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ARCHAEOMAGNETIC DATING: INVESTIGATING NEW MATERIALS AND TECHNIQUES

Catherine Mary Batt

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**A thesis submitted in fulfilment of the requirements for the degree of
Doctor of Philosophy**

**Department of Archaeology
University of Durham**

August 1992



2 DEC 1992

This thesis is dedicated to my parents.

Abstract

This thesis describes the application of archaeomagnetic techniques to the study of archaeological materials from Britain and China. It also explores the compilation and construction of the archaeomagnetic calibration curve, with particular reference to British data.

One of the primary objectives of this study has been to extend the range of materials dated by archaeomagnetism to include waterlain sediments. Over 30 different sediments from a wide variety of archaeological environments were investigated by archaeomagnetic methods. Information on the environment of deposition was provided by measurements of magnetic fabric, while isothermal remanent magnetisation determinations were used to identify the magnetic minerals present. The results have been compared with the archaeological evidence and in many cases good correspondence has been found. It has been possible to make some general inferences as to which environments are most likely to yield sediments datable by archaeomagnetism.

Similar measurement techniques were used to study six, dated, fired structures from the Xi'an area of Shaanxi Province, China. Together with other archaeomagnetic data published for this vicinity, these measurements provided the nucleus of information necessary for the construction of a calibration curve for this region and their magnetic properties were compared with those of the sediments.

Central to both the study of sediments and Chinese fired material was the construction and use of the archaeomagnetic calibration curve. A database was formulated and implemented in order to archive British archaeomagnetic information and provide a basis on which to construct a revised curve. A number of methods of curve production were examined, particularly 'moving window' smoothing, which provided a rigorous, mathematical approach and produced a curve with realistic error bounds.

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Last, but by no means least, I want to thank my parents for their constant love, encouragement, interest and support, both practically and spiritually. Their contribution has meant more to me than I can express here.

I declare that the work contained in this thesis has not been submitted for a degree at this university or any other. All the work presented herein was conducted by the author unless stated otherwise.

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Glossary of abbreviations

The following abbreviations are used throughout this thesis. They are defined when first used in the section indicated.

α_{95}	Alpha 95 error term (Section 2.5.1)
AD	calendar years <i>Anno Domini</i>
AMS	Anisotropy of Magnetic Susceptibility (Section 2.3.2)
ARM	Anhyseretic Remanent Magnetisation (Section 1.4.5; Section 2.2.2)
BC	calendar years Before Christ
$(B_o)_{cr}$	Coercivity of Remanence (Section 2.4.1)
BP	calendar years before AD1950 (known as Before Present)
CRM	Chemical Remanent Magnetisation (Section 1.4.3)
CVP	Conversion Via Pole (Section 5.5)
DRM	Depositional Remanent Magnetisation (Section 1.4.2)
h%	overall percentage degree of anisotropy (Section 2.3.2)
IGRF	International Geomagnetic Reference Field (Section 1.3)
INGRES	Interactive Graphics and Retrieval System (Section 5.4.3)
IRM	Isothermal Remanent Magnetisation (Section 1.4.5; Section 2.4.1)
NRM	Natural Remanent Magnetisation (Section 2.2.1)
PDRM	<u>Post-Depositional Remanent Magnetisation</u> (Section 1.4.2)
q	ratio of lineation to foliation (Section 2.3.2)
RRM	Rotational Remanent Magnetisation (Section 2.2.2)
S	Remanence Ratio (Section 2.4.1)
SI	Stability Index (Section 2.5.2)
SIRM	Saturation Isothermal Remanent Magnetisation (Section 2.4.1)
SQL	Structured Query Language (Section 5.4.3)
SRM	Shear Remanent Magnetisation (Section 1.4.5)
TRM	Thermoremanent Magnetisation (Section 1.4.1)
VGP	Virtual Geomagnetic Pole (Section 5.3)
VRM	Viscous Remanent Magnetisation (Section 1.4.4)

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Chapter 1

Introduction

1.1 THE OBJECTIVES OF THIS RESEARCH

Scientific dating methods have revolutionised the study of archaeological remains by providing absolute and relative time scales for the events of human development. Their impact on archaeology has been far-reaching, ranging from potassium-argon dating of early hominid remains in Africa from over a million years ago (Curtis & Hay, 1972), through the radiocarbon revolution which upset the traditional hypotheses of the diffusion of culture from the Near East (Renfrew, 1973), to the use of thermoluminescence to distinguish modern fake ceramics from archaeological originals (Fleming, 1975). Aitken (1990) provides a comprehensive introduction to the laboratory-based dating methods currently in use in archaeology.

It is useful to divide dating techniques into two distinct groups: clock methods and pattern matching methods. Clock methods are based on a rate dependent process, such as radioactive decay in the sample (e.g. radiocarbon or potassium argon dating), the effects of radioactive decay (e.g. fission track or thermoluminescence dating), or on other chemical or physical rate dependent processes (e.g. obsidian hydration, amino acid racemization or acquisition of viscous remanent magnetisation). Pattern matching methods involve the comparison of a pattern of change in a parameter with an existing dated master record of such changes, as with dendrochronology or use of the palynological record. Each method is applicable to a particular material or group of materials from a specific environment and may only be appropriate to certain archaeological periods.

Archaeomagnetic dating using direction or intensity falls in the pattern-matching category, as it involves dating fired materials or sediments from an archaeological context, by comparing their magnetisation with a calibration curve showing changes in the geomagnetic field over time. Archaeomagnetic dating has many practical advantages over other techniques. It is applicable on a wide range of archaeological sites, virtually non-destructive, cheap (commercial rates are around £150 per date as opposed to £200 for conventional radiocarbon and £300 for an accelerator radiocarbon date, at 1990 prices) and quick enough for measurements to be interactive with excavation. The precision attainable depends on many factors (Section 2.6) but may be of the order of

±25 years, and improves as more data are collected for the calibration curve. However, it must be noted that archaeomagnetic dating is inherently dependent upon other dating methods to provide the absolute dates for its calibration curve. Archaeomagnetic studies are also of interest to those studying the origin and behaviour of the geomagnetic field and the processes of magnetisation of natural materials.

Archaeomagnetic studies have traditionally concentrated on the dating of fired materials, but any extension of the applicability of the technique to other materials is obviously of great interest. For this reason, a major part of this study concerned an investigation into the feasibility of using archaeomagnetism to date waterlain sediments from archaeological contexts (Chapter 3). Conventional archaeomagnetic sampling and measurement techniques (as described in Chapter 2) were used in the investigation of sediments from a number of different environments. The aim of the study was to establish which sediments were most suitable for dating by archaeomagnetic means and to identify the problems that might arise in such an investigation. In most cases, the deposit could be dated by its archaeological context or another scientific dating method, enabling a comparison to be made with the archaeomagnetic information. An attempt was also made to use the sediment's magnetic properties to determine the mineralogical origin of its magnetisation and its environment of deposition.

In Britain, archaeomagnetic dating is made possible by a calibration curve compiled from a large number of archaeomagnetic measurements on features of known date. However, in some other regions there are, as yet, insufficient archaeomagnetic measurements to construct such a calibration curve. Chapter 4 describes the results of archaeomagnetic studies of six dated, fired structures from the Xi'an area of China. This work contributed towards the data needed for an archaeomagnetic calibration curve for the region, giving an indication of the behaviour of the ancient geomagnetic field in the region. These measurements were compared with other archaeomagnetic data from the vicinity and with direct observations of the geomagnetic field in China, which include the earliest recorded observations in the world. The study also provided data for the comparison of the magnetic properties of sediments and fired material.

Collecting data for the Chinese archaeomagnetic calibration curve and using the existing British curve for dating sediments, brought to light a number of issues concerning the compilation and construction of calibration curves for use in archaeomagnetic dating. Chapter 5 discusses the development of the British curve, its current form, disadvantages and how calibration curves for other regions are drawn. A number of improvements to the method of curve production are discussed, with particular emphasis on the establishment of a British archaeomagnetic database and

adopting a more rigorous approach to drawing the calibration curve than that currently employed.

1.2 THE GENERAL PRINCIPLES OF ARCHAEOMAGNETIC DATING

The basic principles underlying archaeomagnetic dating can be summarised as follows. The Earth has a magnetic field whose direction (i.e. declination and inclination) and intensity change over time (Section 1.3). Certain archaeological events record the geomagnetic field at a particular instant of time and may retain that record to the present day (Section 1.4). If this record of the ancient field can be measured and compared with a calibration curve showing the changes in the geomagnetic field over time (Chapter 5), then the event that caused the field to be recorded can be dated. In practice the method is a great deal more complicated. The magnetisation may not give a true record of the ancient field direction, there may be no stable record, the magnetisation retained may be an extremely complex combination of magnetisations with only one relating to the event to be dated, or there may be more than one occasion when the geomagnetic field has had the same magnetic properties. The construction of a calibration curve is particularly fraught with difficulties as discussed in detail in Chapter 5. It must be noted that, because archaeomagnetic dating depends on a comparison of measurements of a material's magnetic properties with previous, dated measurements, the technique does not establish a chronology but transfers one (Aitken, 1990 p225) and so is dependent on the information provided by other dating methods and is subject to their limitations.

The actual dating process can be carried out using one or more of three methods.

1.2.1 *Dating by intensity*

The intensity of magnetisation of a fired material containing magnetised particles is expected to be proportional to the strength of the geomagnetic field in which it was heated and cooled. The ancient field can be determined by comparing a sample's measured intensity with the magnetisation it acquires on heating and cooling in a known laboratory field. Material does not have to be *in situ* to be suitable for intensity dating and thus the technique is widely applicable, using material such as pottery sherds. With a highly sensitive cryogenic magnetometer (Section 2.2.1; Walton, 1977) 3mm³ samples can be used, making the technique minimally destructive, and enabling museum-quality artefacts to be used. However, the measurements required to determine the strength of the field in which the magnetisation was acquired are difficult, time consuming and not always reliable (Aitken *et al.*, 1986 & 1988). Laboratory reheating of the sample often causes mineralogical changes, which lead to a high failure rate in the dating process

(Aitken *et al.*, 1988). Problems also arise from the non-homogeneity of samples, their magnetic anisotropy and the difficulty of re-creating the original heating atmosphere and rate in the laboratory (Tarling, 1983 p149). As the amplitude of changes in the intensity of the geomagnetic field appears to be less than the amplitude of directional changes, the method cannot be expected to attain the same resolution; the highest precision suggested has been ± 80 years for dating in the 2nd millennium BC in Greece (Aitken *et al.*, 1989). Despite these problems, intensity dating is used in many areas, often in conjunction with directional dating; for example China (Wei *et al.*, 1987; Tang *et al.*, 1991); Bulgaria (Kovacheva, 1983); France and North Africa (Thellier, 1977); Asia, Egypt and Greece (Aitken *et al.*, 1989; Hussain, 1983); South-west America (Sternberg, 1989a) and the USSR (Burlatskaya & Chelidze, 1991).

Determining the intensity of magnetisation of the ancient field as recorded by a deposited sediment presents particular problems as the magnetisation may be affected by depositional or post-depositional disturbance such as current flow (discussed fully in Section 1.4.2). Natural conditions are virtually impossible to replicate in the laboratory and so palaeointensity studies are generally restricted to fired materials (Tarling, 1983 p103).

1.2.2 Dating by direction

Directional dating is the most common type of archaeomagnetic dating and is the most successful at producing dates. In this method, material is dated by comparing the direction of its magnetisation with a calibration curve showing the variation with time of declination, inclination or, preferably, both. The position of samples when their magnetisation was acquired must be known and so only material which has remained *in situ* is suitable. Datable material includes fired structures (Section 1.4.1), which are generally strongly magnetic and therefore easily measurable, and sediments (Section 1.4.2) which are more problematic but are much more common on archaeological sites (see Chapter 3 for a fuller discussion). Occasionally unoriented materials such as glazed pottery or bricks can be dated using only the inclination of their magnetisation, if their orientation on firing can be deduced, for example from glaze runs, diagnostic marks of manufacture or the excavation of similar still-loaded kilns (e.g. Wei *et al.*, 1981). While the same values of declination and inclination occasionally occur at different times, the date can usually be obtained by considering other archaeological evidence, in addition to the measurements of magnetisation. The declination of the geomagnetic field has changed by over 70° and its inclination by over 20° in the last 3000 years in Britain, making it possible to date with more precision than with intensity measurements. This increased precision and ease of measurement of magnetic direction, as opposed to intensity, mean that the former is more widely used in dating.

1.2.3 Dating by viscous remanence

The magnitude of the viscous remanent magnetisation (Section 1.4.3) acquired by a material increases with time. In principle, it should be possible to determine how long a specimen has been lying in a particular orientation by measuring its total viscous magnetisation and determining the rate of acquisition of viscous magnetisation. Heller and Markert (1973) attempted such an analysis on stones from Hadrian's Wall with limited success. However, a number of problems arise in assessing the rate of acquisition of viscous remanent magnetisation, because the geomagnetic field strength changes over time. The time dependence of acquisition must be determined and this is a particular problem for magnetic constituents of mixed domain states, although a thermal method may allow such information to be recovered (Atkinson & Shaw, 1991). While viscosity dating might be capable of broad age distinctions, it is unlikely to have wide applicability in archaeology, as the viscous remanent magnetisation acquired over periods of archaeological time is normally very small. There may be limited applicability of the study of viscosity to give a broad indication of the authenticity of *in situ* artefacts.

This study concentrated entirely on directional dating as it is commonly used in Britain, the measurements required are reasonably quick and simple and it seems to be the method with the most potential of providing precise and reliable dates in archaeological periods. In addition to dating, archaeomagnetic studies can yield other information (Section 1.7).

1.3 THE GEOMAGNETIC FIELD

Although the existence of the geomagnetic field has only been consciously acknowledged over the last few centuries, its effects were recognised much earlier (Tarling, 1983 p1-2). By 600BC the Greeks were familiar with the magnetic properties of lodestone and, in AD69, the Chinese produced the first magnetic compass from a lodestone spoon revolving on a smooth board (Section 4.2). However, it was not until the end of the 16th century that the Europeans attempted to study scientifically the properties of the Earth's magnetic field (Gilbert, 1600) and discussions about its origins and morphology are still being actively pursued.

The magnetic field at any point on the Earth's surface can be described by a vector comprising of three magnetic elements; declination, inclination and intensity (Fig. 1.1). Declination is the angle between geographic North and the horizontal component of the field vector, inclination is the dip angle between the total vector and the horizontal, and intensity is the magnitude of the total field vector. The geomagnetic field varies

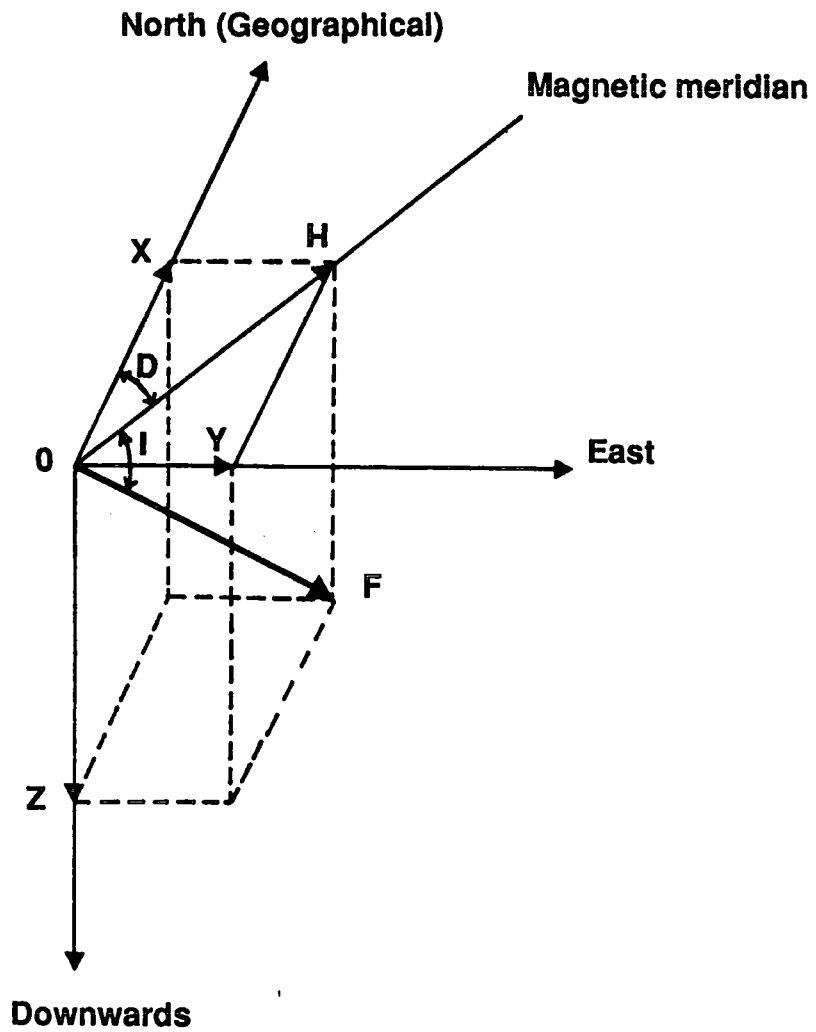


Figure 1.1: The main elements of the geomagnetic field (from Jacobs, 1963). The field can be expressed in its polar coordinates, declination (D) and inclination (I); or in cartesian coordinates as the magnitudes of the components along three mutually perpendicular axes, north (x), east (y) and down (z). F is the field intensity.

spatially and all three elements of the present field are known in many parts of the world from measurements at over 200 magnetic observatories, satellite measurements, and land and sea surveys (Tarling, 1983 p163). Contour maps of declination, inclination and intensity (e.g. Barraclough *et al.*, 1975; Fabiano *et al.*, 1983) indicate that much of the present field can be modelled by a geocentric magnetic dipole, inclined at 11.5° with respect to the Earth's rotation axis, which would give magnetic poles at $78.5^\circ\text{N } 70^\circ\text{W}$ and $78.5^\circ\text{S } 110^\circ\text{E}$. Spherical harmonic analyses of the field have shown that about 80% can be described in this way, although a better fit could be acquired by displacing the dipole about 340km north from the Earth's centre (Tarling, 1983 p168). The remainder of the field is attributed to non-dipole components of the geomagnetic field, which are generally much weaker than the dipole field, but cause regional perturbations in it. The non-dipole components of the field seem to act in about 12 regions of roughly continental scale (Loves & Runcorn, 1951).

In addition to spatial variation of the geomagnetic field, it is also well established that the field changes over time; a phenomenon known as its *secular variation*. The first recorded direct measurements of the geomagnetic field were made in China in around AD720 (Section 4.2) and further measurements have been made intermittently in many parts of the world since then. Systematic recording of the field's properties in London started in the mid-16th century (Malin & Bullard, 1981). Records also exist for the last four centuries from Paris and Rome, and for Boston since AD1700 (Bauer, 1899). Since 1965 there has been global monitoring of the field by magnetic observatories. Regional surveys are carried out in more inhabited areas every 5 to 10 years and the coefficients of the International Geomagnetic Reference Field (IGRF) are published annually. This detailed information reveals changes in the magnetic field, both regular and irregular, over a wide range of time scales (Barraclough, 1982). There are short term, transient changes with intensities 0.1-1% of the normal field, some of which are regular with cycles of 12 or 24 hours, monthly or yearly and some irregular, for example those arising from magnetic storms associated with sunspot activity. Other changes have much longer periods. The secular variation records show that both the strength and direction of both dipole and non-dipole components change and that there are significant regional differences in these changes. Roberts and Piper (1989) provide a comprehensive overview of the evidence for the behaviour of the geomagnetic field. From the rather complicated overall picture of secular variation, in which different components of the field increase, decrease or remain unchanged in different areas (Thompson, 1984), two clear trends are revealed by the historical data. The non-dipole field appears to have been drifting west over historical time at a rate of 0.2° longitude per year, a phenomenon which is discernible from a plot of the non-dipole field over time or from the secular variation record at a single site (Bullard *et al.*, 1950; Skiles, 1970; Evans, 1987). The historical data also show a decrease in the dipole moment by about 6% per century over

the last 160 years (Roberts & Piper, 1989). The total intensity of the present field varies from $30\mu\text{T}$ near to the equator to $60\mu\text{T}$ near to the poles.

The geomagnetic record can be extended far beyond direct measurements by magnetic measurements on oriented samples of rocks and sediments, which preserve a record of the past geomagnetic field (Section 1.4). Such studies reveal that for the last 7000 years the position of the magnetic pole has been scattered around the geographic pole. Palaeomagnetic measurements also indicate that reversals in the polarity of the geomagnetic field can occur and these are recorded in rocks and sediments across the world, providing a series of stratigraphic markers. There is also evidence that excursions take place when the pole position does not necessarily reverse, but moves to low latitudes or even into the other hemisphere. Some of these events may be too brief to be recorded palaeomagnetically. For rocks from a single location over a period of millions of years the position of the palaeomagnetic pole deviates further from the geographic pole with increasing age, a phenomenon known as *polar wander*. Palaeomagnetic measurements from different continents give different polar wander paths which can best be explained by relative movements of the continents. The intensity of the ancient field is more difficult to determine as few rocks retain a reliable record of palaeointensity. What evidence there is, suggests that the field strength fluctuates with a period of about 10,000 years (Roberts & Piper, 1989).

Some features of the present non-dipole field appear to have persisted for a long period of time. Doell and Cox (1971) have used the palaeomagnetic record from lavas in the Pacific as evidence that secular variation in the region has been low for several million years. Yukutake and Tachinaka (1968) suggested that the non-dipole field is comprised of both standing and drifting anomalies and this is supported by an analysis of lake sediment palaeomagnetic data (Creer & Tucholka, 1982b).

The geomagnetic field is known to be mainly of internal origin. A small contribution from electromagnetic phenomena in the upper atmosphere accounts for the very high frequency changes in the surface field. Many complex theories have been developed to explain the origin and behaviour of the geomagnetic field. Lund and Olson (1987) summarise the most recent theories in the light of historic and palaeomagnetic secular variation. The most accepted suggestion is that the field is constantly regenerated in a self-sustaining dynamo process by electromagnetic interactions between the existing field and the electrically conducting fluid in the outer liquid core of the Earth (Elsasser, 1939). This theory is not yet sufficiently developed to duplicate the observed behaviour of the geomagnetic field and more experimental measurements of the ancient field are needed for the development of the model. In fact, archaeomagnetic measurements provide the most precise and well-dated record of secular variation and hence are

invaluable in the development and testing of geomagnetic models (e.g. Burlatskaya & Braginsky, 1978).

1.4 ACQUISITION OF NATURAL MAGNETISATIONS

As described in Section 1.2, the crucial factor that makes some materials datable by archaeomagnetism is that they record the geomagnetic field at a particular moment in time and retain that record to the present day. There are a number of ways in which such a magnetisation might be acquired and a number of mechanisms by which it might be overprinted or destroyed by a subsequent magnetisation.

1.4.1 *Thermoremanent magnetisation (TRM)*

The acquisition of TRM by heated archaeological materials was the phenomenon that first prompted interest in archaeomagnetism as a dating tool (Section 1.5). Even today most archaeomagnetic studies concern the magnetic properties of fired materials and structures, with calibration curves relying heavily on such measurements (Section 5.2). Much research has been conducted into the processes of TRM acquisition and the description here is intended to be a brief introduction. For more detailed discussion the reader is referred to Tarling (1983, Chapter 2).

The soils, clays and stones used in the manufacture of kilns, ovens, fireplaces and similar structures often contain magnetic iron oxides, usually in the form of fine grained inclusions. The most common iron oxides; magnetite (Fe_3O_4), titanomagnetites (e.g. Fe_2TiO_4), haematite ($\alpha\text{Fe}_2\text{O}_3$) and maghemite ($\gamma\text{Fe}_2\text{O}_3$), have a spontaneous magnetisation; that is they are magnetised even in the absence of a magnetic field. These may make up as much as 5% of some pottery clays (Tarling, 1975). Goethite (αFeOOH), an iron hydroxide commonly associated with weathering may also contribute to the magnetisation; although it converts to haematite on heating in air to temperatures above about 200°C (Thompson & Oldfield, 1986 p17). The magnetic grains are frequently so small (less than around 1 μm) as to be in the form of *single domain* grains, with their magnetisation lying along one of their easy axes of magnetisation, which are determined by the axes of the crystal structure. These grains are generally randomly oriented, so that the effect of their individual magnetisations will tend to cancel each other out, giving a very small overall magnetisation. An external magnetic field, for example the Earth's magnetic field, will produce a force acting on magnetic moments not aligned with it. If this force is strong enough, the direction of magnetisation within the domain will 'flip' into the easy axis alignment which is closest to the alignment of the external field, almost as soon as the external field is applied. This flip can only take place

if the moment is strong enough to overcome the internal energy barriers. Hence, in weak applied magnetic fields there may not be sufficient energy to cause the flip until thermal vibrations allow the energy barrier to be exceeded. The characteristic time taken for a domain to acquire a magnetisation in the easy axis direction closest to the external field is known as the grain's *relaxation time*.

