	-25.78					
8251	Cleatham	MT84FT 2	9.10	-25.66					
8249	Elsham	EL76PZ 3	2.26	-25.00					
8248	Elsham	EL76PZ 2	2.77	-25.15					
8247	Elsham	EL76PZ 1							
8246	Elsham	EL76PY 3	2.29	-25.27	2.09	-25.18	0.26	6.52	9.4
8244	Elsham	EL76PY 1	2.36	-25.30					
8242	Elsham	EL76NN 2	1.45	-25.57					
8239	Elsham	EL76MN 2	4.20	-25.22					
8236	Elsham	EL76IL 2							
8233	Elsham	EL75LW 2							
8232	Elsham	EL75LW 1							
8231	Elsham	EL75ES 3	3.65	-24.60					
8229	Elsham	EL75ES 1	1.48	-26.18					
8228	Elsham	EL75DX 3	9.53	-26.82					
8226	Elsham	EL75DX 1	4.52	-26.21	4.83	-26.27	0.47	6.10	11.9
8225	Elsham	EL75DW 3	4.58	-26.13	4.30	-26.13	0.46	8.20	11.0
8221	Elsham	EL75AP 2	2.65	-25.04					

- Samples in this table are from cremation burials
- Sample designations taken from original excavations followed by an arbitrary designation of 1-3 representing the first, second and third samples selected from each individual
- %C and %N measured as wt. %
- Initial run of samples using 0.3mg to 0.5 mg of collaged produced unreliable nitrogen data, those samples with sufficient collagen remaining were re-run using 3 mg to 5 mg of collagen
- Data available as spreadsheet in supplemental materials.