Increasing the temperature, that is increasing the thermal vibrations, results in a decrease in the relaxation time because more domains acquire sufficient energy to flip their alignment. The temperature at which a domain has sufficient energy to reverse its direction is known as its *blocking temperature*. The blocking temperature depends upon the size, shape and mineral composition of the grain, the strength of the applied field and the angle of the domain's magnetisation to the applied field. Therefore, there will be a range of blocking temperatures in most materials. Hence, TRM will be acquired in steps over successive temperatures and the strength of the magnetisation will be directly related to the strength of the applied field (Néel, 1955). The upper limit of the blocking temperature range is the Curie temperature of the material, at which point the spontaneous magnetisation disappears.

Large, magnetised grains (greater than around $1\mu\text{m}$) reduce their total energy by dividing into more than one domain by domain walls and are termed *multi-domain grains*. In these grains the magnetisation of the domains is still aligned along the easy axes of the domains, but the orientations of these axes are further complicated by the magnetostatic forces produced by adjacent domains. Domain walls form a pattern and any changes involve a rearrangement of the entire pattern (Stacey & Banerjee, 1974 p58-62). The behaviour of multi-domained particles in an applied field can be explained in terms of movements of the domain walls. In an applied field of sufficient energy, the domain wall will tend to move so as to increase the volume of domains aligned with the external field, at the expense of those at an angle to it. Initially, the walls will move back to their original position if the external field is removed. However, if sufficient energy is provided by the external field to overcome energy barriers within the material, the movement is less reversible and a magnetisation is acquired. As with single domain grains, an increase in temperature will reduce the relaxation time, as more domains attain a magnetisation in the direction of the applied field.

It is helpful to summarise the implications of these phenomena in archaeological environments. The material used in construction of, for example, a kiln, contains magnetic grains of a variety of sizes and mineralogies, whose magnetisations are initially oriented randomly. As the structure is heated, the relaxation times of the magnetic grains are reduced and an increasing number of domains gain sufficient energy to become oriented in the direction of the geomagnetic field. If the material is heated to above its

Curie temperature the domains disappear altogether. As the structure cools, the relaxation time increases again, often to thousands or millions of years and the magnetisation of a domain is 'frozen' upon cooling through its blocking temperature. Thus a weak, but permanent, magnetisation is imparted along the easy axes of magnetisation closest to the direction of the ambient field. This magnetisation will remain unaffected by changes in the geomagnetic field until the material is heated again or the grain's relaxation time is exceeded. For grains with low blocking temperatures, say less than 200°C, the relaxation time will be very short and hence its magnetisation will be unstable and may change with the geomagnetic field (Section 1.4.3). Grains with higher blocking temperatures will retain their alignment for a longer period at low temperatures, providing a record of the direction of the geomagnetic field at the time of cooling, if the structure remains undisturbed.

If a structure is subsequently reheated in a different geomagnetic field to temperatures up to or above those of first heating, the magnetic carriers will remagnetise when their blocking temperatures are exceeded and all traces of the previous TRM will be destroyed. Thus, the field recorded is that at the time of last cooling of the structure. If, however, the reheating is to a lower temperature than the first heating and the geomagnetic field has changed, the resulting magnetisation will be a combination of the two, with different stability grains recording different magnetic fields. This may be identified by stepwise demagnetisation (Section 2.2.2), as demonstrated experimentally by Smith, G.P. (1990). In practice, reheating is seldom discernible in the archaeomagnetic record because the geomagnetic field rarely changes appreciably during the lifetime of use of a feature, although Section 1.7 gives some examples of circumstances when this property has been of use.

A number of factors may mean that the TRM measured in the laboratory is not an accurate record of the ancient field. If firing is only to a low temperature, the remanence may not be stable enough to be retained over archaeological time. The structure may have been subject to physical changes after firing, such as structural movement or differential subsidence, or weathering may have produced an over-printing chemical remanent magnetisation (Section 1.4.3). In addition, the geomagnetic field at the time of cooling may have been disturbed by iron objects or slag in the vicinity or by the magnetisation of the baked structure itself. There has been considerable interest in the latter problem; some large, strongly magnetised, fired structures show significant differences in magnetic direction from one part of the structure to another. This phenomenon has been termed 'magnetic refraction' (Aitken & Hawley, 1971), a term which implies an analogue of the optical distortion of light on passage through different media. The process appears to be a cooling rate effect, in which the magnetisation of parts of the structure that have already cooled, distort the field in which slower cooling

parts acquire their magnetisation. Experimental investigation of this effect led to the suggestion that the inclination of the magnetisation of floor samples was too shallow by about 2.4° and the declination of wall samples varied with azimuth (Hoye, 1982; Aitken & Hawley, 1971). While there has been experimental evidence that such distortions of the magnetic direction do occur (Harold, 1960; Weaver, 1961 & 1962), a number of studies have failed to find systematic effects (Tarling *et al.*, 1986; Gentles, 1989). It has recently been shown that magnetic refraction is very unlikely to cause the observed scatter of directions (Evans & Hoye, 1991) and that this might be more attributable to sample inhomogeneity and anisotropy or to cracking of the fired structure (Tarling *et al.*, 1986). Until further research has been conducted, the best procedure would seem to be to distribute samples throughout the stable areas of the structure, in order to obtain a representative mean direction and scatter (Clark, 1980). Samples taken by the button method (Section 2.1.2) used in these studies are less likely to be affected by distortion as they represent the fast-cooling surface of the structure.

In addition to fired clay structures, there has been some success in dating burnt soils (e.g. Sapcote in Clark *et al.*, 1988) and stone structures (e.g. Beeston Castle in Clark *et al.*, 1988). It must be remembered that in the latter case, stone will retain the magnetisation of its formation and so a stable magnetisation may not be archaeological in origin. Materials which have been heated and contain large grained iron or iron oxide impurities, such as coins, tend to have a less stable magnetisation which may, however, be stable over archaeological time periods (Section 1.7). Iron itself, unless particularly fine-grained, is unsuitable for archaeomagnetic dating as it is too easily remagnetised to retain a stable record of the ancient field. Lava flows can also retain a stable TRM (Doell & Cox, 1963). When the flow can be dated by historical references (Tanguy, 1970) or radiocarbon dating of associated organics, the directions of magnetisation can be added to the calibration curve.

1.4.2 Depositional remanent magnetisation (DRM) and post-depositional remanent magnetisation (PDRM)

Some sediments have been found to retain a permanent record of the geomagnetic field, albeit weaker than that in fired material, and many palaeomagnetic studies have focused on the correlation of features of the secular variation record obtained from sediments (e.g. Creer & Kopper, 1976; Creer & Tucholka, 1982a; Bonifay & Creer, 1987). A number of environments have been shown to produce sediments with a stable magnetisation, including the deep ocean, fresh water lakes, estuarine mud, loess, glacial varves and archaeological contexts. Despite numerous palaeomagnetic studies of natural sediments, the process or processes by which sediments acquire their magnetisation are still not fully explained. The basic principle is simple; detrital material,

produced by the weathering of the parent rock, contains particles which already have a thermal (Section 1.4.1) or chemical (Section 1.4.3) remanent magnetisation as a result of the formation process of the rock. As these magnetised particles settle through water (or possibly air), they are free to rotate mechanically, aligning with their magnetisation parallel to the ambient geomagnetic field (Fig. 1.2). Thus, when they reach the sediment-water interface they have acquired a depositional remanent magnetisation (DRM) in the direction of the geomagnetic field. However, laboratory experiments and measurements of the magnetisation of natural sediments have made it clear that a number of factors may disturb this DRM and that a different process may also be acting on the magnetic grains within the sediment, producing a magnetisation subsequent to deposition. This post-depositional remanent magnetisation (PDRM) was recognised by Irving (1957) and attributed to the alignment or realignment of magnetised grains within water-filled pore-spaces in the sediment matrix. The magnetised grains are subsequently locked in when the sediment is consolidated. Thus, there is a paradox; whilst the processes of DRM acquisition are fairly well understood, both theoretically and experimentally, they appear to be restricted in their applicability to natural sediments. Conversely, there has been limited investigation into PDRM processes, even though they appear to be dominant in many natural sediments. Verosub (1977) provides a useful review of research into DRM and PDRM processes and the research is described in more detail below.

Early attempts to explain how sediments acquire a magnetisation concentrated on DRM processes and the interactions of settling grains with the sediment surface. In particular, a number of experiments involving the redeposition of sediments under a variety of laboratory conditions were carried out. Initial experiments involving the redeposition of crushed basalt (Nagata *et al.*, 1943) and natural sediments (Johnson *et al.*, 1948) in applied fields demonstrated that declination of the applied field was accurately recorded, but the latter found that inclination was consistently too shallow. Prompted by a similar systematic shallowing of measured inclination in Swedish varved sediments (Griffiths, 1955), King (1955) reproduced the phenomenon, which he termed 'inclination error', by redepositing silt in a tank surrounded by Helmholtz coils, capable of providing a variable magnetic field. He derived an empirical formula for inclination error (King, 1955), which he explained using a model of grain by grain deposition of a sediment comprising of a mixture of spherical and platy particles. On settling on the sediment surface, the spherical particles remained aligned with the geomagnetic field but the platy particles, magnetised along their long axes, settled with their long axes horizontal. Thus the platy particles did not reflect the inclination of the applied field. Griffiths *et al.* (1960) conducted further deposition experiments in still water using clay and silt grade material and showed that inclination error was apparently independent of particle size. They proposed a different model, whose predictions were more consistent

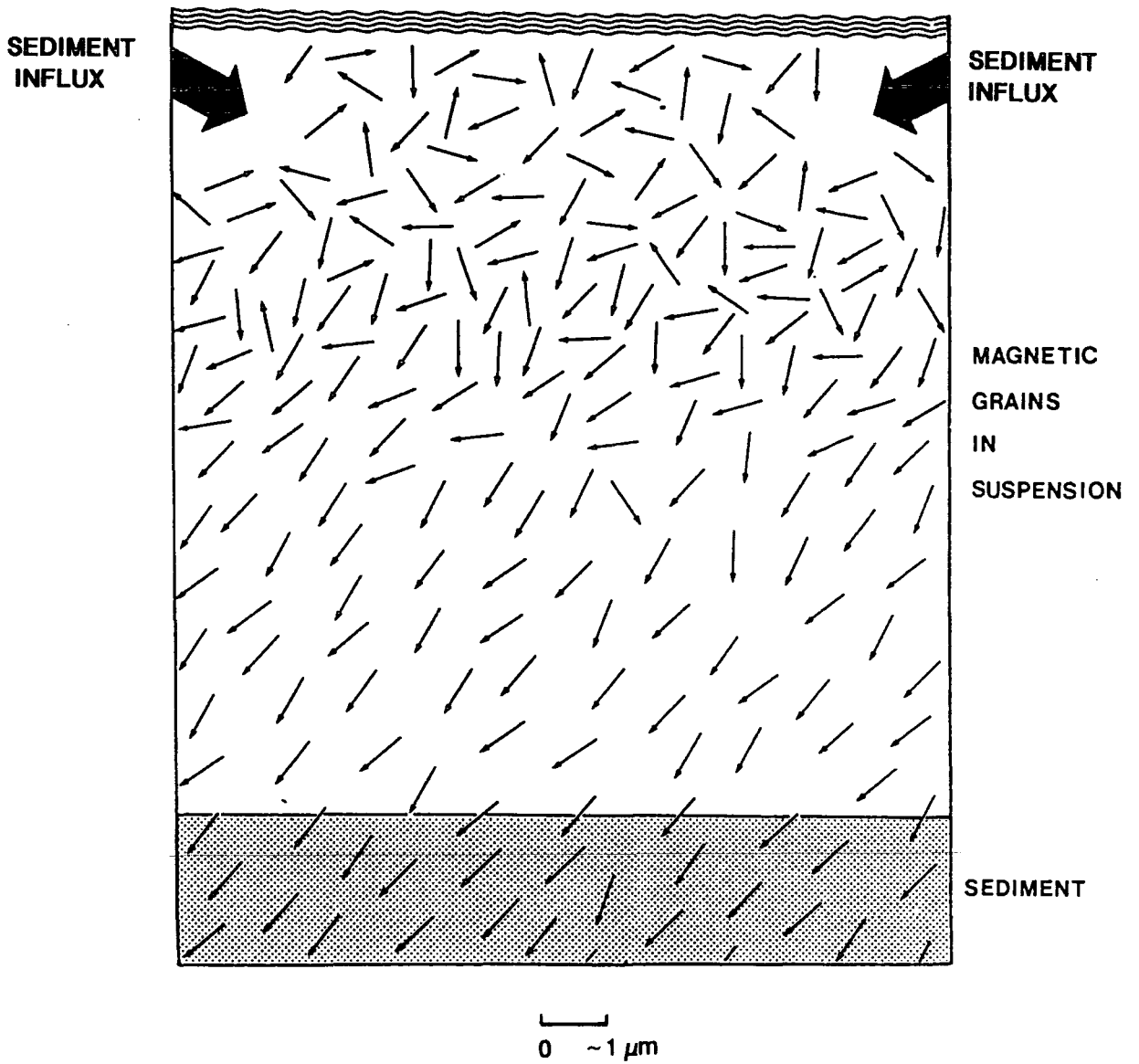


Figure 1.2: Alignment by the Earth's magnetic field of detrital magnetic grains in suspension (from diagram by Noel, pers. comm.)

with the results of laboratory experiments, in which inclination error arose when particles rolled into nearby depressions in the sediment surface.

King (1955) observed that deposition from still water onto a sloping surface produced a deviation in the remanent magnetisation termed 'bedding error'. Flume experiments by Hamilton and King (1964) led to an empirical formula for the bedding error and an explanatory theory was developed, based on spherical particles rolling into depressions in the tilted sediment surface (King, 1955; Griffiths *et al.*, 1960). Deposition in flowing water was also investigated by King (1955), who observed deviations in declination of 10° to 50° and attributed them to the 'current rotation effect'. This was explained by the velocity gradient produced by a current leading to shear stress on particles, rotating them about horizontal axes, perpendicular to the direction of flow and resulting in a deviation of both declination and inclination. The effect was reproduced in flume experiments by Griffiths *et al.* (1960) and Rees (1961).

The inclination error, bedding error and current rotation effect would all be expected to disturb the DRM of a sediment at the sediment-water interface. However, Irving (1957) observed that slumped Precambrian Torridonian sandstones had uniform directions of remanent magnetisation, suggesting that the magnetisation was post-depositional in origin. He developed a qualitative theory to account for this post-depositional magnetisation (PDRM) in which magnetic carriers were free to rotate in water-filled voids in the sediment matrix after deposition. When the water content dropped below a critical value, the magnetic carriers could no longer rotate and the magnetisation became locked in. PDRM was demonstrated in the laboratory by Irving and Major (1964) who produced a stable magnetisation by stirring wet, synthetic sediments and draining and drying them in an aligning field. Kent (1973) performed similar experiments using a reconstituted slurry of deep sea sediments and also found post-depositional alignment of magnetite grains, as did Graham (1974) in experiments using reconstituted estuarine sediments. Thus two possible scenarios developed (Verosub, 1977): if the initial water content was greater than a critical value, PDRM would occur and no inclination error, bedding error and current rotation effects would be present; if the water content was below the critical value no reorientation of the magnetic carriers would be possible and the DRM would be recorded and preserved, with its associated errors.

Subsequent experiments by Verosub *et al.* (1979) showed that, in most cases, the water content was insufficient to allow for post-depositional grain realignment and concluded that the mechanism of PDRM acquisition must also involve some physical disturbance of the sediment. This might be through stirring, as in the laboratory experiments of Irving and Major (1964), Kent (1973) and Graham (1974), or by the

bioturbation, slumping or vibration of natural sediments (Verosub *et al.*, 1979). This conclusion was supported by Tucker (1980a) who found that in undisturbed sediments less than 20% of grains were free to rotate in water-filled voids, but that a gentle stirring or tapping of the material in an applied field would produce a PDRM (Tucker, 1980b). Payne and Verosub (1982) conducted redeposition experiments using natural sediments preserved in their original state, rather than the synthetic sediments or reconstituted natural material of previous studies. From their experiments they concluded that the ability to acquire a PDRM was directly related to the bulk particle size distribution of the sediment; for sediments with less than 60% sand, the magnetisation did not change when the direction of the applied field was altered, unless the sediment was subjected to mechanical disturbance. On the other hand, the direction of magnetisation in a sediment with over 60% sand and a sufficiently high water content did change with the applied field. These observations fitted the simple model of magnetised particles within water-filled voids, because in a mainly sand matrix the voids would be larger and hence the magnetised grains could rotate more easily. Grains in a matrix with smaller pore spaces would be less able to rotate and electrostatic and chemical bonding forces would become more significant.

It has been proposed that PDRM becomes fixed when the sediment is sufficiently dewatered (Irving, 1957), although there has been little experimental work on this aspect of remanence acquisition. As Verosub pointed out (1977), natural dewatering occurs by compaction and not dehydration as in laboratory experiments. In the laboratory Løvlie (1974) reproduced the apparent downwards displacement of a palaeomagnetic boundary, a phenomenon seen in deep-sea cores by Dymond (1969). In his experiment, Løvlie deposited reconstituted deep sea clays through a column of water in an applied field, reversing the field at a specific time. This reversal was recorded in the sediment deposited 5-10 days before the actual event and he attributed this to the time taken for the sediment to become consolidated and the magnetic carriers to be immobilised. In contrast, redeposition experiments with organic lake sediments (Barton and McElhinny 1979), using slower deposition rates over a longer period of time and no drying prior to subsampling, found that the magnetisation was 'locked in' in less than 2 days. However, correlation of these results with natural sediments is difficult as the deposition rates are ten to a thousand times slower. It has been suggested that in organic sediments the magnetisation becomes 'locked in' in a matter of months by the action of organic gels (Stober & Thompson, 1977 & 1979), whereas in clay based sediments the magnetic particles might be immobilised by interaction with clay floccules (Ellwood, 1979). Hence, while a sediment with a PDRM would be expected to be free from the inclination error, bedding error and current rotation effect associated with a DRM, there is a problem in ascertaining when the magnetisation was acquired. Recording of the geomagnetic field will not be instantaneous, and strong but short lived fluctuations in direction will be

smoothed out, so the detail of secular variation recorded in a sediment will depend upon its rate of deposition.

As discussed previously, laboratory experiments have identified at least two processes by which sediments may become magnetised, DRM or PDRM. In considering natural sediments it would be expected that, if DRM was the mechanism responsible for magnetisation, there should be inclination error and, in the appropriate circumstances, bedding error and current rotation effects. If these effects are not present, it might be inferred either that the sediment has acquired its magnetisation after deposition, or that the laboratory experiments do not accurately represent the natural situation (Verosub, 1977). Unfortunately, it is very difficult to ascertain which processes are occurring in natural sediments. Determining the presence of inclination error is particularly difficult because the effect must be distinguished from secular variation itself (Verosub, 1977). The absence of PDRM in glacial varves has been demonstrated by a palaeomagnetic investigation of deformed varves (e.g. Granar, 1958). Studies of recent varves from a period when inclination is well known (Granar, 1958; Griffiths, 1955; Griffiths *et al.*, 1960) indicated that inclination error might occur, but to a lesser extent than predicted by laboratory experiments. Bedding error does occur in varved deposits and appears to be consistent with the values predicted by laboratory experiments (Griffiths *et al.*, 1960; Rees, 1964). Sediments from the deep-sea environment are in marked contrast. Deposition rates are much slower, say a few mm per thousand years, a thousand times less than the deposition rates of varves, and there is extensive bioturbation by marine organisms (Sanders & Hessler, 1969) which would destroy any DRM. Despite this, deep-sea cores show a stable magnetisation with no indication of inclination error which must, therefore, be post-depositional in origin. Deposition rates in lakes are of the order of tens of cm per thousand years and Graham (1974) has demonstrated that such material can give a PDRM under laboratory conditions. However, as with other natural sediments, alignment effects, climatic effects, temperature, water depth and presence of organisms may all be complicating factors.

Marked changes in remanence direction have been observed after prolonged storage or drying (e.g. Granar, 1958). A secondary magnetisation may be acquired if a sediment is rewetted and this may be difficult to detect as the realigned remanence will have similar properties to the original depositional remanence (Thompson & Oldfield, 1986 p158). Drying of inorganic sediments may produce a physical change, causing a drying remanence to be acquired (Henshaw & Merrill, 1979) and in organic sediments it has been observed to cause as much as a 50% reduction in remanence (Stober & Thompson, 1977 & 1979). There are three possible outcomes to drying of a sediment (Thompson & Oldfield, 1986 pp158-160). Firstly, the remanence may be stabilised (e.g. Payne & Verosub, 1982). Secondly, there may be a loss of remanence as smaller

magnetic particles are pulled towards larger particles by surface tension effects (Noel, 1980) or particles rotate randomly (Otofuji *et al.*, 1982). Thirdly, a new stable remanence may arise. There may also be chemical, biochemical and dimensional changes in the sediment.

Clearly, the processes involved in the acquisition of magnetisation by sediments are much more complex than the early laboratory models of DRM indicated. DRM and PDRM processes may both occur in a natural sediment, sometimes in competition with each other. Their action will be determined by the shape, size and mineralogy of the magnetic particles and the rest of the sediment matrix. Of particular importance is the ratio of sediment grain size to magnetic carrier grain size, which will determine the volume within which the magnetised particles can rotate and hence whether they can acquire a PDRM. Additional research into the process of compaction and 'locking in' of the magnetisation is required. The major difficulty in explaining these processes is in relating the simple models and laboratory experiments using reconstituted sediments and fast deposition rates, to the natural environment where deposition is much slower and the process of remanence acquisition may be affected by other factors such as temperature, bioturbation, pore-water chemistry and fluctuations in water content. Anisotropy of magnetic susceptibility may provide further insight into the mechanisms involved (Section 2.3) in natural sediments. It is vital to understand the processes of DRM and PDRM acquisition in order to determine how accurate a record of secular variation can be provided by sediments. Archaeomagnetic studies of fired structures can fulfil a crucial role, providing a dated record of secular variation for comparison with secular variation recorded in sediments, enabling the presence or absence of inclination error to be determined.

1.4.3 Chemical remanent magnetisation (CRM)

A stable remanence can arise from chemical changes and may overprint an existing TRM or DRM. A CRM might arise from the growth of new magnetic minerals or the chemical alteration of pre-existing ones. When a magnetic mineral is produced by chemical changes, it can acquire a remanence in the direction of the ambient field in which it is formed. When the magnetic grain grows larger than a critical size, known as its *blocking volume*, the magnetisation will be 'locked'; if the grain continues to grow it will eventually change from being single domain to multidomain (Tarling, 1983 p29). Such changes are most likely to occur in sediments either shortly after deposition or after post-depositional changes. Examples would be the alteration of haematite to magnetite in the reducing conditions provided by organic matter in a deposit, or chemical changes triggered by changes in the water content of a deposit. Weathering of fired material and sediments may also produce a CRM. Such remanences may partially or totally obscure

the original TRM or DRM; for example most consolidated sediments have a remanence that reflects the geomagnetic field at the time of chemical diagenesis or compaction, rather than the original deposition. In some cases the CRM is of interest to the archaeomagnetist; for example CRM in stalagmites, which arises from the precipitation within solutions in caves (Latham *et al.*, 1979) can record secular variation. However, in most archaeological cases CRM arises from weathering and needs to be removed before the original remanence can be studied. A CRM is generally of lower magnitude than a TRM, as it usually affects a smaller proportion of the magnetic grains, but may be more stable.

1.4.4 Viscous remanent magnetisation (VRM)

The term 'viscous' refers to time dependent changes in magnetisation. If the magnetic field acting on a material changes (for example, owing to secular variation or removal of samples to the laboratory), grains with short relaxation times will acquire a magnetisation in the new field direction. The acquisition of a viscous remanence depends on the time in the magnetic field, the strength and constancy of the magnetic field, and on the relaxation time spectrum, which in turn is determined by the temperature, grain size and composition of the material. Grains with very short relaxation times may reorient in a matter of minutes, those with longer relaxation times might take years, centuries or even longer. Although theory and laboratory experiments concerning the growth of viscous remanent magnetisation are not well-developed, it is known that it may have an approximately logarithmic time dependence (Dunlop, 1973; Walton, 1980) and hence can be used as dating tool, although there are many problems with this application (Section 1.2.3).

While in archaeological materials, the viscous magnetisation is likely to be small in comparison with a TRM or DRM, because it has had such a short time in which to form, it will dominate magnetisation of low stability magnetic grains. Therefore, its contribution must be assessed. This can be achieved by determining the rate of acquisition of VRM of a sample held in a magnetic field for a measured time (Heller & Markert, 1973), by storing the sample in zero field and measuring the rate of decay of VRM or by demagnetisation (Section 2.2.2). In early archaeomagnetic investigations, before alternating field or thermal demagnetisation were common, samples were either stored in zero field for a number of months to allow the VRM to decay or stored in the same position relative to the geomagnetic field as they had been in the field (Aitken & Weaver, 1962).

1.4.5 Other naturally occurring magnetisations

It has been observed (Games, 1977) that a remanence, known as shear remanent magnetisation (SRM), is induced in clays when they are thrown into a mould. This manufacturing procedure was employed in the production of sun-dried bricks in ancient Egypt and is still common in some parts of the world, such as Egypt and Peru. Games (1977) has used such bricks to evaluate the intensity of the ancient field. While there has been little investigation into the process by which such a magnetisation is acquired, it has been shown that the acquisition occurs as the clay is thrown into the mould and is separate from any VRM acquired as the brick sets (Games, 1983). One explanation for this phenomenon is that, as the clays are shocked on impact, they behave thixotropically (i.e. become fluidised) for a short time. During this time, small magnetic particles are free to align with the geomagnetic field, thus inducing a weak but permanent magnetisation in the clay (Tarling, 1983 p70). A similar process might lead to the magnetisation of clays, plasters and cements tamped onto floors or thrown onto walls, but few experimental studies have been carried out.

A number of other remanences can be produced under unusual circumstances. The strong magnetic field associated with a lightning strike may magnetise material in its vicinity with an isothermal remanent magnetisation or IRM (Section 2.4.1), produced by the strong steady field, and an anhysteretic remanent magnetisation (ARM), produced by the geomagnetic field in the presence of a strong alternating field. Such magnetisations can be isolated in the laboratory (Sternberg, 1982) and can affect deposits to depth of 20m (Tarling, 1983 p72). Their existence would suggest that particular care should be taken when examining material from exposed locations. Some forms of bacteria can synthesise magnetite in both aerobic and anaerobic environments (Bazylinski *et al.*, 1988). There are also bacteria with a magnetic moment of their own, which are passively oriented in the ambient magnetic field and move along field lines by self-propulsion (Petersen *et al.*, 1989). When such bacteria die their magnetite becomes part of the remanent magnetisation of their environment. However, the contribution this magnetisation makes to the overall sediment magnetisation is likely to be very small (Petersen *et al.*, 1989).

1.5 THE HISTORICAL DEVELOPMENT OF ARCHAEOMAGNETIC DATING

The development of archaeomagnetic dating is intrinsically linked with the development of geomagnetic and palaeomagnetic studies. While these have been reviewed by Tarling (1983 p1-8) and Wolfman (1990c, from where the following

references to French and Italian work have been taken), a brief examination of the historical perspective is useful to put the current study into context.

Archaeomagnetic dating is probably the earliest geophysical dating technique. The foundations were laid by Boyle's demonstration that bricks acquired a magnetisation along their long axes on heating and cooling in the geomagnetic field (Boyle, 1691) and by the discussion of secular variation and westward drift by Halley (1692). However, apart from a study of the magnetisation of volcanic blocks from the Roman theatre at Pompeii (Melloni, 1853) and an investigation into the remanent magnetisation of pottery (Gheradi, 1862), major progress on archaeomagnetic dating did not occur until the very end of the 19th century. In a series of papers, Folgerhaite discussed the potential of archaeomagnetic dating (Folgerhaite 1896, 1897a, 1897b & 1899) and Mercanton presented experimental results of a study into the magnetic properties of pottery (Mercanton, 1907 & 1918). Unfortunately the experimental results were poor, possibly due to the inadequacies of the available instrumentation or the selection of unsuitable samples. Nevertheless in 1925, Chevallier presented the first secular variation curve produced by archaeomagnetic studies, derived from a stratified series of historically dated lavas from Mount Etna, Sicily.

The investigations that laid the foundations for modern archaeomagnetism were carried out by Emile and Odette Thellier between 1930 and 1960 in Paris. These developments included effective sample collection techniques (Thellier, 1936 & 1967), the construction of laboratory equipment (Thellier, 1933 & 1938), the introduction of thermal demagnetisation (Thellier, 1938; Thellier & Thellier, 1942) and alternating field demagnetisation (Thellier & Rimbart, 1954), and a method for the study of palaeointensity (Thellier & Thellier, 1959; Thellier, 1977). The experimental work concerned the basic magnetic properties of fired clay and measurements of the magnetisation of baked archaeological features, with the aim of investigating the geomagnetic field. At around the same time, the first measurements of secular variation recorded by sediments were made (Section 3.3; Ising, 1942; McNish & Johnson, 1938; Johnson *et al.*, 1948). Technological developments in the 1950's led to improvements in the design of magnetometers (Section 2.2.1) and to the computerisation of routine tasks. The number of groups studying fired archaeological materials increased to include Watanabe in Japan (1959) and Burlatskaya and Petrova in the Soviet Union (1961), while the main focus of developmental research moved to Britain.

Cook and Belshé initiated work in Britain, conferring with Thellier on technical details (Cook & Belshé, 1958). Their investigation had two aims; to construct a secular variation curve by measuring the direction of magnetisation of baked clay and stone structures of known date and to use that curve to date other fired archaeological

material. The initial study included over 40 kilns and hearths from the Roman to the historical period, but the results varied greatly in precision and reliability. In the same year, Aitken published the results of a study into the inclination of magnetisation as recorded by Chinese Yüeh pottery (Aitken, 1958), with a view to dating it by comparison with the inclination record compiled for Japan by Watanabe (1959). This project was successful, although the dates obtained were not as accurate as had been hoped. In a series of papers over the next 10 years, the Research Laboratory for Archaeology at Oxford measured samples from a large number of archaeologically dated fired structures in Britain, to collect information from which to compile a record of secular variation in Britain over archaeological time (Aitken & Harold, 1959; Aitken & Weaver, 1962; Aitken, Hawley & Weaver, 1963; Aitken & Hawley, 1966 & 1967). The Oxford group also investigated the magnetisation acquired by two reconstructed kilns (Weaver, 1961 & 1962), which stimulated discussion on the problems of magnetic refraction (Section 1.4.1; Aitken & Hawley, 1971) and the difficulties in using a magnetic compass to orient samples (Hawley, 1964). In the late 1960's Oxford discontinued its work into archaeomagnetic directional studies to concentrate on thermoluminescence dating, but continued archaeointensity studies (Weaver, 1966; Walton, 1977; Rogers *et al.*, 1979; Aitken *et al.*, 1989).

During the 1960's, the focus of research moved from archaeomagnetism to palaeomagnetism. This change partly occurred because of the interest generated by geomagnetic reversals and continental drift (Section 1.3) and partly because of the very large number of archaeomagnetic measurements that were required before the method could be used as a dating technique. However, archaeomagnetic studies were pursued in a number of regions and, after a period of sampling and measurement, several calibration curves have been produced (Section 1.6).

Following the development of the British calibration curve (Section 5.2), archaeomagnetic directional dating is now a routine method for dating fired archaeological material in Britain, the majority of studies being carried out by Clark Consultancy and the Ancient Monuments Laboratory of English Heritage. In addition to the collection of archaeomagnetic samples in order to further refine the calibration curve, research into other areas of the subject continues in Britain. There is interest in the development of viscosity dating (Atkinson & Shaw, 1991) and in the archaeomagnetic properties of sediments (Hammo-Yassi, 1984; Batt & Noel, 1991; Batt, in prep.). Other recent research projects have included the archaeomagnetic properties of vitrified hillforts (Gentles, 1989) and archaeomagnetic studies in collaboration with scientists abroad, for example in the field of Chinese archaeomagnetism (Batt & Noel, 1991).

1.6 INTERNATIONAL ARCHAEOMAGNETISM

There is world-wide interest in archaeomagnetic dating for a number of reasons, outlined in Section 1.1. In some regions and for some periods of time it may be the only applicable method. This is particularly true in circumstances where there are fired remains, but no organic material suitable for radiocarbon dating and the ceramic typologies are undated. Other advantages are the potential to provide precise dates for any period in which the calibration curve is well defined, wide applicability, minimally destructive sampling techniques, speed of measurements and cost. In many cases the event dated, for example the last cooling of a hearth can be closely related to an archaeological event, such as the abandonment of a structure. Despite these advantages, development of archaeomagnetic dating has been slow in comparison with other dating techniques, owing to the length of time taken to make the measurements necessary to construct the calibration curve and to the fact that a well-developed archaeological chronology is necessary to provide independent dates for the calibration curve. However, there are currently a number of calibration curves throughout the world, enabling archaeomagnetic dating to be carried out.

The early stages of the development of archaeomagnetism are reviewed in Section 1.5. In Britain, archaeomagnetic work has been carried out since 1958 and dates can now potentially be provided between the present and 1000BC, although the precision depends upon a number of factors (Section 2.6). Archaeomagnetic development in France started very early with the pioneering work of Emile and Odette Thellier (Section 1.5) in the 1930's in Paris and the technique is now well established in France (e.g. Barbetti *et al.*, 1980).

Of particular note in European archaeomagnetic studies is the work of Kovacheva in Bulgaria and south-eastern Yugoslavia. Her extensive studies of fired features from the region, summarised in Kovacheva (1980) and Kovacheva and Zagniy (1985), have led to calibration curves in declination, inclination and intensity for most of the last 8000 years, although the earlier periods, particularly the Prehistoric, are restricted by the imprecise dating available from radiocarbon. These studies are particularly important as they use all three geomagnetic elements (Kovacheva, 1986 & 1991) and the resulting calibration curves have been used to date a number of sites (e.g. Kovacheva, 1989). The calibration curves she has compiled show similar extreme values in the 12th and 13th centuries to the French and British curves and may show some periodicities of the order of several hundreds of years (Kovacheva, 1982). Kovacheva also pioneered archaeomagnetic work in North Africa (Kovacheva, 1984), although studies in this region are still not far advanced.

In Hungary, archaeomagnetic measurements have been made on almost 60 fired structures from the last 2000 years and are supplemented by direct geomagnetic observations, by information from early maps and by deductions of the geomagnetic field as revealed in the manufacture of early astronomical instruments (Márton, 1991). In southern Italy, directional measurements have been made on samples from fired structures including kilns, ovens and funeral pyres from 17 sites, dating to between 550BC and 520AD (Evans & Mareschal, 1989). The resulting secular variation curve is similar to the British lake sediment data (Turner & Thompson, 1982), but archaeomagnetic studies in the region are still in their infancy. In the USSR archaeomagnetic studies commenced in the early 1960's (Burlatskaya and Petrova, 1961) and have been carried on in a number of regions, mainly concentrating on measurements of inclination and intensity of the ancient field, using baked clay objects and bricks (Burlatskaya *et al.*, 1970; Rusakov & Zagniy, 1973; Burlatskaya, 1983).

South-western U.S.A. has proved to be a focus for archaeomagnetic work because the abundant cultural remains include a large number of fired materials, particularly hearths, and excellent dating control is often available from the well-established tree-ring chronology. Much archaeomagnetic work in the area has been carried out by DuBois (1988 & 1989). However, a detailed discussion of these results has been hampered by the unavailability of the raw numerical results (Sternberg, 1982). In south-west Colorado, the Dolores Archaeological Program was established to excavate a number of prehistoric (AD700-900) villages under threat from a dam. 82 archaeomagnetic directions were obtained and independently dated using dendrochronology and ceramic typology for use in a calibration curve (Eighmy *et al.*, 1990; Hathaway *et al.*, 1983). Also in the south-western USA, Sternberg and McGuire (1990b) have measured samples from 73 independently dated fired features from AD700-AD1450 and obtained a similar secular variation curve to that of the Colorado study, described above. A secular variation curve between AD1200-AD1500 for Arkansas and neighbouring states has been drawn by Wolfman (1990a), on the basis of directional measurements from samples taken from 79 features. He suggests that, given suitable archaeological excavations, the archaeomagnetic record could be extended back much further. Wolfman has also produced 200 archaeomagnetic directions from features in Mesoamerica (Wolfman, 1990b), the area that encompasses central and southern Mexico, Guatemala, Belize, El Salvador and western Honduras. These measurements produced a curve spanning AD1-AD1170, in addition to a number of short sections. The curve was used to help interpret the native Calendars for the area. Attempts to obtain a secular variation record from stalagmites have also been carried out in Mexico (Latham *et al.*, 1989).

Archaeomagnetic studies in China are reviewed in Section 4.3. In Japan archaeomagnetic investigations started very early (Watanabe, 1959) and there are now measurements of secular variation from approximately 3650BC-2450BC and for the last 1700 years. Unfortunately, the independent dating control is too imprecise for them to be used in a calibration curve. A useful contribution to the Japanese dataset was provided by archaeomagnetic studies of roof tiles from Buddhist temples dating from 7th-9th centuries AD and from the N-S alignment of the temples themselves. Studies of kilns from the stoneware ceramic industry in Thailand (Barbetti & Hein, 1989) dating from AD900-AD1600 have successfully shown how the technological developments in kiln construction proceeded. In Iran, small scale investigations have been carried out (Kawai *et al.*, 1972; Hammo-Yassi, 1984) and, in Egypt, bricks from 8 sites have been sampled to obtain inclination values (Hussain, 1983). Recently, an archaeointensity curve has been produced for the Tamil Nadu Province of India, covering 500BC to the present (Ramaswamy & Duraiswamy, 1990). A study of a series of ancient hearths in Australia (Barbetti, 1983) even provided evidence of a geomagnetic excursion and the declination and inclination measurements from there corresponded well with the changes in magnetic direction recorded in a lake sediment curve for the region.

1.7 USES OF ARCHAEOMAGNETIC INVESTIGATIONS IN ADDITION TO DATING

Although this research has concentrated on the ability of archaeomagnetic measurements to provide absolute dates for fired material and sediments, other investigations have demonstrated a number of further possible applications. As discussed in Section 1.4.1, if a remanence carrying material is heated to temperatures above its Curie point, all record of any previous TRM will be eradicated. However, if it is heated to temperatures below its Curie point, not only will evidence of any previous heating to a higher temperature be distinguishable by demagnetisation, but it may also be possible to determine the maximum temperature reached. This principle was used by Kent *et al.* (1981) when investigating the magnetic properties of the pyroclastic deposits which covered Herculaneum when Mount Vesuvius erupted in AD79. Using thermal demagnetisation, they distinguished between the magnetisation acquired on formation of lithics in the matrix and the magnetisation acquired at lower temperatures on emplacement, concluding that the pyroclastic material had not reached temperatures of over 400°C. Similar investigations of burnt clay from a lower Pleistocene site in Kenya (Gowlett *et al.*, 1981) revealed it to have a maximum firing temperature of 400°C, typical for open camp fires. This temperature determination, along with studies of the magnetisation typically produced by bush fires, led to the suggestion that this locality, dated to over 1.4 ± 0.7 Myr, provides the earliest evidence of controlled fire associated

with a hominid occupation site. Calculations have also been made of the length of time of firing of a structure. Meng and Noel (1989) measured the depth of remanence acquisition and thermal diffusivity of tiles from a hearth in York. Using a simplified model of the hearth as part of a semi-infinite solid with uniform surface temperature, they calculated that the hearth had been fired continuously for at least 56 hours.

Another area of interest in the investigation of fired material is the reconstruction of structures and ceramics using their remanence characteristics. If the date is known and the magnetisation is stable, slumping or fragmentation of a structure can be corrected for by rotating the feature, or its parts, until their remanence directions coincide with the expected magnetic direction for that date (Clark, 1980 and Noel, 1990 give some practical examples). In a similar way, the direction of magnetisation of pot sherds can be used to help in the reconstruction of pottery by matching pieces of common magnetic direction, as demonstrated by Burnham and Tarling (1975). While this method may not be as effective as an experienced person 'jigsaw' fitting the pieces, particularly on irregularly shaped vessels, it does allow the determination of vessel shape from only a few fragments by placing them in their original relative positions and may assist 'jigsaw' fitting by enabling shards to be sorted into bands with common magnetic direction.

There has been considerable interest in the application of studies of the magnetisation of ancient coins. Tanner *et al.* (1979) demonstrated that ancient copper-based coins contained magnetic impurities which might reflect the origin of the ore and it has been shown that many ancient coins retain a stable magnetisation (Tarling, 1982). Unfortunately, this remanence does not accurately reflect the inclination or intensity of the geomagnetic field at the time of the coin's manufacture (Goulpeau *et al.*, 1987), possibly because of distortions of the ambient field by iron rings used to reinforce the dies (Tarling, 1982; Hoye, 1983). However, it is possible to distinguish which side was uppermost when the coins were struck and that coins were held roughly vertically when being silvered (Tarling, 1982). An investigation of the remanence carriers can also be used to distinguish between cast and struck coins and to investigate the thermo-mechanical history of the coin (Hoye, 1983).

Magnetic measurements have proved useful in the provenancing of archaeological materials and sediments. Using basic magnetic measurements such as initial intensity of magnetisation, saturation magnetisation and low field susceptibility McDougall *et al.* (1983) demonstrated the possibility of sourcing obsidian samples from the Mediterranean and Near East. While these measurements were not always as precise as minor element analyses, they were considerably cheaper, quicker and had the advantage of being non-destructive. Magnetic measurements have also been used to distinguish between sources of sediment (Oldfield, 1991) and to determine the environment of deposition. As a major topic of investigation in this thesis, the use of sediment magnetic properties in these ways is discussed fully in Section 2.3.

Chapter 2

Techniques of Sampling and Measurement

2.1 SAMPLING TECHNIQUES

2.1.1 *Introduction*

Investigations of magnetic remanence, fabric and mineralogy were carried out in the laboratory and so it was necessary to take samples of material on site. Suitable material was selected (as described below) and its position and orientation in the geographic reference frame and its archaeological context were recorded. Archaeomagnetic sampling techniques have been adapted from those used in palaeomagnetism to suit the particular requirements and constraints of the archaeological environment.

In palaeomagnetism, consolidated material is conventionally sampled by drilling cores in the field or by removing oriented blocks (usually 1-5l) with chisels and hammers, then subdividing them in the laboratory (Collinson, 1983 pp192-195). The former method is faster and more widely applicable, but more expensive as drill bits wear out quickly. Fired archaeological remains are generally more friable than geological material and drilling is rarely feasible. The low sensitivity of early magnetometers meant that archaeological samples needed to be approximately 400cm³ (Aitken & Weaver, 1962). These were most easily obtained by isolating a block of material and surrounding it by a wooden frame, which was then filled with plaster of Paris (e.g. Thellier, 1937). The plaster surface was levelled, the orientation scratched on and, when the plaster was set, the frame could be removed and the sample cut away from beneath. A similar technique is currently used in sampling friable fired material (Section 2.1.2) but with the increased sensitivity of modern magnetometers, a piece of fired material as small as 1cm³ usually has a measurable magnetisation, and samples can sometimes be considerably smaller. This enables sampling to be minimally destructive; an important consideration when investigating structures which are to be preserved for display or further investigation. The button sampling technique described below (Section 2.1.2) is a miniaturisation of the palaeomagnetic 'block sampling' procedure and is particularly suited to taking small, accurately oriented samples of consolidated material.

Unconsolidated materials, such as lake or sea-bottom sediments form an important part of palaeomagnetic investigations and are generally sampled by conventional coring methods using a Mackereth (Mackereth, 1958 & 1969), hydraulic (Prell & Gardner, 1980), gravity or piston corer (Livingstone, 1955, Vallentyne, 1955). Continuous cores, 1-10m in length, can be obtained and subsamples taken in the laboratory from the undisturbed centre of the core. Accurate orientation is difficult as the corer often twists upon insertion or extraction and the palaeomagnetic record obtained is usually expressed in terms of relative changes in declination and inclination. Coring is unsuitable for many archaeological sediments because they are too hard to be cored without substantial disturbance and accuracy of orientation is necessary as absolute values of declination and inclination are required. The tube sampling method described below (Section 2.1.3) is a miniaturised coring process which causes minimal disturbance and allows specimens to be oriented individually. Unfortunately, the technique is restricted to accessible sediment faces. Homonko (1978) suggested sampling sediment sections by pushing an aluminium channel into an exposed face; this should be quick and subsampling could be carried out under controlled conditions in the laboratory. However, trials have suggested that considerable force is required to insert the channel into more consolidated sediments, accurate orientation is hard to attain and there is less flexibility over choice of sample location.

2.1.2 Fired materials

In this study, fired material was generally sampled by the 'button method' (Clark *et al.*, 1988), illustrated in Fig. 2.1, using the equipment shown in Plate 2.1. The sampling points selected varied according to the type of structure and its state of preservation and are discussed in detail for each feature. The general criteria were that the material was structurally stable, appeared well-fired, unweathered and undisturbed. Each area chosen was scraped and brushed to remove loose material, thereby aiding adhesion and displacing randomly oriented surface particles. To further improve adhesion, the area was dried by dabbing with acetone. A plastic button (Fig. 2.3a) was then attached to the surface using quick setting epoxy resin (e.g. Devcon from Devcon Corp., Danvers, MA01923), mixed on the button stub, which had been roughened to improve adhesion. The button was levelled with a bull's-eye spirit level and held in position by a small piece of Plasticine until the glue had set, normally about 10-15 minutes. When the resin had set each specimen was oriented (Section 2.1.4) and cut away using non-magnetic or demagnetised tools (for example the knife, trowel and hammer shown in Plate 2.1), leaving a small piece of fired material attached to the button.

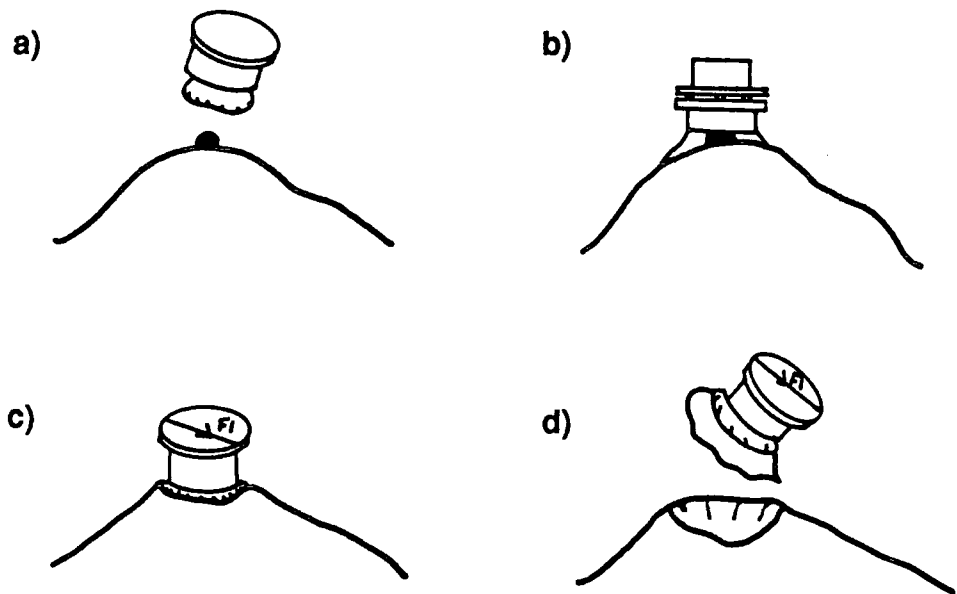


Figure 2.1: Sampling of fired material by the button method (after Clark *et al.*, 1988). A bead of plasticine was placed on the cleaned sampling point (a), epoxy resin was mixed on the button stub and the button pressed into the plasticine. The button was levelled with a bull's-eye spirit level (b) and, when the resin had set, the orientation was marked on (c). The button was then cut away (d), with the sample attached.

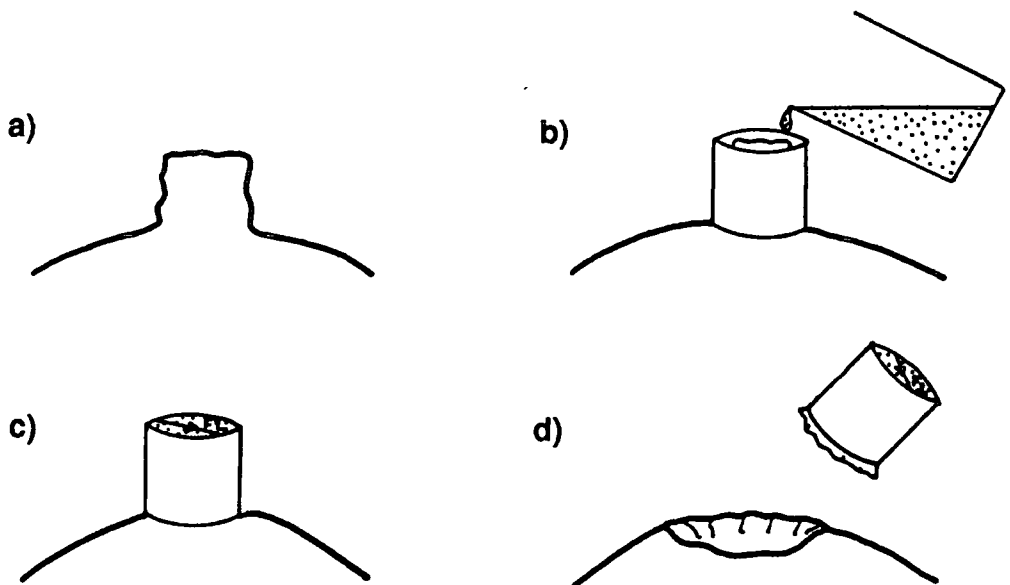


Figure 2.2: Sampling of fired material by the pillar method. A pillar of material was cut (a) and encased in a tube into which plaster of Paris was poured (b). When set, the plaster surface was levelled and the orientation marked on (c). Sample and tube were then cut away from below (d).

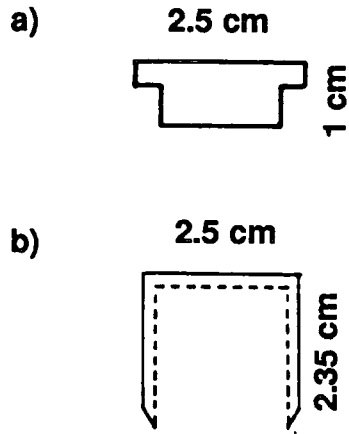


Figure 2.3 a: The sample button.
b: The sample tube

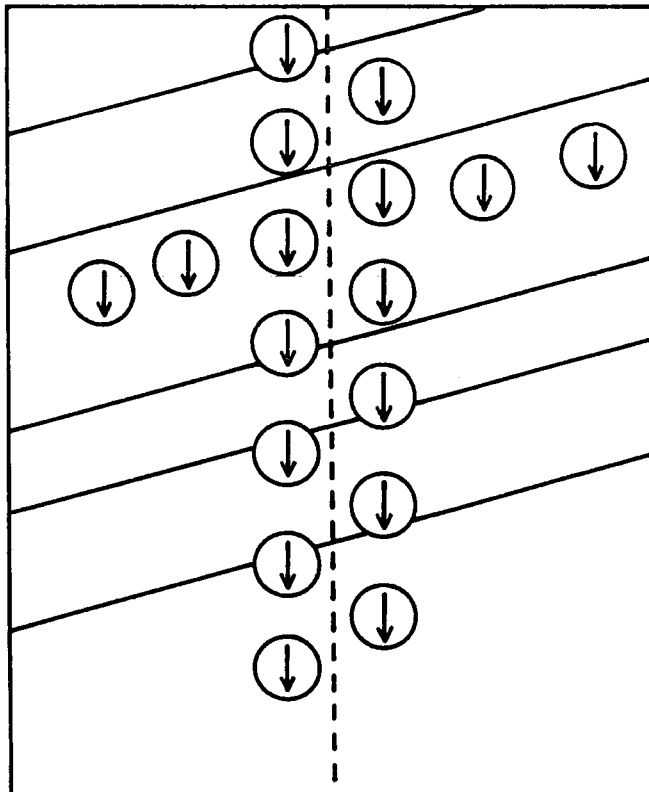


Figure 2.4: Schematic diagram showing how samples were positioned down a vertical sediment face. The samples overlapped and a number were taken from one stratigraphic horizon.

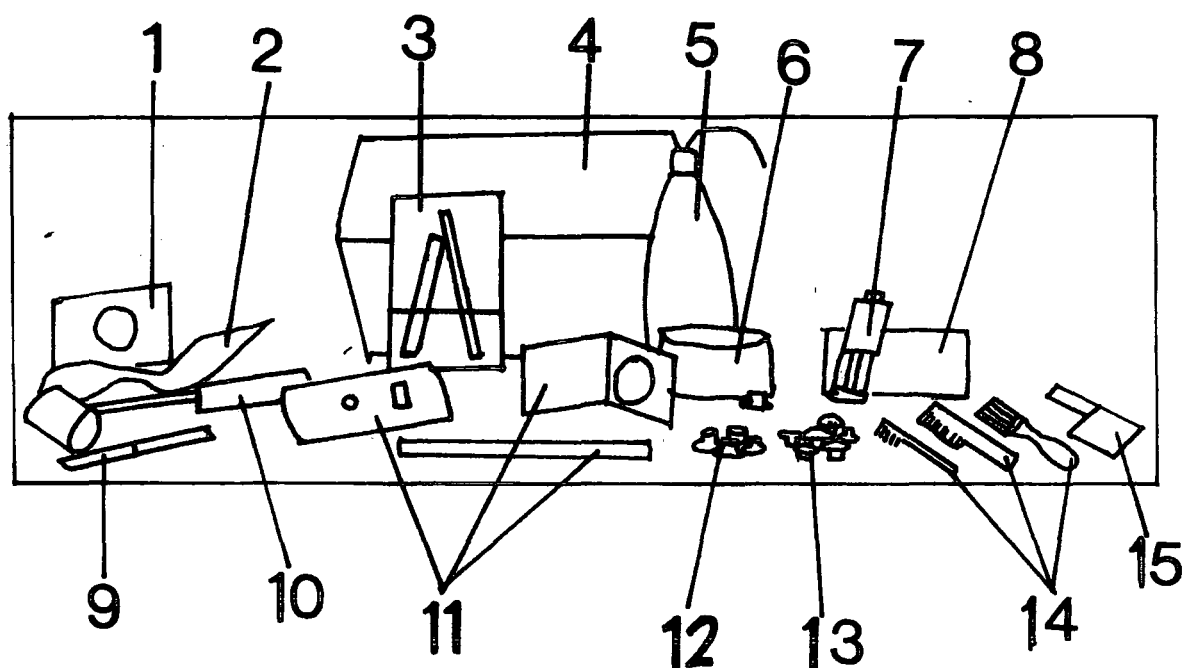
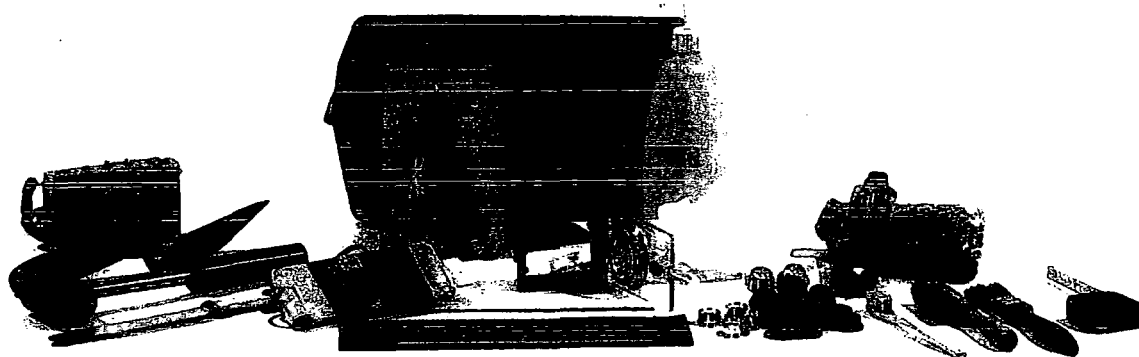


Plate 2.1: Equipment used in the sampling of fired materials.

Key: 1 = camera, 2 = trowel, 3 = notebook, waterproof marker pen and pencil, 4 = carrying box, 5 = methylated spirit, 6 = packing material, 7 = epoxy resin, 8 = Plasticine, 9 = knife, 10 = hammer, 11 = fluxgate, sun and conventional compasses, 12 = spirit levels, 13 = plastic buttons, 14 = brushes, 15 = tape measure

Occasionally samples were also obtained by cutting a pillar of material *in situ*, over which a tube was placed and levelled (Fig. 2.2). The tube was then filled with plaster of Paris and the excess scraped away when partly set. Orientation marks were cut into the plaster surface and, when set, the tube and sample were cut away together (Clark *et al.*, 1988). The pillar sampling method was particularly applicable to very friable fired material or consolidated sediments.

All the materials used were required to have a negligible magnetic remanence. To check this, measurements were made of the remanence of test samples made up entirely of plaster of Paris, Plasticine and glue. It has been reported that the pigments in some colours of Plasticine exhibit a slight remanence (Clark *et al.*, 1988) and some varieties of plaster of Paris acquire a random or detrital remanent magnetisation (Sternberg, 1989b). However, the remanence of all the materials used in this study, including empty sample tubes and unused buttons, was found to be below the noise level of the magnetometer. As an additional precaution tubes and buttons were cleaned and demagnetised before use.

For statistical validity a minimum of seven specimens were required from each context (Section 2.5.1). However, in this study, at least fifteen were taken from each fired structure. This made it possible to discard samples that fell apart, provided archive material for future investigations and allowed specimens with anomalous magnetic directions to be rejected without affecting the statistical validity of the average direction. If it were possible to distribute samples throughout the structure, the presence of refraction effects (Section 1.4.1; Aitken & Hawley, 1971) and systematic subsidence could be investigated and the mean magnetic remanence directions corrected accordingly.

Detailed observations and descriptions were made of the features investigated; they were drawn, photographed and described in the field and a detailed examination of all the samples was carried out in the laboratory. Particular attention was paid to any evidence of slumping or displacement of the structure or the surrounding ground and to any evidence of weathering.

2.1.3 *Soft sediments*

Sediments and other unconsolidated materials, for example burnt soil, were sampled using plastic tubes (Fig. 2.3b). These had a 25° chamfer at the open end and an air hole at the closed end, so that minimum disturbance was produced on insertion into the sediment. The tubes were made from glass-filled nylon or P.V.C. as these were rigid enough to prevent deformation on insertion and had a negligible remanence. A freshly

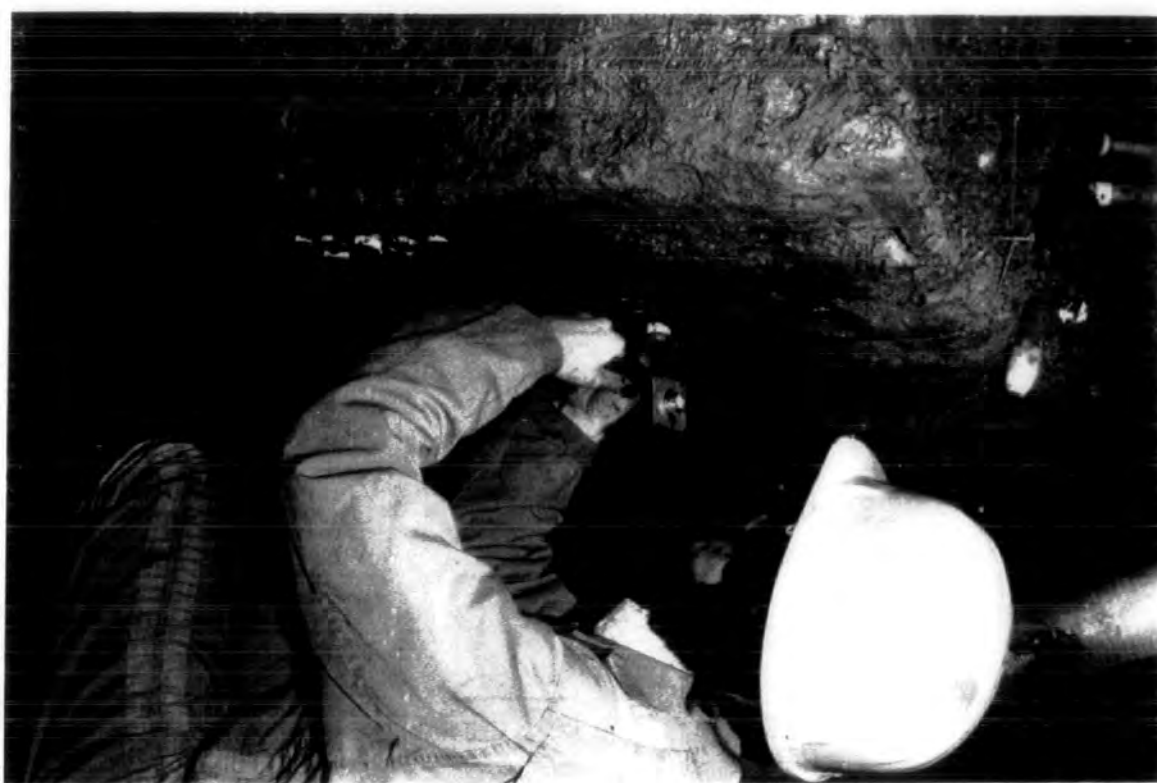
cut horizontal or vertical section was cleaned with non-magnetic tools and the tubes pushed in vertically or horizontally, at approximately 90° to the face, using a plate incorporating a spirit level to control the angle of insertion (Plate 2.2). If insertion was horizontal, a vertical fiducial line, ascertained with a spirit level or plumb line, was marked on the end of the sample holder with a pencil. Samples were then oriented (Section 2.1.4) and cut away using non-magnetic tools (Plate 2.2). The necessary field equipment is shown in Plate 2.3. Vertical sections were sampled using a sequence of holders inserted in an overlapping fashion down the section in an attempt to reveal any variations in remanence with depth. A number of tubes were inserted into a single stratigraphic horizon in order to ascertain the scatter of measurements on material expected to preserve a single magnetic direction (Fig. 2.4). If the material was too hard to allow sample holders to be pushed in, they could be hammered in. However, this was inadvisable as the holders often deformed or the impact of the hammer caused disturbance. In such circumstances it was preferable to use the button or pillar methods described in Section 2.1.2.

Sample holders made from 5.3cm diameter plastic drainpipe are also commonly used in archaeological investigations (Clark *et al.*, 1988) and are usually pushed vertically into a prepared horizontal shelf in the sediment. The smaller sample holders used here were preferred as they were quicker to insert, more samples could be taken, stones and roots could be avoided more easily and the geomagnetic record obtained was more detailed, because each sample represented a more localised 'snapshot' of the remanence. However, it was acknowledged that any disturbance caused on tube insertion would be greater with small tubes.

Detailed observations and descriptions were made of the contexts investigated; they were drawn, photographed and described in the field and a detailed examination of all the samples was carried out in the laboratory. Particular attention was paid to the description of extent of the deposit, sedimentary or pedogenic structures (Collinson & Thompson, 1989), colour, grain size, consistency and any evidence of disturbance, including post-depositional movement and bioturbation.

2.1.4 Orientation methods

Accuracy of orientation of samples with respect to true North should be comparable with the accuracy possible in the laboratory measurements, considered to be about 1° (Section 2.6; Tarling, 1975). A number of methods were employed, each suited to overcoming the specific problems presented by different archaeological circumstances.



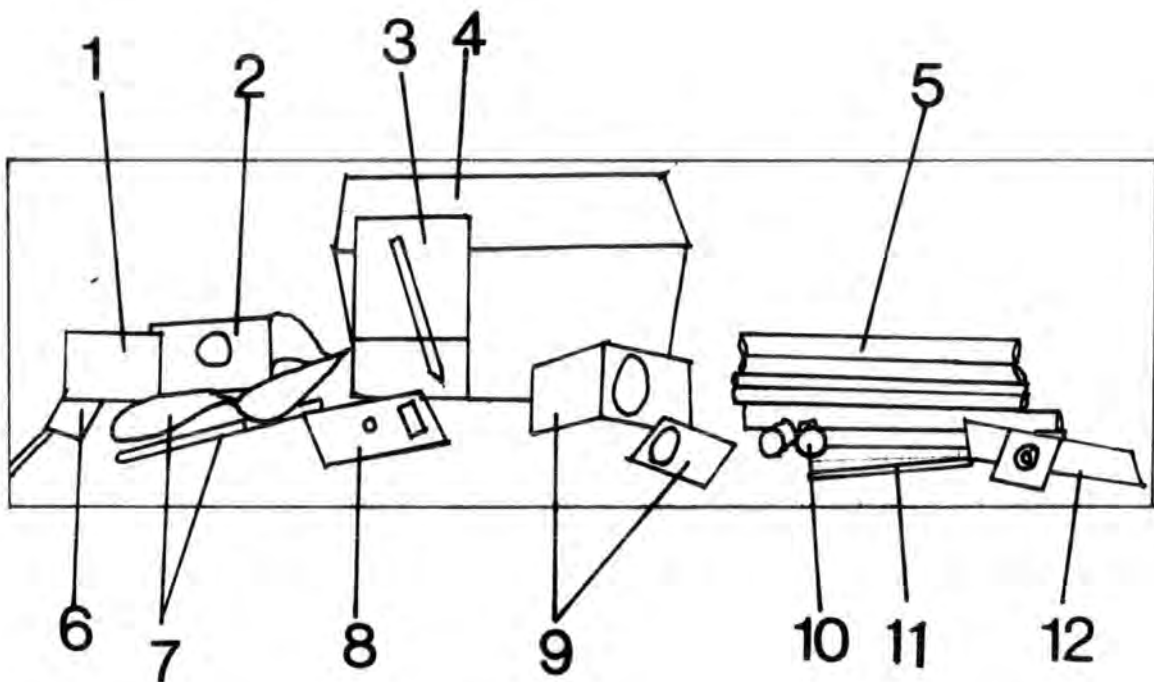


Plate 2.3: Equipment used in the sampling of sediments.

Key: 1 = plastic scraper blades, 2 = camera, 3 = notebook and pencil, 4 = carrying box, 5 = sample transport tubes, 6 = tape measure, 7 = trowel and knife, 8 = fluxgate compass, 9 = conventional magnetic compasses, 10 = sample tubes, 11 = small brass scraper blade, 12 = pusher plate with spirit level

The simplest and most commonly used procedure was to orient samples using a magnetic compass, which had the advantage of being fast, easy to use and very portable. Correction had to be made for the local variation of the geomagnetic field, which was obtained from an Ordnance Survey map of the area or the value given by the International Geomagnetic Reference Field (I.G.R.F.). However, a magnetic compass can be affected by local magnetic anomalies arising from the strength of magnetisation of the fired structure being sampled (Hawley, 1964), changes in local geology or nearby steel shoring, which is commonplace on the deep excavations necessary for many urban archaeological investigations. Using a stand-off to separate the compass from the structure reduced the first problem, but in some circumstances a magnetic compass was unsuitable.

The other method of orientation used in this study was to locate geographic North using a gyroscope attachment on a theodolite (in this case a Wild GAK 1, manufactured by Wild Heerbrugg). The instrument consisted of a mechanical gyroscope in the form of a disc, suspended inside a cage on a thin metal tape and spun at 22,000 revolutions per minute about its horizontal axis. A gyroscope's main property is that it tends to maintain its position in inertial space; if an external force is applied it will react by rotating, or precessing, about its vertical axis to a position where the force is minimised. The horizontal component of the Earth's rotation provides just such an external force and as the couple is zero when the gyro's spin axis is in the meridian plane, the gyro can be used as a North seeking instrument. The inertia of the device causes the spin axis to overshoot the meridian and a couple is applied in the opposite direction; observation of the turning points of these oscillations gives a determination of the direction of geographic North (Reversal point method) to an accuracy of 20' (Kennie & Petrie, 1990 pp87-95). The gyroscope was attached to a conventional theodolite, enabling site observations to be related to geographic North. The major advantage of a gyrotheodolite was that it was unaffected by any local magnetic anomalies and hence could be used in any archaeological situation. It was, however, very expensive, delicate, cumbersome (particularly as a battery attachment is needed), required practice to be used with accuracy and each determination of geographic North took about 20 minutes.

A sun compass is often used in archaeomagnetic investigations (Creer & Sanver, 1967). It has the advantages of being fast, accurate, portable, simple to use and, most importantly, unaffected by local magnetic anomalies. However, obviously it could not be used where the sun was not visible; for example, in cloudy weather, down deep trenches or when sampling inside a standing building, although in the latter cases a sighting could be made outside the trench or building, and the reference direction transferred using a theodolite. The restrictions to the use of a sun compass meant that it was not applicable on the sites on this study.

2.1.5 Laboratory preparation and storage of samples

After careful transportation to the laboratory, fired samples were trimmed to fit in the magnetometer holder, using a rock saw or pliers. If fragile, they were consolidated. A suitable consolidant was found to be 10% Polyvinylacetate in acetone (Clark *et al.*, 1988) which penetrated well through the matrix, set very hard and did not leave the surface sticky. Long-term storage was in a sealed box. This would ideally be in field free space provided by Helmholtz coils or a mumetal shield. However, in the absence of such facilities, the boxes were stored in dry, cool surroundings; away from strong magnetic fields. In the case of sediments, potentially disturbed material was removed from the open end of the samples, an end cap glued on and the air hole sealed, to prevent water loss and subsequent grain rotation (Noel, 1983; Otofujii *et al.*, 1982). They were then weighed and stored in a refrigerator at about 8°C to further reduce water loss. The magnetic field produced inside the refrigerator by its motor was tested using a Hall probe and found to be no higher than the field elsewhere in the laboratory. All samples were stored with their long axes vertical, standing on either the closed end of the tube or the end sealed in the laboratory. The fiducial marks were oriented in different directions to ensure that the direction of any viscous remanent magnetisation acquired would vary from sample to sample, and thus be distinguishable on demagnetisation (Section 2.2.2).

2.2 INVESTIGATION OF THE REMANENT MAGNETISATION

2.2.1 Measurement of Natural Remanent Magnetisation

A number of different types of magnetometer are currently employed for the measurement of the natural remanent magnetisation (NRM) of samples (Collinson, 1983 Chapter 9). The astatic magnetometer is one of the oldest (Blackett, 1952) and is still used for the measurement of irregularly shaped samples. In this instrument a pair of magnets, equally and oppositely magnetised, are suspended on a torsion fibre and the specimen placed beneath. The magnet system twists in response to the field gradient produced by the sample's magnetisation and a measurement of the rotation can be used to determine the NRM. Spinner magnetometers are the type most commonly used in palaeomagnetic studies. Specimens are spun near a pick-up coil and their rotating magnetisation induces a current in the coil, from which the intensity and direction of the sample's magnetisation can be determined. Specimens with a moment as low as $5 \times 10^{-10} \text{Am}^2$ can be measured and the procedure is relatively fast (Molyneux, 1971). The use of cryogenic magnetometers in archaeomagnetism is a more recent innovation (Goree & Fuller, 1976; Walton, 1977); the instrument comprises of a superconducting coil maintained at liquid helium temperatures. When a magnetised specimen is inserted

into the coil, a current flows which is proportional to the magnetic moment along the axis of the coil and is measured by a S.Q.U.I.D. (Superconducting Quantum Interference Device). Cryogenic magnetometers are very sensitive (moments as low as $1 \times 10^{-10} \text{Am}^2$ are measurable) but their main advantage is that each measurement can be carried out more quickly than with a spinner (Tarling, 1983 p88).

This study utilised a Molspin slow-speed, spinner fluxgate magnetometer (Molyneux, 1971), linked to a micro computer (Fig. 2.5), because it was quick, cheap to run and gave the required level of sensitivity, around 10^{-9}Am^2 . The sample was spun at 6Hz about a vertical axis inside a triple shielded fluxgate, positioned at the centre of the fluxgate sensor to give maximum output signal. A current was induced in the pick-up coil by the rotating magnetisation. The amplitude of the current produced depended on the intensity of magnetisation in the plane perpendicular to the axis of rotation and its phase angle depended on the direction of magnetisation in that plane. The output signals for each rotation were summed and, after a preselected number of rotations, Fourier analysed to determine the first harmonic of amplitude and phase. This was then expressed as the North and East components of the magnetisation of the specimen, relative to the fiducial mark. The slow speed of rotation meant that fragile samples could be measured.

To determine the direction and intensity of the sample's magnetisation, it must be measured in at least two orthogonal positions in the coil. In practice six spin positions were used, giving redundancy in the measurements and allowing increased precision. All measurements were relative to the fiducial mark made on site and orientation corrections were carried out after the magnetic vector had been determined. The noise level and hence sensitivity of the instrument were determined by carrying out the same measurement process without a sample in the holder. The sensitivity increases as the spin time is increased (Molyneux, 1971). 'Short spin' i.e. 6 seconds was found to be adequate for most purposes but 'long spin' i.e. 24 seconds was used for standard sized specimens with moments of less than $1 \times 10^{-8} \text{Am}^2$. Repeated measurements without a sample present showed that the noise level was around $2.5 \times 10^{-10} \text{Am}^2$ for six positions on long spin. Specimens of both fired material and sediments generally had moments well above the noise level of the instrument (Chapters 3 & 4). Repeated measurements of a single sample showed that the direction and relative intensity of remanence could be determined to within 2° (circular standard deviation) and 5% respectively. The magnetometer was calibrated using a standard specimen and recalibrated at 30 minute intervals, since the output signal drifted from the calibration value with time. Repeated measurements of the calibration sample in a single, fixed position showed that the calibration value drifted smoothly by about 5° in declination and 2° in inclination over two hours. There was no significant change in relative intensity value.

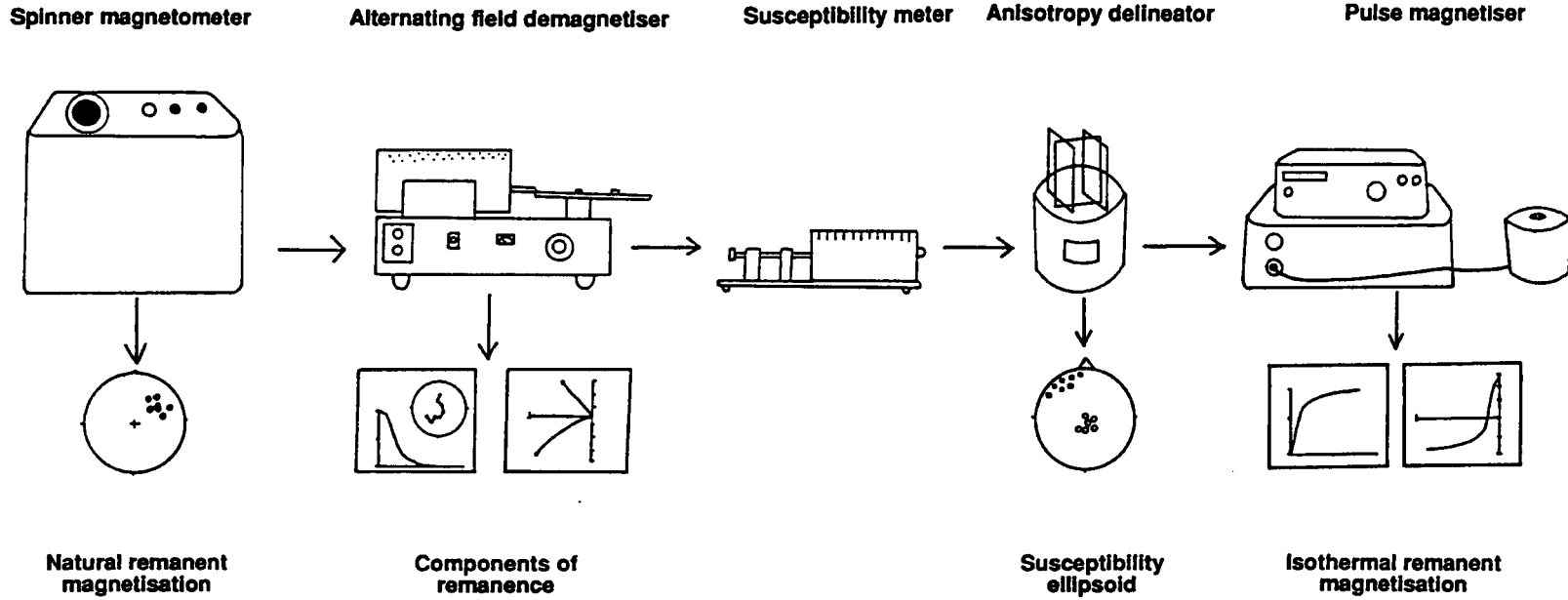


Figure 2.5: Schematic diagram showing the sequence of measurement procedures used for all groups of samples in this study and the quantities measured in each case.

The directions of magnetisation for a group of samples from a single fired structure or sedimentary horizon were represented on an equal angle stereographic projection (Fig. 2.6a). Each sample magnetic direction was plotted as a point with declination measured clockwise from North and inclination measured from the perimeter to the centre of the plot. Conventionally, the projection is lower hemisphere with positive inclinations plotted as solid symbols and negative inclinations as open symbols (Phillips, 1971). Declination, inclination and intensity from a vertical sediment section were plotted against depth (Fig. 2.6b) to reveal changes down the section.

2.2.2 Demagnetisation procedures

Early archaeomagnetic and palaeomagnetic studies were based on the measurement of NRM alone. However, anomalous results made it clear that the NRM might not accurately reflect the primary magnetisation (that is, the magnetisation acquired at the time of last cooling or deposition). In 1937, Thellier introduced thermal demagnetisation into intensity studies and used it to identify components of remanence. Subsequently, alternating field demagnetisation was proposed (Section 1.5; Thellier & Rimbert, 1954; As & Zijdeveld, 1958) and since the 1960's demagnetisation or 'magnetic cleaning' has been a routine feature of directional magnetic studies (Irving, 1964 p86).

In order to make inferences about the geomagnetic field at the time of deposition or firing it is necessary to identify the primary magnetisation and assess its stability. The primary magnetisation may have been overprinted by secondary, later, components of magnetisation arising from the growth of a viscous remanent magnetisation (Section 1.4.4), low temperature reheating of a fired structure (Section 1.4.1), chemical changes in the magnetic minerals (Section 1.4.3) or even lightning strike (Section 1.4.5). Demagnetisation techniques aim to identify specific components of the remanence and to assess their stability by determining the range of blocking temperatures or the coercivity spectrum of a sample. The underlying principle is that secondary magnetisations are generally of lower stability than primary and hence can be removed by the application of sufficient energy (magnetic or thermal) to realign randomly the particles carrying the secondary component, leaving the primary magnetisation intact (Collinson, 1983 p308).

As discussed in Section 1.4.1, a TRM is acquired in steps over successive temperatures. In thermal demagnetisation (Thellier, 1937) this blocking temperature spectrum can be determined by heating a sample in a furnace at steps of increasing maximum temperature and cooling in field free space created by Helmholtz coils or a mumetal shield (Tarling, 1983 pp90-91). Chemical changes to the specimen may arise, as many common magnetic minerals decompose during heating and new ones are created.

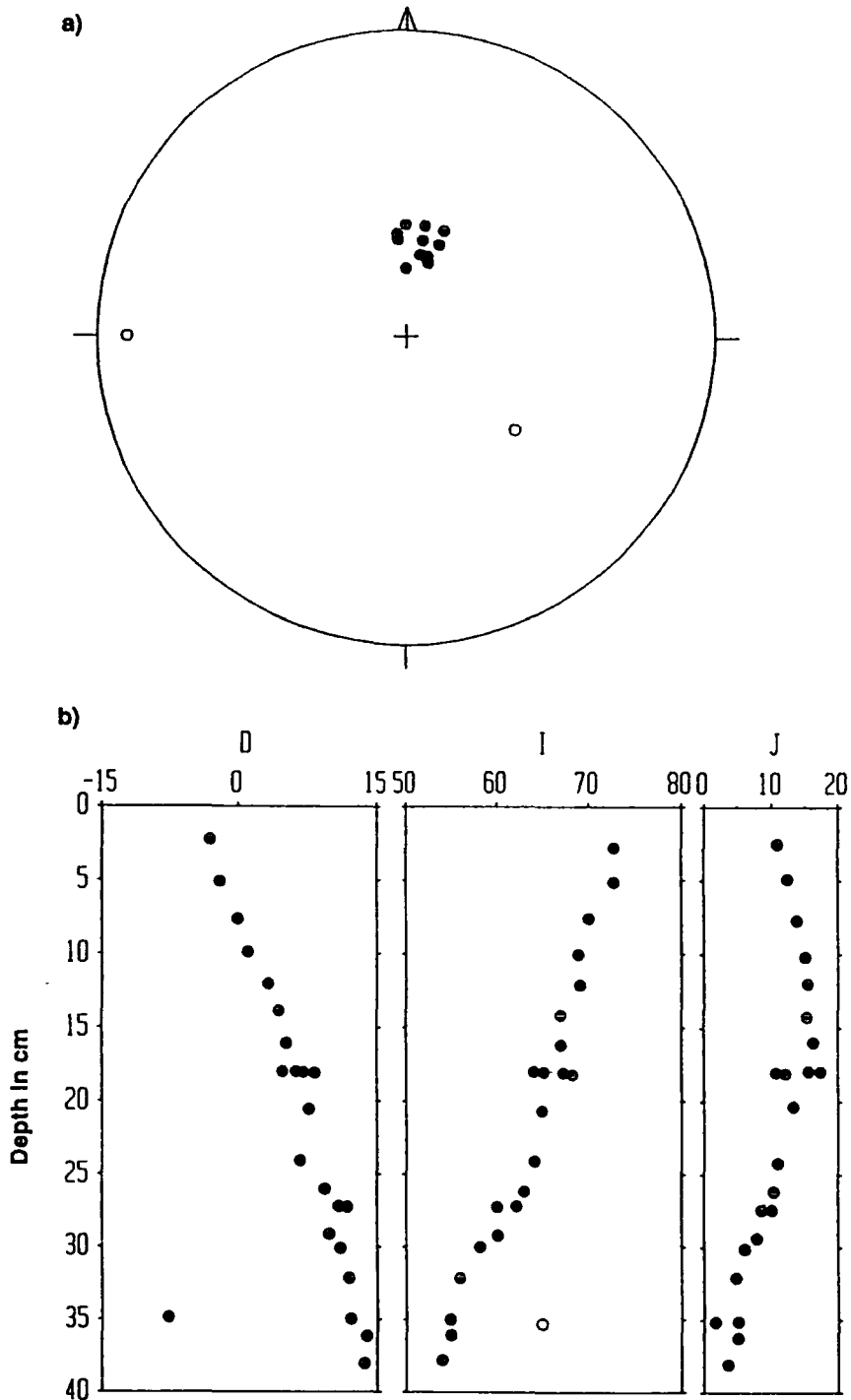


Figure 2.6 a: A stereographic plot of magnetic directions of samples from a single context (see text). Positive (or normal) inclinations are plotted as solid symbols, negative (or reversed) ones as open symbols. This particular plot shows a group of samples with similar, normal, magnetic directions and two outliers with negative inclinations.

b: A depth plot of declination (D), inclination (I) and intensity (J) versus depth of samples taken down a vertical sediment section. Normal inclinations are plotted as solid symbols, reversed ones as open symbols. This particular plot of synthetic data shows smooth variations in declination, inclination and intensity down the section, with little scatter in measurements from a single depth. There is one sample with an anomalous magnetisation at 35cm depth. D and I are in degrees and J in SI units.

Carrying out the heating process in an inert atmosphere or vacuum will reduce oxidation of the specimen, but other chemical changes may still occur (Collinson, 1983 pp351-352).

Alternating field demagnetisation dissects the remanence according to the coercivity spectra of the magnetic particles. If the specimen is placed in a weak alternating field, magnetised grains with a coercivity lower than the strength of the applied field will realign with the applied field. If the applied field is then reduced in the absence of an external field, the magnetisation of those particles will be left in the direction of the easy axes of magnetisation. Hence their magnetisations will cancel each other out, provided that the easy axes are randomly oriented and the applied field is symmetric. The measured remanence will then arise only from particles with coercivities greater than that of the applied field (As & Zijdeveld, 1958; Zijdeveld, 1975). Increasing the applied field will cause the unblocking of grains with higher coercivities, redirecting more of the remanence. Measurement of the remanence after each step reveals the components of magnetisation of the specimen and their hardness with respect to applied magnetic fields.

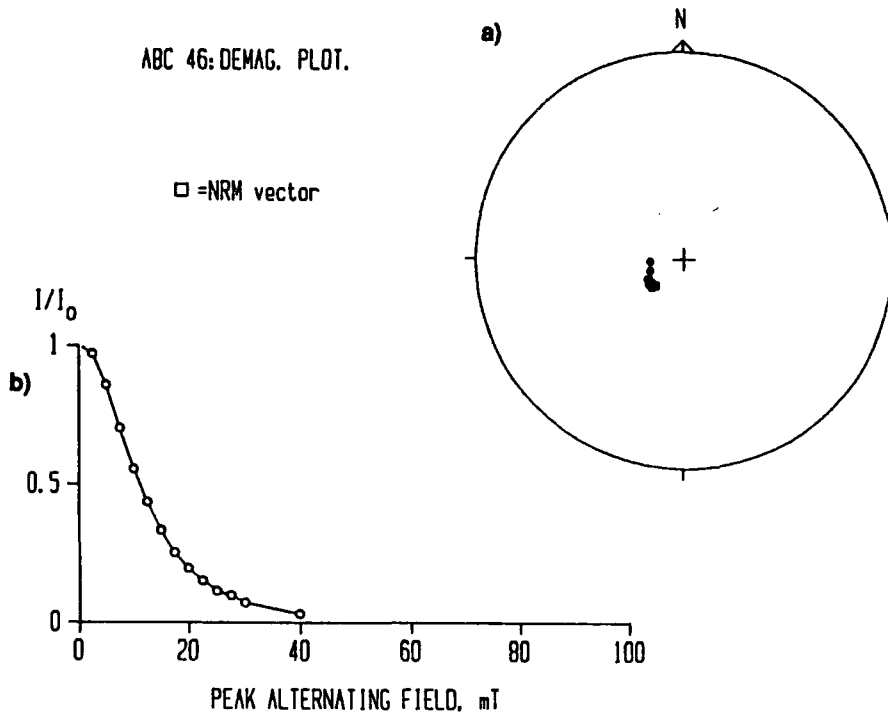
Direct magnetic fields have been used for partial demagnetisation by Russian workers (Khramov & Andreyeva, 1964). The specimen is oriented with the remanence direction antiparallel to a steady applied field. It is remeasured, reoriented if the remanence direction has changed, and a slightly higher field applied. When the direction of remanence does not change with applied field, a stable vector has been isolated. This technique is simple in theory, but not widely popular in practice as accurate changes in sample position are hard to achieve and adding an artificial remanence might obscure a small but stable natural magnetisation.

Thermal demagnetisation was considered unsuitable for the sediments in this study, as it would lead to water loss and associated grain reorientation and possible chemical changes. Therefore alternating field demagnetisation was employed throughout. Demagnetisation was carried out using an alternating field demagnetiser (Fig. 2.5), consisting of a coil through which an alternating current was passed, creating an alternating magnetic field along the axis of the coil (Collinson, 1983 pp325-329). The Molspin demagnetiser used in this work produced 180Hz peak alternating fields from 2.5mT to 100mT. Samples were tumbled about two axes within the field (Doell & Cox, 1967), thus exposing at least 95% of their possible axes to the field (Hutchings, 1967) as the field ramped up at 2mTs^{-1} , held for 5s and then reduced to zero. The coil was shielded by a double walled mumetal bucket shield and the instrument was aligned east-west.

Pilot samples from each context were subjected to stepwise demagnetisation at applied fields from 2.5 to 100mT. Twelve demagnetisation steps were usually used, but the number varied according to the hardness of the magnetisation. Larger steps were taken where there was less change, so as to obtain the most informative coercivity spectrum. At least 20% of specimens were demagnetised in a stepwise fashion but more pilot demagnetisations were carried out if the material was inhomogeneous, the pilot samples showed varied behaviour, or the NRM values were widely scattered. The selection of pilot samples is discussed separately for each context in Chapters 3 and 4.

For each pilot sample, the demagnetisation results were presented in three ways: a stereographic plot, an intensity plot and a Zijderveld plot (Fig. 2.7); providing a comprehensive picture of the behaviour of the magnetic vector on demagnetisation. A stereographic projection (Fig. 2.7a) showed changes in vector directions only. If two remanence components of different stability were present, the movement of the vector between them appeared as a series of directions falling on a great circle path between the two directions (Creer, 1959). Stable directions appeared as a cluster of points. The plot of change in normalised intensity with increasing applied field (Fig. 2.7b) revealed the relative hardness of different components of magnetisation to alternating magnetic fields. The Zijderveld plot (Fig. 2.7c) showed an orthogonal projection of the end point of the horizontal and vertical components of the NRM vector during demagnetisation (Zijderveld, 1967), thus combining direction and intensity information. This was usually the most informative plot, clearly showing the removal of a single component of magnetisation as a linear segment, if it was accompanied by changes in intensity. The stability of components of magnetisation over a range of demagnetising fields was derived subjectively from the demagnetisation plots and objectively, by computational methods (Section 2.5.2). From the information provided by the pilot samples, a bulk demagnetisation field was chosen for the remaining samples. The field selected appeared to eliminate the secondary components of magnetisation whilst leaving a measurable part of the primary magnetisation. Because the orientation of samples to true North was carried out after demagnetisation, the plots are relative to the fiducial mark on the sample.

Unwanted remanences may be induced during the demagnetisation procedure itself. Anhysteretic remanent magnetisation (ARM) occurs if there is a steady magnetic field over the sample as it is demagnetised; for example if the geomagnetic field is not completely cancelled, the applied field is asymmetric or the magnetic grains are not randomly oriented. A rotational remanent magnetisation (RRM) arises along the axis of rotation of samples in some demagnetisation apparatus (Wilson & Lomax, 1972; Noel, 1988). Repeated demagnetisations of the same sample at the same applied field showed that little change in measured direction occurred, even when the specimen was inserted



ABC 46 : ZIJ PLOT.

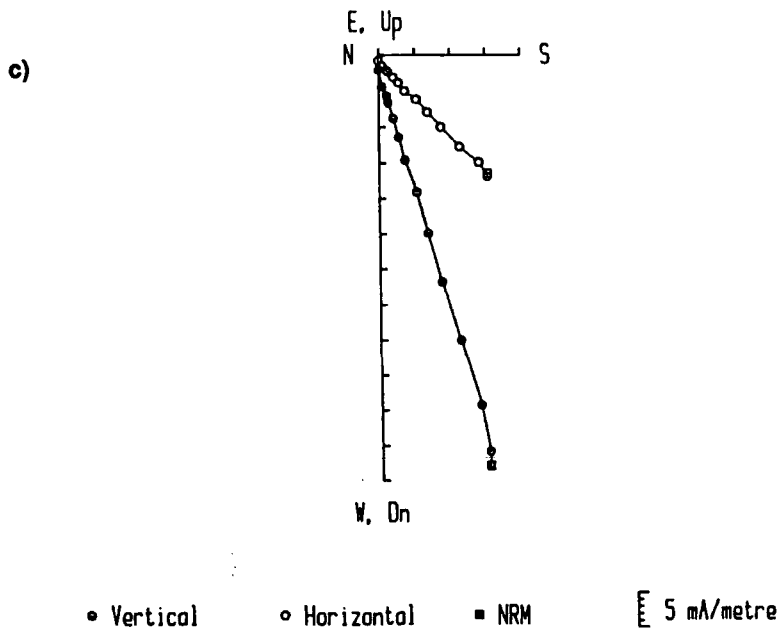


Figure 2.7 a: Stereographic projection of the direction of magnetisation of a sample during demagnetisation. The magnetisation of this particular sample showed little change on demagnetisation.

b: Plot of change in normalised intensity with increasing applied field for a sample during demagnetisation. The intensity of magnetisation of this particular sample fell very quickly as demagnetisation progressed.

c: Zijderveld plot (see text) of the demagnetisation of a sample with a magnetisation of at least two components; one very soft and removed in the first few demagnetisation steps, the other much harder.

into the sample holder in different orientations. These tests indicated that laboratory produced remanences were only a problem at high demagnetisation fields. Fine grained haematite cannot be easily demagnetised by alternating fields as its coercivity can exceed 2T, due to its strong magnetocrystalline anisotropy (Collinson, 1983 p310). Hence even a viscous magnetisation acquired in only a few weeks or years might require a peak field of over 100mT to remove it. Thermal demagnetisation is most suitable for this material, because this method is not dependent on coercivity (Dunlop & Stirling, 1977). However, alternating field demagnetisation has proved successful for magnetite and titanomagnetite bearing rocks and sediments.

2.3 INVESTIGATION OF THE MAGNETIC FABRIC

2.3.1 *Low field susceptibility measurements*

Magnetic susceptibility is a measure of the ease with which a material can be magnetised and depends on the grain size, concentration and mineralogy of the magnetic minerals present. Volume susceptibility (κ) is defined as:

$$\kappa = M / H$$

where M is the volume magnetisation induced in a material of susceptibility κ in an applied field, H.

At low applied fields, susceptibility is approximately independent of the intensity of the field and is reversible. The initial susceptibility of all samples in this study was measured in a Molspin balanced air-cored transformer (Collinson, 1983 pp26-30) using the same cylindrical samples measured in remanence investigations (Fig. 2.5). The sample was introduced into the transformer by means of a plunger. The degree of imbalance it created was assumed to be linearly proportional to the magnitude of the sample's susceptibility along the cylindrical axis. The instrument was calibrated using paramagnetic salts of known susceptibility and of the same size and shape as the specimens to be measured e.g. $\text{NiCl}_2 \cdot 6\text{H}_2\text{O}$, $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ or $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$. Susceptibility measurements were very fast, enabling 100 samples an hour to be processed.

The susceptibility of many natural minerals is dominated by magnetite (Thompson & Oldfield, 1986 p26), because it has a high specific susceptibility (i.e. volume susceptibility/density). However, the susceptibility of antiferromagnetic, paramagnetic and diamagnetic minerals (all of which are very weak magnetic properties) becomes

significant in samples with very low ferromagnetic mineral concentration (Oldfield *et al.*, 1985). Thus, susceptibility measurements provide a useful guide to the total magnetic content, in addition to being necessary to scale ellipsoids of anisotropy of magnetic susceptibility (Section 2.3.2). They can also be used to help to determine the source of some archaeological materials (Section 1.7; McDougall *et al.*, 1983).

2.3.2 *Susceptibility anisotropy measurements*

Studies of the anisotropy of magnetic susceptibility (AMS or magnetic fabric) are becoming common in palaeomagnetic investigations because they can provide useful information about the shape and orientation of magnetic grains within a material, and clues as to the causes of such orientation. A useful review of developments can be found in Hrouda (1982). MacDonald and Ellwood (1987) provide an summary of current applications.

AMS is a measure of the relative ease with which a material can be magnetised in different directions and arises from preferential alignment of the magnetisable fraction. There are two main causes of AMS; anisotropy in the shape of the magnetic mineral and magnetocrystalline anisotropy (Uyeda *et al.*, 1963). Shape anisotropy occurs because non-equidimensional crystals of materials which are inherently isotropic, such as crystals of cubic titanomagnetites, are more easily magnetised in some directions than others. For example, magnetite grains have a maximum susceptibility in the direction of their largest dimension. Magnetocrystalline anisotropy is predominant in crystals of lower symmetry, where the material is intrinsically anisotropic. Examples are haematite, where the direction of minimum susceptibility is perpendicular to the basal crystallographic plane, and goethite. Both shape and magnetocrystalline anisotropy may occur in a sample containing different minerals (Rees, 1965), but at room temperature, shape-anisotropy is the more significant (Stephenson, 1971). It has been shown (Fuller, 1963) that AMS in sediments usually arises from preferential orientation of non-equidimensional grains of magnetite, unless the magnetisation is dominated by the weakly magnetic iron hydroxide, goethite, which typically arises in weathered material.

Magnetic grains may be aligned by a number of different forces which act on them as they settle out of suspension or move within pore spaces in the sediment (Section 1.4.2). These forces include gravitational, hydrodynamic, magnetic and grain interaction forces (Fig. 2.8). Gravitational forces cause particles to settle in the position of lowest gravitational potential energy. For example, they may roll into hollows or non-spherical particles may settle with their minimum dimension approximately perpendicular to the depositional surface. Such preferential orientations give rise to a nearly horizontal magnetic foliation, that is a plane of excess magnetic susceptibility (King & Rees, 1966;

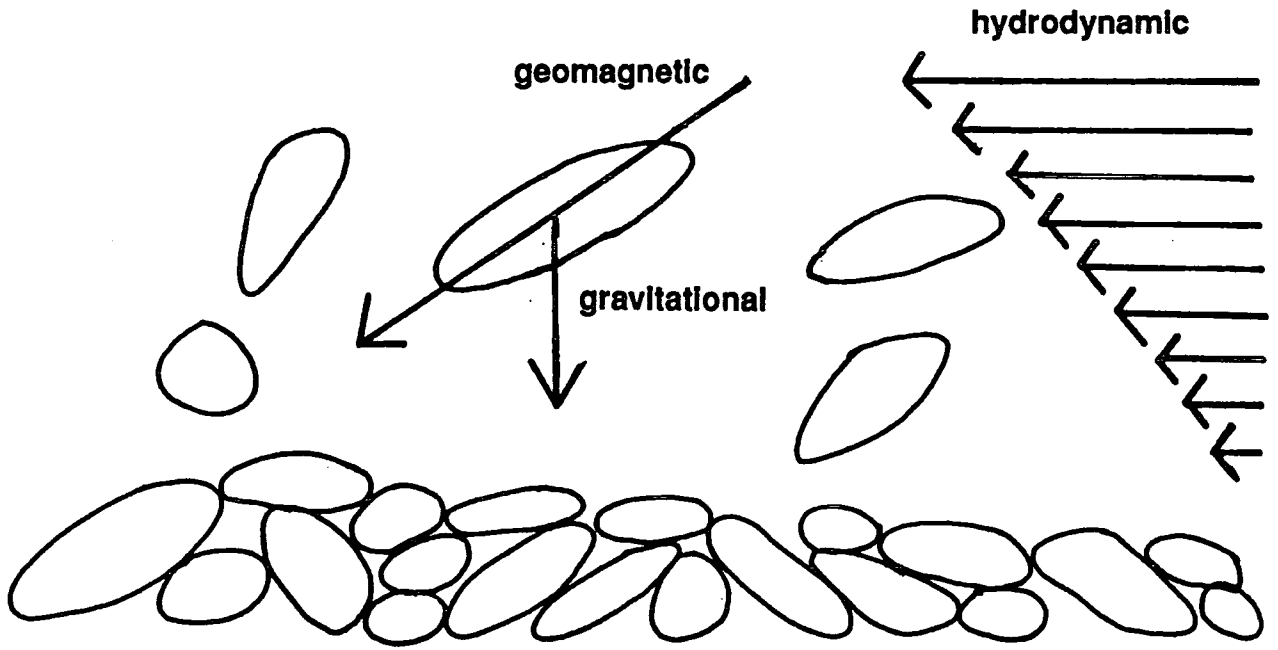


Figure 2.8: Some of the forces acting on a magnetised grain as it settles from suspension in water.

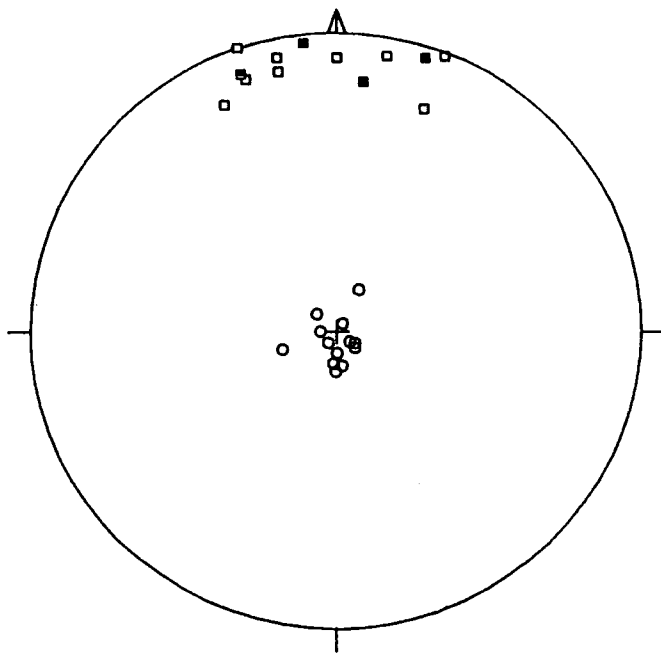


Figure 2.9: Directions of the principal axes of susceptibility. Minimum axes are represented by circles and maximum axes by squares. Closed symbols represent positive inclinations and open symbols represent negative inclinations. An equal area projection is used. This particular example shows a primary depositional fabric (see text).

Rees & Frederick, 1974). Hydrodynamic forces systematically align elongated grains with their long axes parallel or perpendicular to the direction of flow, giving rise to a magnetic lineation (Rees & Frederick, 1974). The geomagnetic field at the time of deposition has been shown to influence the orientation of strongly magnetic particles less than 10μ in diameter. However, there is negligible effect on larger, multidomain grains or those magnetic particles which are so soft that they have no preferred direction of magnetisation (Rees, 1965). Grain interaction forces typically result in the alignment of elongated particles and a magnetic lineation (Rees, 1979 & 1983). Of these factors the geomagnetic field acts only on magnetised particles, whereas the other factors will affect all grains in the material to a varying degree, depending on their shape and size.

Grain orientation can be measured in a number of ways, including inspection of thin sections or making photometric measurements. Susceptibility anisotropy methods have the advantage of being fast, sensitive, able to give three-dimensional information and are applicable to a wide variety of materials. Good agreement has been found between susceptibility anisotropy determinations, point counting on thin sections and the measurement of quartz optic c-axes to determine grain orientation (Taira & Lienert, 1979). The alignment of magnetisable grains has been found to be representative of the alignment of all the grains (Rees, 1965). The disadvantage of susceptibility anisotropy measurements is that grain orientations can only be expressed as an ellipsoid of susceptibility from which individual components of AMS cannot be determined.

In this study the low field susceptibility anisotropy of all sediment samples was measured using a Molspin anisotropy delineator (Collinson, 1983 pp39-58), controlled by a BBC microcomputer (Fig. 2.5). The sample was spun at 6Hz about a vertical axis within two sets of mutually orthogonal coils. One coil was driven at 10kHz, producing a field of 0.7mT (r.m.s.) at 90° to the axis of rotation of the sample. If the sample was magnetically isotropic, the applied field was not distorted and hence, no field was detected by the secondary or pick-up coils. If the sample was anisotropic, the applied field was distorted and a voltage was induced in the pick-up coils. The magnitude of the detected field was proportional to the sample's AMS about the axis of rotation. Measurement along six sample axes allowed the calculation of directions and magnitudes of the three mutually perpendicular axes of maximum, minimum and intermediate susceptibility making up the susceptibility ellipsoid (using the specific susceptibility value to calibrate the axes). The complete measurement of one sample took 2-3 minutes; the number of spins could be varied from 32 to 512 revs. according to the strength of the susceptibility and AMS. The size and shape of the samples have been shown to be significant (Kent & Lowrie, 1975; Thompson & Oldfield, 1986 p55; Hounslow *et al.*, 1988), for example the susceptibility anisotropy of irregular or cuboid samples has been shown to reflect the sample shape rather than its magnetic fabric. This study utilised the

same cylindrical samples used in both remanence and mineralogical measurements, which were considered to have a suitable diameter/height ratio (Hounslow *et al.*, 1988).

A number of studies have employed high field susceptibility anisotropy methods (Hrouda, 1982). In these investigations, inducing fields of different intensities were applied to the specimen and the anisotropy was measured within the field (Collinson, 1983 pp70-103), thereby enabling the effects of different minerals to be isolated. Measurement of the anisotropy of remanent magnetisation has also been used to provide information concerning grain orientation (Stephenson *et al.*, 1986). A remanence, for example an isothermal remanence, was induced along one axis of the specimen and its effects measured. The sample was then demagnetised and a remanence induced along another axis and so on. Whilst both of these methods could provide useful information, the restrictions of time meant that they were not used in this study.

Various parameters have been proposed to quantify the shape and strength of magnetic fabrics. These reflect the many types of instrument in use and the variety of objectives of different studies (summarised in Hrouda, 1982 and Tarling, 1983 p142). Comparison of the parameters is difficult because many are affected by variations in the total susceptibility. In this investigation the following parameters were chosen for their simplicity, their wide use in sediment magnetic studies and their relative independence of bulk susceptibility:

the magnitude and direction of the principal axes of susceptibility; k_{\max} , k_{\min} and k_{int}

q , ratio of lineation to foliation = $(k_{\max} - k_{\text{int}}) / (0.5(k_{\max} + k_{\text{int}}) - k_{\min})$

$h\%$, overall percentage degree of anisotropy = $((k_{\max} - k_{\min}) / k_{\text{int}}) \times 100$

As defined by Granar (1958), q has a theoretical range of 0 to 2. Laboratory based experiments have identified certain ranges of values as being characteristic of particular depositional environments, as discussed below. $h\%$ is a useful indication of the overall anisotropy (Rees, 1966) and is largely independent of the fraction of magnetic mineral. AMS is a second order tensor which can be represented as an ellipsoid with principal axes, k_{\min} , k_{\max} and k_{int} . Maximum and minimum axes of susceptibility are usually represented on an equal area plot (Fig. 2.9). This projection is appropriate as it separates vectors on the zenith of the plot. Fisher statistics (Section 2.5.1) have been used previously to quantify the clustering of maximum or minimum axes, but the distribution rarely fulfils the necessary criterion of being uniaxial. Other possible statistical treatments are summarised in Hrouda (1982), but in this study qualitative observations were considered to be sufficient.

Extensive laboratory studies of the magnetic fabric of artificially deposited sediments were carried out in the 1960's. These studies investigated the AMS produced by deposition of various grades of sediment from standing or flowing water onto horizontal or sloping surfaces in a flume (summarised in Hamilton & Rees, 1970). These experiments provided an indication of the effects of depositional conditions on remanence (Section 1.4.2) and anisotropy and also attempted to identify magnetic fabrics that were characteristic of certain depositional processes. Subsequent investigations of naturally occurring sediments have demonstrated the validity of many of these experiments. However, they have also made it clear that the natural sedimentary environment is far more complex than the laboratory simulation (e.g. Noel, 1986a). Complicating factors in the natural environment include the much slower rates of deposition (commonly a thousand times less), interaction of settling grains, biological activity, and effects arising from the temperature and composition of the fluid.

Grain by grain deposition from still water onto a flat surface in the laboratory, that is with gravity the only force acting, resulted in a near-horizontal magnetic foliation (Rees, 1961). Hamilton (1967) showed that in laboratory experiments the orientation of the axis of maximum susceptibility was controlled by current flow for all but fine sediments at small values of fluid stress. Only with small grain sizes (e.g. fine silt, <0.03mm diameter) was the maximum axis controlled by the ambient magnetic field (Rees, 1965; Hamilton, 1963). Larger grains were rotated by the current flow (Rees, 1961), giving a characteristic AMS termed a 'primary magnetic fabric' (Hamilton & Rees, 1970; Fig. 2.9). In a primary fabric, the minimum axes of susceptibility cluster close to the perpendicular to the depositional surface, defining a magnetic foliation. The maximum axes define a lineation, oriented parallel to the direction of flow. The orientation of the maximum axes can be used as an indication of flow direction (Rees, 1961). This idea was adapted quantitatively by Noel and Rudnicki (1988) in a technique which connected the remanence and k_{\max} directions for each specimen by a small circle path, representing the rotation due to the current, away from the palaeofield direction. As the current varied locally, the small circle paths for all the samples were not identical, but the zone in which they intersected was taken to represent the best estimate of the palaeofield direction. This method has been used with some success on cave sediments (Noel, 1986b & 1987), but results must be interpreted with caution since the model assumes that the grains rotated only about a horizontal axis. Rees (1966) experimented with deposition from still water onto a slope and obtained fabrics similar to those produced by deposition from flowing water onto a horizontal bed, with a downslope lineation. In a sheared deposition (Rees, 1983) the long axes of grains tended to align parallel to the direction of flow, but at some sediment concentrations a transverse alignment occurred. q was found to fall in a range 0.06-0.67 (Hamilton & Rees, 1970)

for sediments deposited from still or running water and to be generally less than 0.42 for sediments deposited on a slope (Rees, 1966).

Scattered AMS axes and anomalous values of q and $h\%$ were generally attributed to a secondary magnetic fabric arising from mineral alteration, tectonic deformation, bioturbation or coring disturbances (Hamilton & Rees, 1970). However, caution must be exercised in interpreting magnetic fabrics for a number of reasons. Ellwood (1984) has shown that an apparently primary magnetic fabric may be found in obviously bioturbated material and Rees (1971) demonstrated that convoluted rocks also still showed a primary fabric. It has been pointed out by Stephenson and Potter (1989) that AMS can be deceptive in the case of small ($\leq 1\mu\text{m}$), single domain grains, with AMS determinations indicating a foliation when in fact a lineation is present (and vice versa), and the magnetic fabric appearing weak when it is in fact strong. They suggest that anisotropy of magnetic remanence would be preferable. However, in most sediments the grain sizes are generally larger and the problem does not arise.

Fired materials may also exhibit alignment of magnetic grains attained by molten materials flowing into a mould (Goulpeau *et al.*, 1989) or by the physical movement of particles, for example when pottery clay is rolled or a pot is wheel-thrown (Rogers *et al.*, 1979). Although it is possible that such grain orientation might affect the alignment of the NRM with the ambient field, the effect is generally small and would be cancelled out if the mean direction of magnetisation is obtained from samples widely distributed over a structure.

2.4 INVESTIGATION OF THE MAGNETIC MINERALOGY

2.4.1 *Isothermal remanent magnetisation (IRM) experiments*

Although the NRM carriers are only part of the total magnetic fraction of a material, it is still of interest to study their mineralogy, grain size and concentration. A number of techniques are available including chemical, X-ray, optical and thermal studies, but the use of laboratory induced isothermal remanences has proved particularly informative (Oldfield *et al.*, 1985; Thompson & Oldfield, 1986 pp29-34). A remanent magnetisation is produced by exposure of a sample to a steady magnetic field at a constant (usually room) temperature. Remanence acquisition depends upon the strength of the applied field and the grain size, composition and concentration of the magnetic minerals in the sample. Strong isothermal remanences can be produced naturally by the large magnetic fields associated with lightning strikes (Section 1.4.5).

As discussed in Section 1.4.1, if a weak field is applied to single or multidomain particles and then removed, the domains will relax back into their easy directions. If the applied field is stronger, internal energy barriers will be exceeded and it will not be energetically favourable for the domains to return to their original position when the field is removed, causing a remanent magnetisation. In yet higher fields, larger energy barriers are exceeded and the intensity of the isothermal remanent magnetisation will increase to a saturation value (Fig. 2.10), where even originally anti-parallel domains flip into alignment. In extremely strong fields, magnetisation within a domain may be forced into greater alignment with the field, away from the local easy direction, but will relax back on the removal of the field to reduce the magnetic energy (Tarling, 1983 pp16-23).

Reversing the applied field causes a gradual realignment of domains with the new applied field, resulting in a complete hysteresis loop for the specimen (Fig. 2.10). Magnetic minerals can be distinguished from their different patterns of IRM acquisition. It is important to note that the quantity measured in these tests is the induced *remanence* remaining after the specimen is withdrawn from the field and not the induced *magnetisation* produced whilst the sample is in the field, hence diamagnetic and paramagnetic minerals do not contribute.

In this research isothermal remanent magnetisations were induced using a pulse magnetiser. A short pulse of magnetic field, uniform over the space occupied by the sample, was produced by the discharge of banks of capacitors through an air cored solenoid (Collinson, 1983 pp60-63). Using both high and low field coils it was possible to obtain pulses ranging in strength from 2 to 2690 mT, repeatable to within 3%. The pulse strength was increased in stages and the remanence was measured between each increase in a Molspin spinner magnetometer (Section 2.2.1). IRM acquisition tests required no extra sample preparation as the same samples were used as for remanence and anisotropy studies and IRM's were quick and easy to produce, causing no chemical changes.

The following measurements, suggested by Oldfield *et al.* (1985), were used in this study as they were particularly diagnostic. A number of other measurements are currently being investigated for use in environmental magnetism and Oldfield (1991) provides a comprehensive review.

Saturation Isothermal Remanent Magnetisation (SIRM, IRM_{SAT} , M_{RS} or J_{RS})

SIRM is the maximum intensity of remanence that can be produced in a material (Fig 2.10) and reflects concentration of magnetic minerals, magnetic grain size and mineralogy. It is mainly used as an indicator of magnetite content, but is strongly influenced by grain size and the presence of other magnetic minerals, such as haematite

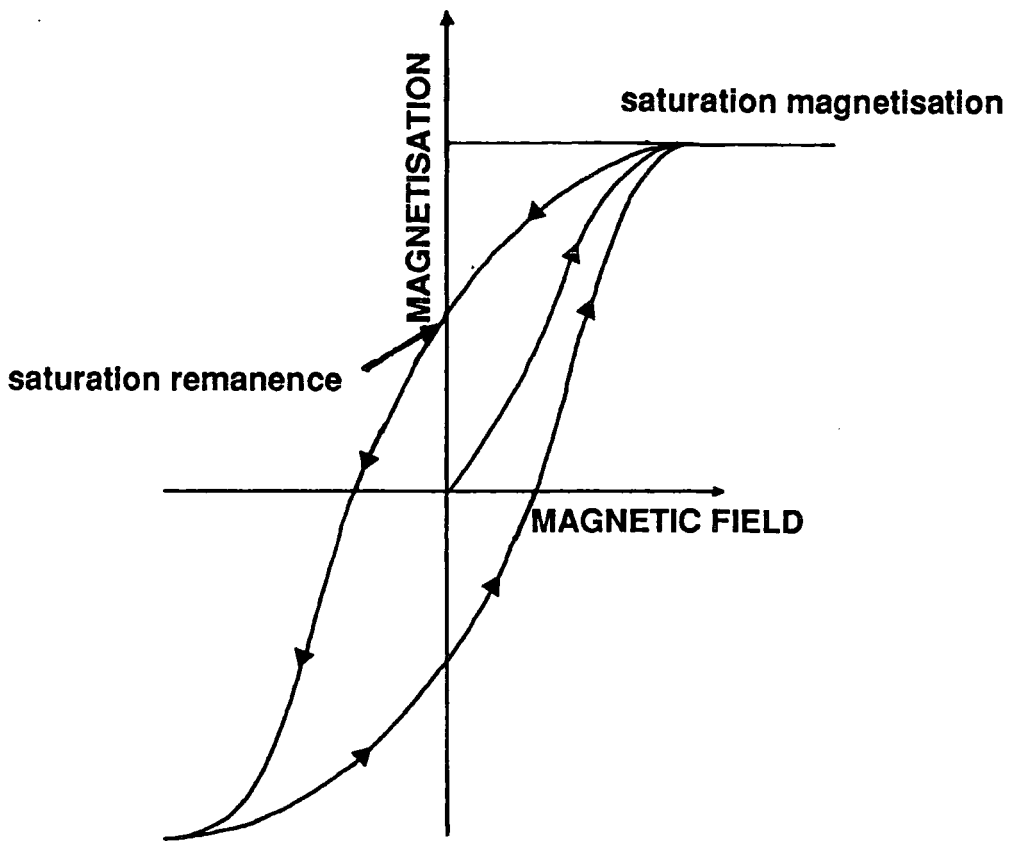


Figure 2.10: Magnetic hysteresis loop, showing saturation magnetisation and saturation remanence. (from Thompson & Oldfield, 1986 p5)

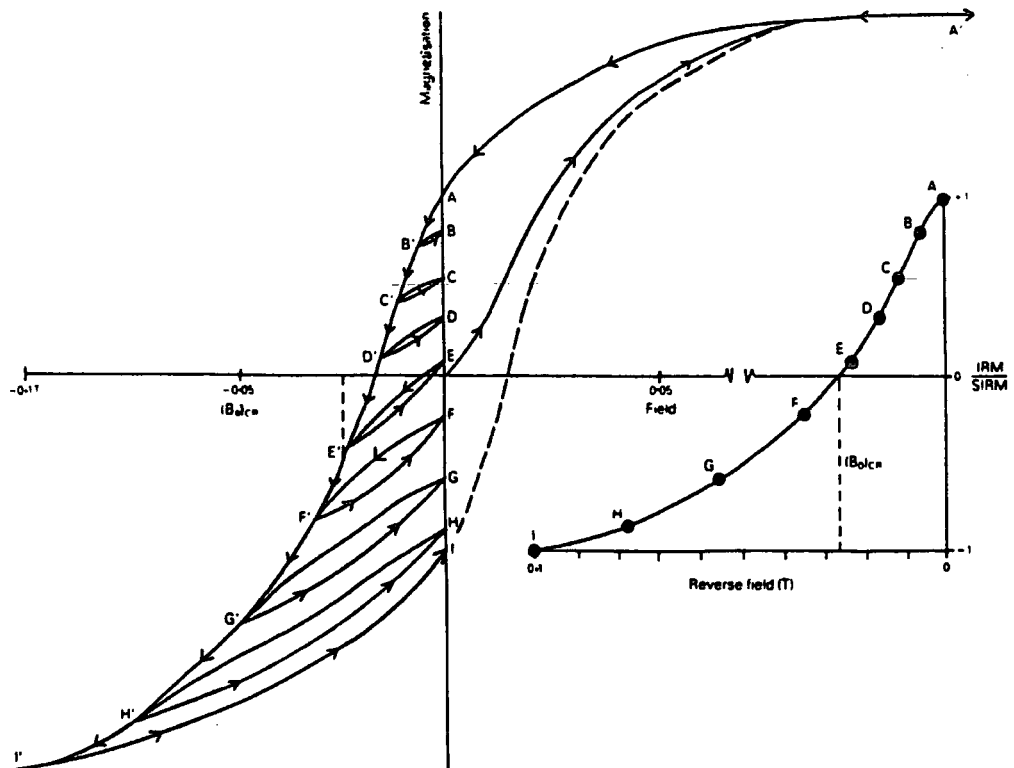


Figure 2.11: Determination of coercivity of remanence (from Thompson & Oldfield, 1986 p6). Sample was subjected to forward saturating field A', followed by a series of increasing back fields (B' to I'). Each change formed a minor hysteresis loop (B'B, C'C,...H'H). Remanent magnetisation (A to I) after each step was plotted against field, giving the coercivity curve shown to the right. The reverse field at which the coercivity curve crosses the x-axis was the coercivity of remanence (B_{0cr}).

or goethite, which saturate in fields in excess of those attainable by conventional pulse magnetisers. For this reason SIRM in this work is taken to be the IRM induced in a field of 2.69T, the maximum field attainable with the equipment available. If more than one magnetic mineral is present, a summation of the IRM acquisition curves is obtained, but minerals such as magnetite with a high saturation moment will tend to dominate even if only present as a few percent of the remanence carrying grains.

Saturating field

The saturating field is that field after which there is no further increase in remanence. This is again dependent on the composition and grain size of the magnetic minerals but, broadly speaking, magnetite is saturated in fields well below 1T whereas haematite requires much higher fields for saturation. Measurement of the percentage of the SIRM acquired in fields up to, say 1T, will give an approximation to the total concentration of remanence carrying magnetite in the sample.

Coercivity of Remanence ($(B_0)_{cr}$)

A previously saturated sample was placed in reverse fields of increasing strength and the new IRM measured at each stage. Plotting diminishing SIRM value versus strength of back field produced a coercivity curve (Fig. 2.11) on which the coercivity of remanence, $(B_0)_{cr}$, is defined as the reverse field required to reduce the SIRM to zero. As it is a normalised parameter, coercivity of remanence is independent of concentration and can be used to determine magnetic mineralogy and grain size and to characterise magnetic mixtures. For material of a single mineralogy it is a sensitive indicator of grain size, with values of <10mT characterising multidomain grains and ranging to values of almost 100mT, which characterise small, single domain, elongated grains (Thompson & Oldfield, 1986 pp29-30).

Remanence ratios

Ratios of the remanences produced in different laboratory fields can also be used to characterise samples. This study used the 'S' ratio (Thompson & Oldfield, 1986 pp32-33), that is the ratio of IRM in a back field of 100mT (IRM_{100}) to SIRM. Most ferrimagnets will have saturated in fields below 100mT so a low $IRM_{100}/SIRM$ ratio will be largely due to unsaturated ferromagnetic contributions from, for example, haematite and goethite. Hence, *S* is a normalised quantity, independent of concentration and may provide an indication of, for example, haematite and magnetite ratios. Specific composition can only be calculated if a pure sample of known weight is investigated.

2.4.2 Determination of Curie temperature

The thermal disorder produced by heating destroys magnetisation by reducing the effects of magnetic interactions. At the Curie temperature, spontaneous magnetisation vanishes and, consequently, a material's magnetic properties change dramatically. As the Curie temperature depends only on crystal structure and composition, it is an intrinsic and diagnostic property and can be used to identify the magnetic minerals present in a sample and to investigate compositions.

The Curie temperature can be determined from an investigation into the changes in induced magnetisation in a specimen, as it is heated in a strong magnetic field. There are two main types of Curie balance used for this purpose; a horizontal translation balance, where the specimen swings horizontally in a magnetic field gradient and a vertical balance, where the specimen is held vertically on a spring in a field gradient (Collinson, 1983 pp70-79). In this study the vertical balance at Newcastle University was used. The sample was placed in a quartz bucket, which was suspended by a fine copper wire inside a quartz tube, around which the heating coil was wound non-inductively. The temperature was measured by a thermocouple placed just below the sample bucket and could reach 700°C. The whole assemblage was situated between the poles of a magnet, which provided large magnetic field gradient (Collinson, 1983 pp106-108). As the temperature was raised, changes in the intensity of the induced magnetisation of the sample gave rise to a force, which acted on the sample, moving it within the field gradient. The force required by a servo mechanism to keep the sample stationary in the field gradient was monitored. This force was proportional to the saturation magnetisation of the sample. Clearly, with a vertical balance, any change in sample weight will affect the readings. For this reason at each heating stage the force required to keep the sample stationary was measured in the absence of an applied field and subtracted from the measurement in applied field.

As with any process which involves heating the specimen, existing minerals may be altered and new minerals formed, particularly through oxidation. This could have been inhibited by evacuating the tube containing the sample, or by filling the tube with an inert gas. Alteration was also reduced by rapid heating. This required small samples, such as chips, which were less likely to break up with the thermal stress of heating. Powders are unsuitable as their greater surface area makes them more prone to oxidation. If the concentration of magnetic minerals in a specimen is low, a magnetic extract can be prepared in order to produce a measurable magnetisation. Measurements of magnetisation as the sample cooled provided an indication of any chemical changes; if the curve did not follow the same path on cooling it indicated that chemical changes had occurred during heating and that magnetic minerals had been created or destroyed. The

presence of more than one magnetic mineral resulted in a curve which represented a summation of the magnetisations, with the inflexion point on the curve corresponding to the lower Curie point (Tarling, 1983 p46). Magnetite with a Curie temperature of 580°C can be easily distinguished from haematite which has a Curie temperature of around 675°C. In this study Curie temperature determinations were performed on small chips of the fired materials under investigation.

2.5 THE STATISTICAL TECHNIQUES EMPLOYED

2.5.1 *Mean directions, precision and scatter*

Gaussian (Normal) statistics cannot be applied to declination, inclination, intensity and susceptibility information because these quantities do not have the appropriate form of distribution. Therefore, a number of other statistical techniques are used in archaeomagnetism and palaeomagnetism, summarised by Tarling (1983 pp108-144). The mean direction of magnetisation of a number of samples from the same context was obtained by a standard summation of the x, y and z Cartesian co-ordinates of their directions of magnetisation (Tarling, 1983 p114) and then converting the mean direction into polar co-ordinates (i.e. declination and inclination). Samples with a stable magnetisation and an intensity above the noise level of the measuring instrument, were usually given equal (unit) weight. It would be difficult to objectively assign differential weights to individual directions as there is, for example, no reason to believe a strong magnetisation is more reliable than a weak one (Tarling, 1983 p115).

To calculate the precision of a mean direction (that is the scatter of directions about the mean) two parameters are required; the total number of observations, N and the length of the resultant vector, R , obtained by summation of individual directions. Fisher (1953) derived a theoretical distribution for unit vectors when considered as points on a sphere, specifically for use in palaeomagnetism. This theory proposed that the probability density of vector points on a sphere, P , is given by:

$$P = ((\kappa \exp(\kappa \cos\psi)) / 4\pi \sinh\kappa)$$

where ψ is the angular distance between an individual point and the true mean of the vector population and κ is the precision parameter. κ can be estimated from:

$$\kappa \cong k = (N - 1) / (N - R)$$

for values of $N > 7$ and $\kappa > 3$.

If $k > 10$, analysis of unit vectors with Fisher distributions have shown that the observed mean is close to the true mean of the total population (Tarling, 1983 p119). However, it may be more convenient to assess the reliability of the mean direction by calculating the probable distance of the observed mean from the true mean of the total population. Thus it is also important to consider the angular radius of the cone of confidence (α) about the observed mean, where:

$$\alpha_{1-P} = \cos^{-1} \left\{ 1 - \frac{N-R}{R} \left[\left(\frac{1}{P} \right)^{1/N-1} - 1 \right] \right\}$$

In palaeomagnetic and archaeomagnetic work α_{95} is commonly used. This represents a 95% probability that the true mean direction lies within that cone of confidence around the observed mean direction. If $k \geq 7$ then:

$$\alpha_{95} \cong 140 / (kN)^{1/2}$$

Errors in declination and inclination can be expressed in terms of α_{95} (Tarling, 1983 p127):

$$\text{error in declination} = \pm \alpha_{95} / \cos(\text{inclination})$$

$$\text{error in inclination} = \pm \alpha_{95}$$

The magnitude of the actual scatter of observations may also be of interest. For a population of vectors with a Fisher distribution, the angular radius (θ) of a circle about the mean containing, say, 63% of the observations is given by:

$$\theta_{63} = 81k^{-1/2}$$

if $N \geq 10$ and $k \geq 7$

θ_{63} is also known as the circular standard deviation.

The measurement of scatter is largely independent of N , whereas the measure of precision decreases as the number of observations increases (Tarling, 1983 p120). As k and α_{95} depend on the total number of observations, N , reduced values can be obtained by combining groups of samples, but there must be a sound physical basis for such combinations.

It is not clear how closely a Fisher distribution models the actual distribution of palaeomagnetic observations, but a very large number of observations would be necessary to conduct rigorous tests. It has been suggested that other statistical

frameworks, for example a Bingham distribution (Onstott, 1980), might provide a better model of observations. However, they are not commonly used because the calculations involved are complicated.

2.5.2 Determination of the stability of vector components

From information provided by demagnetisation procedures it may be possible to identify a primary component of magnetisation (Section 2.2.2). Components of remanence can be identified and their stability assessed subjectively, from Zijderveld, intensity and stereographic plots; or objectively, by computational methods. A number of statistical methods have been proposed to distinguish specific vectors and quantify their stability.

The *stability index* of Tarling and Symons (1967) is one of the earliest of such computational methods and is based solely on changes in direction. As the magnetic vector moves from a low stability to a higher stability component, its direction will remain constant for several successive demagnetisation increments. This gives a tightly grouped set of directions with small scatter. The stability index attempts to identify the lowest scatter (circular standard deviation) over the widest range of demagnetisation treatment and is defined as:

$$SI = \max (\theta_{63} / \text{range of treatment}^2)$$

where the range of treatment is in °C or 0.1mT units, as appropriate.

After measuring the stability index for a number of samples which were demagnetised both thermally and with alternating fields, Tarling and Symons suggested a number of categories of remanence:

SI <0.5, unstable; 0.5-1, metastable; 1-2.5, poorly stable; 2.5-5, stable; 5-15, very stable and over 15, extremely stable.

The method can be modified to isolate any vectors stable over three or more successive demagnetisation steps.

Other stability indices have been proposed, mainly based on the alternating field demagnetisation of igneous rocks. The *Briden Index* (Briden, 1972) combines the effect of changes in direction and intensity at successive demagnetisation steps. It ranges between +1 and -1. However, demagnetisation values must be at constant intervals of applied field or temperature. The Symons and Stupavsky palaeomagnetic stability index,

P.S.I. (Symons & Stupavsky, 1974) depends on the rate of change of the vector components as demagnetisation progresses.

The Tarling and Symons stability index was used in this study because the other two indices appeared to over emphasise the importance of changes in intensity. Archaeological material, particularly sediments, often has a magnetisation which is of a constant direction but rapidly decreasing intensity on demagnetisation. The Briden or *P.S.I.* indices would define this as low stability behaviour, whereas the Tarling and Symons index would define it as high stability. The Tarling and Symons index was also simple to calculate and could be used to define optimum ranges of demagnetisation treatment. Any of the stability indices can only be effective if a single component of remanence has become dominant over at least two demagnetisation increments. Other tests are available to ascertain the linearity of vector components (Kirschvink, 1980), but in this work a visual examination of the Zijdeveld plot and calculation of the stability index were considered to be sufficient.

2.5.3 Assessing trends in archaeomagnetic data

Most archaeomagnetic investigations previous to this study, have involved a determination of the direction of primary magnetisation acquired during a single event. Hence, all the magnetic directions measured would be expected to be a record of the same geomagnetic field and the statistical treatment of such replicate values is well established (Section 2.5.1). The same situation arises when the study is of a sediment representing a single depositional event, such as an inundation of flood water. The majority of sediments studied in Chapter 3 fall into this category. However, when a sediment section, thought to record variations in the geomagnetic field with time, is sampled, treatment of the magnetic directions is more complex. An assessment of trends in declination and inclination is essential to separate the proportion of scatter arising from random recording, orientation and measurement errors, and that arising from geomagnetic fluctuations. Quantifying these trends would seem to be vital, not only for describing archaeomagnetic observations quantitatively but also, and perhaps more importantly, in allowing such records to be compared with each other and with the calibration curve.

A number of samples can be taken from a single horizon within a vertical sediment section (Section 2.1.3) and standard statistical treatments used to give an indication of the dispersion of the magnetic directions (Section 2.5.1). If the material in the horizon is thought to have been deposited at one time, this will provide some indication of the fidelity of the material as a magnetic recorder. However, the remainder of the section is usually sampled by a vertical sequence of overlapping sample holders

(Section 2.1.3) and the difficulties arise in assessing the trends of magnetic direction obtained from these measurements.

The assessment of trends has rarely been required in archaeomagnetism because the majority of the deposits sampled are assumed to record a single geomagnetic field, as described above. Where such an assessment has been required (e.g. Tarling, 1983 p154) it has usually been based purely on a graphical presentation of the data and the visual comparison of apparently significant changes in values of declination or inclination with similar records. Often such presentation is accompanied by a verbal description of the 'trends' such as 'a slow and steady 11-12° shift in inclination between 5800 and 3900 BP' (Mörner & Sylwan, 1989), but attempts at statistical justification of trends are rare. One of the problems with defining trends in archaeomagnetic data is the fact that the sections are often very short and even the most detailed sampling can only yield a very limited record. One might expect a more rigorous approach to the problem in palaeomagnetic studies, where the sequences are several meters long and may record secular variation over thousands of years. However, even in this field of study, descriptions of smoothed or unsmoothed data are also frequently based on visual observation and verbal description. Large scale features are usually identified and labelled with Greek letters, a convention adopted from Mackereth (1971), and different sediment records are matched by visual comparison of sequences of these features, rather than their absolute magnitudes. Using these criteria, it has proved very difficult to match records, even from the same lake. Creer *et al.* (1975) found visual correlations between only 39 of 175 cores taken from Lake Geneva in Switzerland. Even when comparing large data sets, such as the pole positions from the south west United States and other areas, trends are assessed by visual examination of the raw and averaged data (DuBois, 1989) and compared on the basis of apparently significant features. The explanation for this is not a lack of data, but the complexity of the declination and inclination patterns observed.

The common practice of reliance upon visual presentation and verbal description of trends in data is clearly not completely satisfactory. Raw archaeo- and palaeomagnetic data can appear to be very complex and determining trends visually from them may be very open to observer interpretation, encouraging a tendency to describe trends that may not be statistically justifiable. Problems particularly arise when publications only include the lines representing the supposed trends in the data, and not the raw data themselves. The main statistical approach to analysing scattered data of this type has been to fit them with a smooth curve. Simple smoothing methods tend to produce ill-fitting, jagged curves, with spurious high frequency components; whereas the most complicated methods can be very time consuming in their application (Thompson & Oldfield, 1986). The most widely used statistical method was developed by Thompson and Clark (1981), and fits smooth curves to palaeomagnetic pole positions using weighted, least squares

cubic splines on the sphere, with a procedure for removing outliers. This treatment has the advantage of being capable of producing confidence limits around the resultant apparent polar wander paths and enabling two paths to be compared mathematically. It has also been suggested that palaeomagnetic data can be analysed by performing time series spectral analysis of the vector sequences (Creer & Tucholka, 1983; Barton, 1983) using the maximum entropy method, in order to identify the principal peaks in the data.

Whilst these methods have met with some success, they have yet to become commonly used and subjective trial and error methods are still widely used for matching declination and inclination curves. The reasons behind this lie in the complexity of the statistics involved and the difficulty in relating these mathematical models to the limitations of the data available. The physical conditions affecting sediment deposition mean that there are a number of reasons why archaeo- and palaeomagnetic data may not conform to the mathematical models. Rates of deposition are unknown and are likely to have been variable, meaning that the relationship between depth and time cannot be assumed to be linear. There may have been hiatuses in deposition or erosion of sediments, and in archaeomagnetic cases there are rarely enough data to define trends quantitatively. As the data have a spherical distribution, Fisher statistics must be used and they are themselves complex. There must be a full awareness of these complicating factors before statistical fitting can be carried out.

Because of the complexities of the statistical assessment of trends described and the limitations of archaeological contexts where the number of samples was so small, this thesis used the common archaeomagnetic practice of verbal and visual description of the trends in the data, in the few cases where this was relevant. It was considered that attempting to develop a new solution to the problem was beyond the scope of this work, although the dispersion within single horizons was always examined and extreme caution was exercised in identifying trends. The methods of Thompson and Clark (1981) would seem to have the most potential for future use as they offer quantitative error bounds, but adaptations would need to be made to account for the small number of samples available. The issue of statistical testing of data has important implications in the dating of sediment sections, as they are commonly dated by comparison with sections of the calibration curve (Section 2.5.4). If a statistical method were to be developed to describe the trends in the calibration curve, the same method could be used to analyse trends in individual sediment records and compare the two. In order to advance such an investigation, the priority must be to develop a more rigorous calibration curve and this is discussed further in Chapter 5. In the introduction (Section 1.1) archaeomagnetic dating was described as a 'pattern matching' method; clearly much work remains in the

statistical description of these 'patterns' before 'matching' can be carried out objectively. Similar problems exist in dendrochronology, where statistical tests must still be complemented by visual methods (Aitken, 1990).

2.5.4 Obtaining an archaeomagnetic date

To include current British methods of obtaining archaeomagnetic dates in a section dealing with 'statistical techniques' is perhaps not entirely appropriate. At present, an archaeomagnetic date is obtained by the visual comparison of the mean remanence direction and its error at 95% confidence, with the calibration curve, which comprises of direct measurements of the geomagnetic field and archaeomagnetic directions from dated materials (Section 1.2 & 5.6.4). The date is estimated to be the point on the calibration curve closest to the mean direction of remanence. The uncertainty in the date is determined from a visual examination of the points where the oval of 95% confidence cuts the calibration curve. There are a number of problems with this procedure; the calibration curve has no representation of errors in magnetic direction or archaeological date, no account is made of the varying density of points on the calibration curve, the curve is constructed by hand and magnetic directions of unknown date are fitted to it by eye. These problems are explored in detail in Chapter 5 and a number of solutions are suggested.

The dating of magnetic directions before 10th century BC, when the calibration curve commences, has been attempted by comparison with the secular variation curve obtained by Turner and Thompson (1988) from lake sediments (Section 3.3). This procedure can only be very tentative as the absolute values of declination and inclination are not independent but have been fixed with reference to magnetic observatory data; the record has been smoothed, reducing the magnitude of extreme values, as discussed in Section 3.3 and the lake sediment curve is itself dated by radiocarbon. Dating sequences of magnetic directions from a sediment, as opposed to a single magnetic direction, is particularly problematic for the reasons discussed above (Section 2.5.3). These conventional methods of obtaining a date were initially used in dating materials in this thesis, and the dates obtained were reconsidered in Section 5.6.4, in the light of advances in the calibration curve.

2.6 THE ACCURACY AND PRECISION OF ARCHAEOMAGNETIC DATING

As with any experimental measurement, random and systematic errors will arise in the determination of the direction of primary magnetisation necessary for obtaining an archaeomagnetic date. Whilst these errors are discussed individually in the relevant sections of this thesis, it is helpful to draw them together so that the overall accuracy and precision of archaeomagnetic dates can be assessed. Wolfman (1990c) provides a comprehensive review of the errors arising in archaeomagnetic dating, in the light of recent investigations in the United States.

Archaeomagnetic dating is based on the assumption that the remanent magnetisation measured reflects the geomagnetic field at the time a fired material was last cooled or a sediment deposited (Section 1.2). However, as discussed previously, factors such as distortion effects (Section 1.4.1) or post-depositional grain reorientation (Section 1.4.2) may effect the measured magnetisation. A number of ways in which the primary magnetisation may be overprinted have also been discussed. These include the formation of a VRM (Section 1.4.4), a CRM (Section 1.4.3) or even an IRM (Section 1.4.5). It is hoped that stepwise demagnetisation enables the primary magnetisation to be identified (Section 2.2.2). However, demagnetisation cannot show systematic disturbances of the feature, such as slumping, differential movement or rolling of grains on deposition. Demagnetisation will also not reveal the effects of magnetic distortion or local magnetic anomalies. These are best revealed by careful observation of the directions of magnetisation of samples distributed widely over the feature. Even if a primary magnetisation can be identified, the magnetisation recorded will vary from sample to sample, depending upon their homogeneity, anisotropy and mineralogical content. The magnitude of these latter errors is hard to assess as it will vary with feature and material, but it will be reflected in the scatter of the directions of magnetisation.

Field collecting procedures will also introduce errors. The preparation of a sediment surface or fired structure prior to sampling may disturb some magnetised grains, as will the sampling itself (Section 2.1). The magnitude of such errors is difficult to quantify, but would normally be expected to be small in comparison with the rest of the sample's magnetisation. Errors in orientation are easier to assess. Samples can be levelled to within 1° with a bull's-eye spirit level and oriented to within at least $1-2^{\circ}$ with a magnetic compass, sun compass or theodolite (Section 2.1.4). However, systematic errors may be introduced into magnetic compass readings by local magnetic anomalies or by incorrect reading of azimuth on a theodolite. In addition, sediment samples may lose water on storage, which will disturb their magnetisation (Section 2.1.5).

Measurements of remanence were found to be repeatable to within 2° (Section 2.2.1) but systematic errors might arise if the instrument was incorrectly calibrated or the sample was incorrectly positioned within the instrument. Repeated measurements have shown that demagnetisation does not appear to introduce errors (Section 2.2.2), but selecting a stable end-point for bulk demagnetisation is not always easy.

Much attention has been paid to developing sampling techniques and instrumentation to reduce the errors mentioned above. With careful sample selection, collection and measurement using sensitive, accurately calibrated instruments, the angular uncertainty associated with archaeomagnetic analyses of fired structures is typically in the range $\alpha_{95} = 1^\circ\text{-}5^\circ$ (Chapter 4; Clark *et al.*, 1988). The α_{95} error incorporates all the random errors arising from imperfect recording of the geomagnetic field, sampling and measurement but cannot reflect systematic errors that have arisen at any stage in the procedure.

Unfortunately, similar attention has not been paid to the process by which an archaeomagnetic date is obtained from a mean remanence direction (Section 2.5.3). Age ranges as low as ± 20 years (at 68% confidence) have been suggested for well preserved structures in Britain in the last 2 millennia (Clark *et al.*, 1988). However, such a generalisation obscures the many problems involved in date determination. The precision of the date will depend in part on the speed of secular variation in the relevant period. Clark *et al.* (1988) have suggested that the potential for archaeomagnetic dating for the periods from AD850 to the present and the last 700 years BC is good, because the curve appears to vary rapidly. In contrast, the Dark Ages and Early Medieval periods are less promising since the curve is slow moving or tightly looped. However, the speed of secular variation is not the only relevant factor. It is also vital to consider the quantity and precision (in both magnetic direction and archaeological date) of the data making up the calibration curve in the relevant period. There has been very little consideration of the problems of constructing the calibration curve and obtaining dates from it and Chapter 5 attempts to rectify this. Aitken and Weaver (1962) observed that an archaeomagnetic date is only as reliable as the archaeological chronology used in the establishment of the reference curve. Until this uncertainty is quantitatively represented in the age ranges given when magnetic directions are dated, the dates obtained by conventional methods of archaeomagnetic dating should be regarded as giving optimistically, even unrealistically, precise dates (Section 5.6.4.).

Chapter 3

Investigations of the Archaeomagnetism of Waterlain Sediments

3.1 THE OBJECTIVES OF THIS INVESTIGATION

Waterlogged and waterlain deposits are among the most informative of all archaeological environments. They often provide anaerobic conditions which protect organic materials, such as wood, leather and textiles; from bacteria, fungi, insects and vermin. Iron is also often well-preserved and the speed with which layers accumulate protects fragile objects from later disturbance. For example, the waterlogged deposits of Coppergate, York (Hall, 1984 p9) yielded a wealth of preserved metals, organic materials and environmental evidence such as molluscs, seeds and pollen. Economic buoyancy in Britain in the 1980's led to considerable redevelopment within cities, often focussing on previously derelict waterfront areas as in York, London and Lincoln; and the excavations preceding these developments have frequently encountered well-preserved archaeological evidence of earlier exploitation of the waterfront. Hence, in recent years the occurrence of waterlain sediments in an archaeological context has increased, as has interest in dating such deposits.

Waterlain sediments are most commonly dated on the basis of the archaeological material they contain. Organics in the matrix can be dated using radiocarbon (Gillespie, 1984); ceramics are datable by typological methods or by thermoluminescence (Aitken, 1985); and artefacts such as coins may be directly or typologically dated. Biological evidence, including the palynological record or the coleopteran fauna, may be able to provide a broad indication of the environmental conditions at the time of deposition and hence a date. A much more precise age may be obtained from a dendrochronological study of wood within the sediment (Baillie, 1982). A comprehensive overview of scientific dating techniques is provided by Aitken (1990).

However, rather than dating the finds within the matrix, it may be preferable to determine when the sediment itself was deposited. Two possible methods exist for dating this event; luminescence and archaeomagnetism. There is currently much interest in the dating of waterlain sediments by luminescence techniques (Berger, 1988), in which the event dated is the last exposure of grains in the sediment to sunlight. There is continued discussion as to the effectiveness of sunlight as a 'zeroing' event in complex, turbid or cloudy fluvial environments, but the technique appears to have considerable potential, particularly when light is used to stimulate luminescence in the laboratory, rather than conventional slow and complex heating methods. Archaeomagnetic studies have the advantage that, in addition to dating the event of deposition, they may provide information concerning the environment of deposition (Section 2.3) and the magnetic mineralogy of the sediment (Section 2.4). Clearly the dating techniques applicable to a particular sediment depend upon the material of the deposit, its mode of deposition, the extent of post-depositional disturbance and the inclusions it contains.

The objective, therefore, of this aspect of the study was to attempt to date waterlain sediments by archaeomagnetism, taking advantage of their increased occurrence on British archaeological sites. Investigations covered a wide variety of geographical locations and archaeological environments, in order to establish which were the most suitable for the application of the techniques and to reveal the problems encountered by such studies. The locations of the sites sampled are shown in Fig. 3.1. Of particular interest were archaeological contexts where the deposit could also be dated by another method, to enable comparison with the archaeomagnetic results.

3.2 ENVIRONMENTS OF INTEREST

As discussed in Section 1.4.2, for a depositional or post-depositional remanent magnetisation to be acquired, magnetised grains within the sediment must have been free, albeit for a short time, to become aligned with the geomagnetic field, either on or after deposition. There are many environments in which this might occur, but this study concentrates on those common on archaeological sites. These exist either as a direct result of human activity, for example sediments accumulated in a well; or as a result of natural processes associated with archaeological remains, such as a flood deposit covering a site. Depositional environments can be divided into four categories; fluvial, lacustrine and static water, aeolian and marine (Selley, 1978 p3).

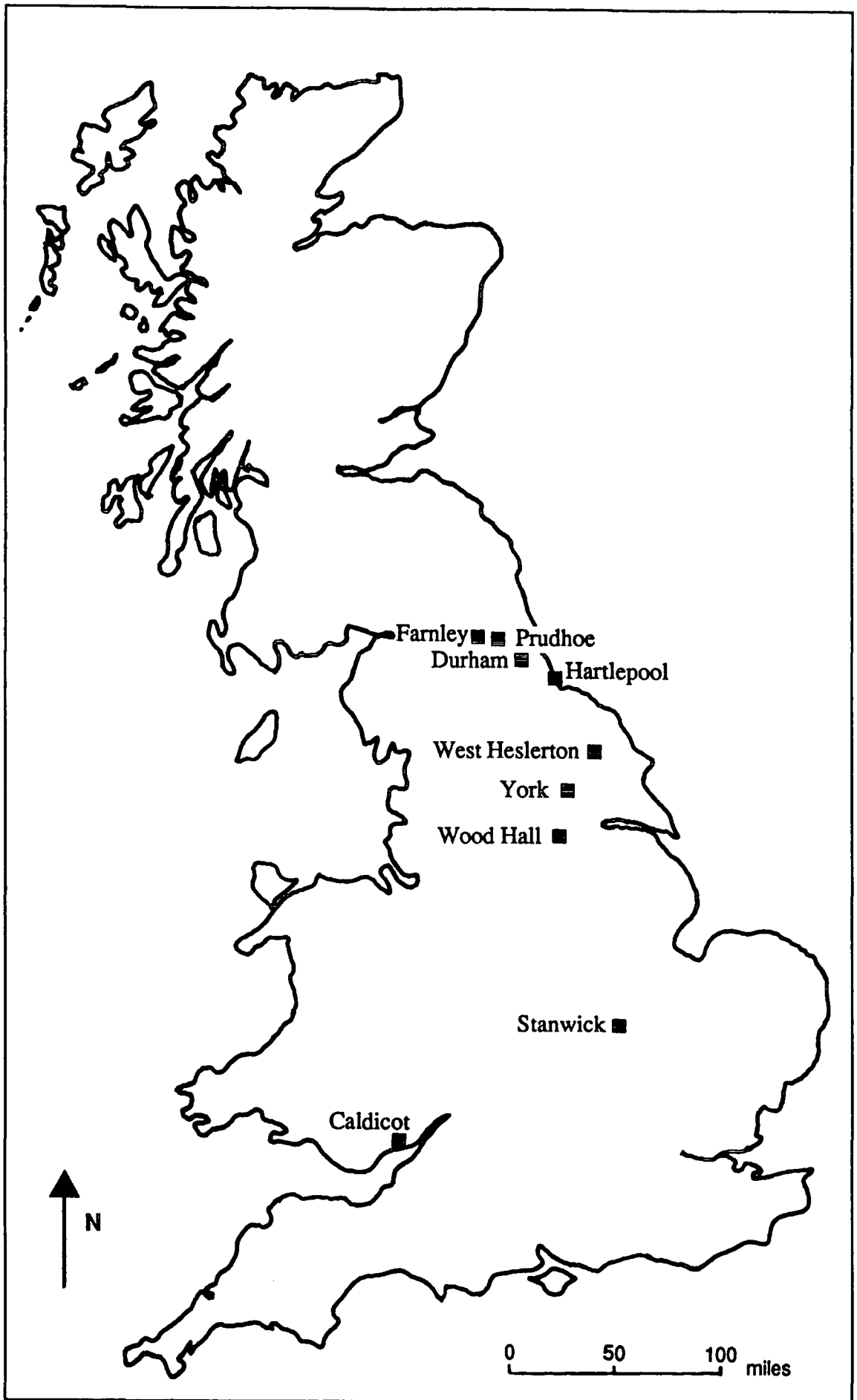


Figure 3.1: Map of Britain, showing the location of the sites from which sediments were sampled in this study. Also shown is Durham, where the laboratory was situated.

3.2.1 *Fluvial environments*

The deposition associated with rivers and streams depends upon the energy of the fluvial environment. A meandering river or stream will typically have a lower gradient and discharge, with lateral erosion often impeded by vegetation. Overbank floods will deposit sheets of very fine sand, silt and clay in the area of the floodplain, largely falling from suspension during floods when the river breaks its banks. Deposits are often laminated and show shrinkage cracks or even soil formation, if they are sub-aerially exposed (Selley, 1978 pp39-41). Lateral migration of the meandering channel will erode the outer, concave bank; scouring the river bed and depositing sediment on the inner bank characterised by an erosional surface, overlain by pebbles, driftwood and a sand sequence of decreasing grain size. If the river meanders back on itself flow may be short-circuited and fine grained deposits will infill the abandoned channel, forming an oxbow lake.

Braided rivers have much lower sinuosity than meandering rivers and occur where the gradient is steeper or the discharge rate higher (Selley, 1978 pp41-43). Erosion will be rapid and the river will often become overloaded with sediment, which is dumped as bars in the centre of the channel, if flow is restricted. Such alluvium is typically composed of sands and gravels, with silts being deposited in abandoned channels.

Drainage ditches or gullies follow a similar pattern to rivers but in an archaeological environment are frequently filled with occupation debris, although water often continues to percolate through. If a ditch has silted up, the fill is likely to be a well-sorted silt.

3.2.2 *Lacustrine and static water environments*

This category covers any landlocked body of non-marine water, ranging from ditches of short duration to permanent lakes. Such features may arise from subsidence, faulting, glacial erosion, damming or the activity of humans or animals. The sediments formed tend to be finer grained deposits, possibly varved (Selley, 1978 p93). Lake deposits are frequently sampled for palaeomagnetic investigations (Section 1.4.2).

One of the most common waterlain sediments found on any archaeological site is the primary fill in a ditch. When a ditch is first cut, soil will slump, be washed or blown in from the sides and surrounding surfaces which are likely to have been disturbed by digging. Coarse material from the sides will then rapidly accumulate, assisted by rain and frost action, with soil formation being slow with respect to weathering processes, unless

the feature is very shallow (Limbrey, 1975 p292), and this forms the primary fill. The secondary fill occurs when the sides of the ditch have been weathered. The rate of fill decreases as slower processes of surface washing, soil creep and wind deposition take over. At this stage biological activity is high because the soil is moist and well sheltered; organic matter, in the form of leaves and animal faeces, is likely to accumulate there. However, worm activity is unlikely to be deep enough to disturb the primary fill, unless the climate is particularly cold or dry. Pits on archaeological sites are also likely to have a primary fill, but this is often obscured by deliberately deposited material, such as ash or organic rubbish. A silt deposit might be expected to form at the bottom of a well shortly after cutting. However, if the sides of the well are lined, for example with barrels, subsequent sediment deposition will be slight. Use of the well often disturbs the deposits, as does the dumping of rubbish in it, when it ceases to provide water.

3.2.3 Aeolian environments

Deposits of wind blown sands and silts can appear very similar to those laid down by running water, since the mechanics of the processes also lead to ripple and dune structures (Selley, 1978 p76-92). No aeolian deposits were sampled in this study as they are rare on British archaeological sites and those encountered were unconsolidated and proved impossible to sample with the methods employed. Previous archaeomagnetic investigations have demonstrated some success in dating these deposits, as detailed in Section 3.3.

3.2.4 Marine environments

The deposits expected in a marine environment depend upon the rate of influx of land derived sediment, the tidal regime, current system, climate and the relative vertical movements of land and sea. There may be a net deposition or a net erosion of sediments, but only a net deposition will leave sediments in the geological record! A delta of alluvium may be formed at an estuary if the river brings more sediment to the sea than can be removed by marine currents. Progressively finer sediments will be deposited as the water gets deeper, because the current velocity reduces seawards (Moore & Asquith, 1971). Linear coastlines occur when marine currents are strong enough to redistribute land-derived sediments to form bars and beaches running parallel to the coast. Such environments are characterised by a sequence of deposits which, like all sedimentary deposits, are distinguishable by their lithology, sedimentary structures and biota (Selley, 1978 p131-136). Furthest inland the sequence usually commences with a fluvial coastal plain of fine-grained flood-plain sediments on a gentle gradient. This is followed by swamps, tidal flats and lagoons, which include peat and laminated muds, silts and fine sands, which are often rippled, burrowed and cut by gullies. These deposits are separated

from the sea by a barrier island complex of well-sorted sand, which may form an island just off-shore or only be exposed at low tide. The exact form of deposits depends upon sediment availability and the rate of rise and fall of sea and land, and may vary with time (Steers, 1971). As far as can be ascertained, no attempt has yet been made to carry out archaeomagnetic investigations upon marine pelagic deposits associated with underwater archaeological excavations, possibly because of the difficulty of sampling and the extent of bioturbation that is common in such sediments.

3.2.5 Disturbance of sediments

A number of processes may disturb a sediment, making it difficult to identify or interpret and partially or totally destroying the depositional remanent magnetisation. A comprehensive review of disturbance processes on archaeological sites is provided by Wood and Johnson (1978), who identify nine sources of disturbance. The most common on British archaeological sites is bioturbation, which includes mixing of the sediment by animals, insects and earthworms, and by the growth and decay of plants. Earthworms are the most widely recognised agents of disturbance on archaeological sites, responsible for burying objects and blurring the edges of features. Cryoturbation, that is disturbance by freeze-thaw action, and argilliturbation (caused by the seasonal expansion and contraction of clays in the soil) may cause opening and closing of cracks in the soil. The mixing and movement of sediments under the force of gravity (graviturbation) is another common problem, including such processes as solifluction, frost creep, soil creep and subsidence. A sediment may also be affected by aquaturbation, by water under pressure, or by aeroturbation, when soil gas disturbs the matrix or wind winnows fine material from the soil. Changes in sediment structure arising from the growth and destruction or dissolution of crystals is a particular problem in subhumid areas, and earthquakes may cause major alteration to a sedimentary sequence. In the sediments sampled in Britain, the main source of disturbance appeared to be bioturbation, particularly arising from worm activity and rootlets.

In most circumstances the mode of deposition of waterlain archaeological deposits can be identified from their lithology, sedimentary structures, biota and location on the site; the evidence for the origin of the context sampled is discussed in detail for each case. Deposits investigated were required to be at least loosely dated by an independent method, such as ceramic typology; to be minimally bioturbated and to be representative of the wide range of archaeological contexts in which waterlain sediments occur. Finding suitable contexts proved surprisingly difficult, partly because of the apparent lack of undisturbed waterlain sediments on archaeological sites, but also because of the difficulty of identifying such deposits in the field. There are, of course, a wide range of investigative techniques that can be applied to both the sediment itself

(such as thin section examination or particle size analysis) and to matter within the sediment matrix (such as the identification of molluscs, pollen or seeds) which might provide additional information to help identify the deposit and its origins (Shackley, 1975). However, the constraints of time and lack of specialist facilities meant that identification rested mainly on inspection in the field and archaeological evidence.

3.3 PREVIOUS INVESTIGATIONS INTO THE ARCHAEOMAGNETISM OF ARCHAEOLOGICAL SEDIMENTS.

The first measurements of secular variation recorded by sediments were made around 50 years ago (Section 1.5; McNish & Johnson, 1938; Ising, 1942). Subsequent palaeomagnetic studies have involved sediments from a wide range of depositional environments, including lakes (Creer & Tucholka, 1983), the oceans (Lowrie, 1989) and caves (Papamarinopoulos & Creer, 1983; Thistlewood, 1991). However, the dating of sediments from archaeological contexts by archaeomagnetism has only developed over the last 20 years and has been applied, with varying success, on less than 30 sites. The delay in application of the technique has been partly due to the concentration of efforts on developing the calibration curve by the measurement of well-dated fired material (Section 5.2). Interest in applications to archaeological sediments was facilitated by the development of more sensitive spinner fluxgate magnetometers (Molyneux, 1971) and cryogenic magnetometers (Goree & Fuller, 1976). Early investigations of clay-muds from a buried lake associated with human activity at the type site for the Hoxnian Interglacial at Hoxne in Suffolk (Thompson *et al.*, 1974) demonstrated that a stable, normal magnetisation had been preserved in the sediment. In the same year, a deposit of colluvial sand representing the final phase of the prehistoric site at Little Bay, Scilly was also found to preserve a field direction similar to that found in Iron Age fired material (Clark *et al.*, 1988). These early investigations pointed the way to the use of archaeomagnetism for dating sediments and in subsequent years, a number of such studies have been carried out. The approach has been necessarily piecemeal, sampling where opportunities have arisen during archaeological excavation, with little control over the material of the sediment or its environment of deposition. While some sediments have proved datable by comparing them with the established secular variation curve (Section 1.2), others have been too disturbed by chemical or physical changes to sustain a magnetisation characteristic of the geomagnetic field at the time of deposition.

While not strictly archaeological, mention should be made at this point of the secular variation curves for the last 10,000 years in Britain, based on the record obtained from lake sediments (Turner & Thompson, 1979, 1981 & 1982). This record was compiled from the summation of declination and inclination measurements from cores of

sediment from Loch Lomond, Scotland; Lake Windermere, Northern England and Llyn Geirionydd, North Wales. The record was calibrated with 30 radiocarbon dates and pollen analysis and provides a continuous record, with much fine detail. The secular variation records from the individual cores appeared to correlate well and show similar features, although the swings in direction did vary in amplitude by tens of degrees, even from cores from the same lake (Tarling, 1983 p156). Rapid swings in direction would have been smoothed out by the sediment recording process and the averaging of magnetic directions from different cores. The absolute values of magnetic direction were not available because of the coring process (Section 2.1.3), but were fixed by comparison of the secular variation in the upper part of the core with the London observatory data. The lower part of the lake sediment curve, below 5000 years BC, was only based on three cores. Despite the reductions in the amplitude of swings and the difficulty obtaining absolute values of magnetic direction, the lake sediment curve gives a very complete record of secular variation over the last 10,000 years and has been used to help define the shape of the current British archaeomagnetic calibration curve (Clark *et al.*, 1988) and to date material before 10th century BC (Section 2.5.4). It must be remembered that the absolute dating of the cores relied on radiocarbon dating and so the limitations of that method must be considered in any dates obtained from comparison with it.

The dating of the primary silts accumulated in ditches shortly after their cutting (Section 3.2.2) has often proved to be successful. Of particular interest are the archaeomagnetic studies by Clark of the primary silts of ditches associated with the hillforts at Felday (Field, 1989), Hascombe (Thompson, 1979) and Holmbury (Thompson, 1979). Such ditches are characteristically 'V' shaped in section, with a slightly flat bottom and are likely to have been initially filled rapidly with silts, possibly in the first winter of their existence. In all three cases the ditches were well-drained and not subject to variations in water-table, as they were cut into porous sandstone hilltops. They appeared to be sterile with little biological activity. The archaeomagnetic dates from the three ditches corresponded well with the expected archaeological dates, based on pottery and radiocarbon (Clark & Thompson, in press). Samples from a silt band sealing an abandoned water-hole in the Iron Age hillfort at Bigberry (Thompson, 1983) also retained a stable magnetisation, despite the sediment being close to the surface and hence vulnerable to weathering. The date obtained was compatible with radiocarbon dates from charcoal in the fill of the water-hole (Clark & Thompson, in press). Other ditch silts have also proved to be of archaeomagnetic interest, with a primary ditch silt from Mucking, Essex (A.J. Clark, pers. comm.) providing a useful point on the archaeomagnetic calibration curve in the pre-Roman Iron Age. A column of samples taken from the alluvial fill of a Neolithic cursus ditch at Drayton, Oxfordshire (Clark, 1988) showed a trend in magnetic directions similar to that characteristic of 1st century AD. However,

precise dating was difficult because the directions were scattered, possibly as a result of the iron redeposition that was evident from the mottling of the sediment and the rusty deposition in root-holes.

Many archaeomagnetic investigations have been carried out on river silts as these often provide extensive sequences of waterlain deposits, recording secular variation in the geomagnetic field over a long period of time. Comparison of these sequences of magnetic directions with the calibration curve in order to obtain a date is problematic, as discussed in Section 2.5.3, particularly because there are often no dated reference points in the sediment record to indicate which part of the calibration curve is appropriate and the rate of deposition is unknown and may be variable. Archaeological sediment sequences are often short, making comparison with the secular variation curve difficult. This is particularly a problem where large samples are taken and not overlapped.

Despite these problems, some very interesting results have been obtained, notably at Brean Down (Clark, 1986) where a vertical group of 31 samples was taken by the tube method from a 1.66m column of alluvial silt, underlying a Bronze Age cemetery on the cliff edge (Bell, 1987). The sequence of archaeomagnetic directions obtained clearly followed the same pattern as the secular variation shown in the lake sediment curve between about 3500BC and 1650BC. A similar column of samples was taken through stream-channel deposits at Runnymede Bridge (Clark & David, 1978) and the sequence of directions of stable magnetisation showed the distinctive sharp eastward movement in declination characteristic of the lake sediment curve between 4200BC and 3650BC. In both cases, the river sediment results suggested that the declination of the lake sediment curves had been placed too far east. Archaeomagnetic investigations of silted up river channels from Walton le Dale, Lancs. (Clark, 1987) and Castle Acre Castle (Clark *et al.*, 1988) have also proved interesting. At the former, a silted-up water channel, bounding an area of Romano-British occupation, was investigated, and in the latter the silt filling a diverted river channel was sampled. In both cases the archaeomagnetic measurements were rather scattered, but were used to provide a broad indication of date. Single units of river flood sediments, representing deposition over a short period of time, have occasionally provided a record of the ancient field precise enough to be used in the construction of the calibration curve. These included the coarse silts accumulated against the abutment of the old town bridge at Kingston (Clark *et al.*, 1988) and samples from a pink silt river flood deposit, which is a persistent feature throughout the archaeological record in Monmouth (Clark, 1990).

A particularly complete record of the secular variation since AD1600 was obtained from the silt accumulated in the millpond at Wharram Percy (Tarling, 1983 p 154; Hammo-Yassi, 1984), although inclinations showed a clear and consistent shallowing of 10° . This might be attributed to an inclination error in the depositional remanent magnetisation (Section 1.4.2). Clark sampled silts of estuarine origin underlying a peat containing prehistoric flint-working debris and charcoal at Westward Ho!, Devon (Balaam *et al.*, 1987). Vertical groups of samples were taken from five different locations within the silts. However, there were large discrepancies between the magnetic directions of samples taken from the same horizons, suggesting that the sediment had been disturbed, possibly by bioturbation. A number of cave deposits with archaeological associations have been investigated, most notably at Westbury in Somerset, where deposits were found to have a weak, but stable, reversed magnetisation. This suggested that the sediments, which were associated with human remains, were at least 720,000 years old, hence providing some of the earliest evidence of humans in Britain (Tarling, 1983 p201; Hammo-Yassi, 1984). Horizontally laminated silty clays containing Upper Palaeolithic flints from Kirkhead Cave (Gale *et al.*, 1984) were found to show much wider swings in declination and inclination than those found in the lake sediment record. The authors attributed this to the higher rate of sediment deposition in the cave, but unfortunately the magnetic record was too scattered to provide detailed dating information. Most recently, Eighmy and Howard (1991) have investigated the archaeomagnetism of clay deposits in a large number of abandoned canals, with a view to dating them and ascertaining their role in irrigation. They found the precision of magnetic direction to be typically less than that common for fired materials and that, while the declinations corresponded well to the values predicted for historically dated canals, the inclinations were often shallower than would be expected.

A number of problems have been brought to light by these previous studies, in addition to the apparent systematic shallowing of inclination and disagreements with the lake sediment secular variation curve mentioned above. Chemical changes and the redistribution of iron compounds after deposition have been shown to scatter results, as with the cursus ditch at Drayton. Hammo-Yassi (1984) found that scattered or anomalous magnetisations arose from inhomogeneous sediments containing sherds or stones. Sediments derived from the chalk soils of Micheldever Wood, Hants. (A.J. Clark, pers. comm.) and Thanet (A.J. Clark, pers. comm.) frequently had scattered remanence directions, possibly due to extensive bioturbation. At Millmead, Surrey (A.J. Clark, pers. comm.) the direction of magnetisation of the sediment appeared to change as the geomagnetic field changed. This might have been caused by the constantly fluctuating water-table allowing the remobilisation of magnetic carriers within the sediment.

In summary, previous archaeomagnetic studies have included sediments from a number of different archaeological contexts, some of which have been successfully dated by archaeomagnetism. However, a number of unanswered questions remain to be addressed by this study, particularly with the new environments, sampling methods and measurements techniques involved.

3.4 THE CONTEXTS EXAMINED AND THE MAGNETIC RESULTS OBTAINED

The numerical results of magnetic measurements of NRM, bulk demagnetisation and magnetic fabric on the groups of samples from each archaeological context can be found in Table 1A (Appendix 1). The results of measurements of pilot demagnetisation and IRM acquisition tests on pilot samples from each context are in Table 1B (Appendix 1). Table 1C contains a summary of the archaeomagnetic and archaeological information concerning contexts that were considered to be datable (Appendix 1) and Table 1D (Appendix 1) records the results of linear regression through intensity and susceptibility data for each context. The key to symbols used in section drawings is in Appendix 2.

3.4.1 Archaeomagnetic investigations in York: the role of the River Ouse and River Foss in the archaeology of York.

The River Ouse and its tributary, the River Foss, which merge at York (Fig. 3.2), have played a crucial role in the development of the City of York; influencing its establishment, growth, trade and economic prosperity. The riverbanks were the focus of trade and commerce in York. A tendency to build out into the rivers and to reclaim adjacent land means that Roman, Anglian, Viking and Medieval waterfronts and quays are preserved under modern buildings, well back from the present river banks. The recent economic boom in York led to the development of redundant sites adjacent to the two rivers and provided the opportunity to investigate the buried waterfronts. Such excavations provided a large and valuable resource of structures, artefacts and environmental evidence (York Archaeological Trust, 1988 p2). Studies of the river deposits were intended to help in the understanding of the environment and human attempts to control it.

The Ouse and Foss probably carried prehistoric vessels, but it would appear that waterfront development only began in AD71, when York was founded as a military base by the Romans. The Roman fortress was established on the spur of land between the Ouse and the Foss, which provided natural defences and excellent supply and communication routes, navigable on only two tides from the Humber Estuary and providing access to the Lincolnshire canal system (Royal Commission on Historical Monuments, 1962 p5). 6000 men were stationed in York and this necessitated the construction of wharves and warehouses for handling supplies, such as the grain stores excavated at 39-41 Coney Street (Kenward & Williams, 1979). A civilian settlement, the *colonia Eboracensis*, also grew up to service the garrison, colonising the far banks of the Ouse and the Foss by draining marginal land and building out into the river. Excavations at 5 Rougier Street (Ottaway, 1981 & 1982) and 39-41 Coney Street (Brinklow *et al.*, 1986) showed that the river regime has changed significantly since Roman times, when the channel was wider and the mean water level lower, with the Ouse bank as much as 40m from its present location. Narrowing of the channel and climatic changes contributed to the rise in water level.

As York's influence grew and the city became the civil capital of the province of Lower Britain in the 3rd and 4th centuries AD, the trading links provided by its rivers became vital to success. There is little archaeological evidence of activity in the Anglian period but Viking and late Saxon times brought further development of the waterfronts; in around AD1000 the city was described as being 'full of merchants from many places, particularly from the Danes' (York Archaeological Trust, 1988 p5). The range of foreign products found in Viking Age deposits at Coppergate (Hall, 1984 pp85-94) and

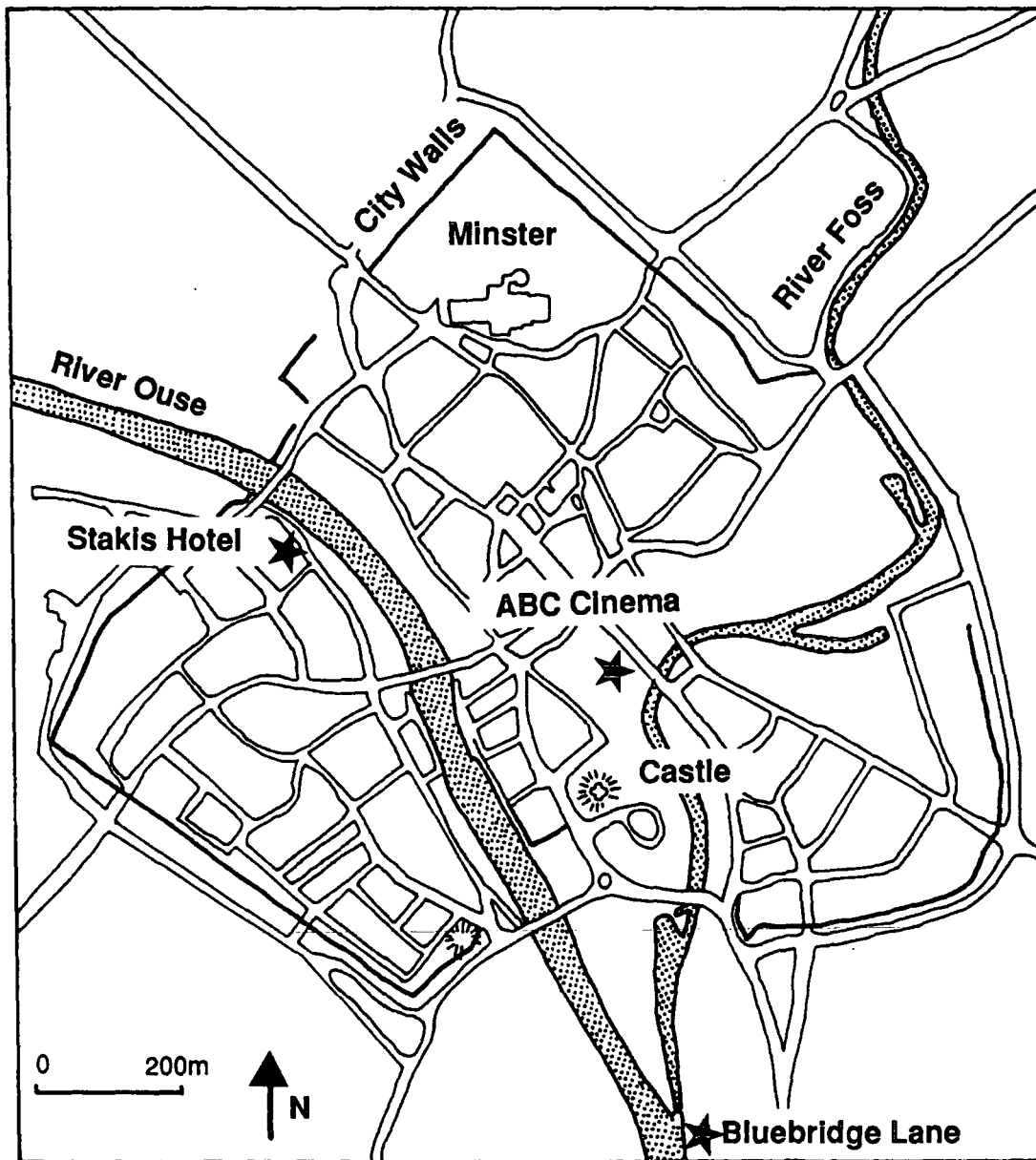


Figure 3.2: Map of York city centre showing the A.B.C. Cinema, Stakis Hotel and Bluebridge Lane sites in relation to River Ouse and River Foss.

historical sources suggest trading links with the Rhineland, the Low Countries, Scotland and Ireland.

Documentation of activities associated with the rivers becomes more common as the Medieval period proceeds and shows that the expansion of population and trade brought a prosperity which depended largely on riverborne trade. The Normans took over the city in 1067-9 and, following several successful attacks on the city and castle, William I improved the defences by damming the Foss just above its confluence with the Ouse (Royal Commission on Historic Monuments, 1972 p10). This provided a wide, deep moat around the castle and created a small lake and marshy area, known as the King's Fishpool or *Stagnum regis*. The Domesday Book recorded that the action caused the loss of about 150 acres of arable land, meadows and gardens. In this period, the Ouse was in constant use for commercial traffic of foodstuffs, building materials and passengers. As ships of deeper draught were developed to carry larger cargoes, deeper berths were built out into the river, forming a narrower river channel with faster flowing water and less possibility of silting up. Within 200 years the waterfront at City Mills, Skeldergate had advanced 28m in two episodes of building, with warehouses being built on the reclaimed land (York Archaeological Trust, 1988 p15).

The rivers maintained their role throughout the Medieval period, until Tudor times when silting up became an insurmountable problem, particularly given the increased draught of sea-going ships. The Foss channel was recut in 1592 and an attempt was made to canalise it in the late 18th century (Royal Commission on Historic Monuments, 1972 p138). However, despite renewed building on the Ouse in the 19th century, river transport could not compete with railways and roads; today the rivers are mainly used for pleasure craft.

Not only has the regime of the Ouse and the Foss changed considerably since Roman times (Ordnance Survey, 1988 a & b), but so has the catchment area from which they flow. On occasions this has been due to direct human action, such as progressive building into the floodplain, causing diversions and restricting flow. In other cases, indirect action upstream or downstream was responsible. Intensive farming in the late Roman period caused silting in the Vale of York, impeding drainage and triggering flooding; deforestation in the Middle Ages caused more rapid water run-off and hence flooding (York Archaeological Trust, 1988 p20). York appears to have frequently been prone to flooding (Radley & Simms, 1971) and it is hoped that archaeomagnetic dating of successive layers of flood deposits, interleaved with debris of human habitation, will date such flood events.

A.B.C. Cinema Excavations, 22 Piccadilly, York
(O.S. Grid Ref. SE 6059 5169)

Site description

Excavations were carried out by York Archaeological Trust on the site formerly occupied by the A.B.C. Cinema (22 Piccadilly) in the centre of York (Fig. 3.2) between 1st September and 6th November 1987. It was to be redeveloped as a retail outlet, which would necessitate major pile-driven foundations and so excavation was concentrated on the four areas (Fig. 3.3) which were to be destroyed by the piling (Finlayson & Pearson, 1988). These were excavated from the modern foundation level down to material that appeared to be undisturbed by human activity, using sondages (literally keyhole; meaning narrow trench) approximately 3m². The main object of the excavation was to find evidence for exploitation of the River Foss, and determine its course in pre-Norman times.

The site was situated 50m to the north of the present River Foss (Fig. 3.2) and adjoining the excavations at 16-22 Coppergate (Hall, 1984). The basement slab of the cinema, where excavations commenced, was approximately 5m below the present street level. There is evidence that Piccadilly had been built up in the 19th century to minimize the effects of periodic flooding (Finlayson & Pearson, 1988) and so only late Medieval and early modern deposits were truncated by the cinema foundations. A maximum depth of 6m of surviving waterlogged archaeological build-up existed; the conditions led to good preservation of organic material, particularly timbers, and made it necessary to pump water from the trenches continuously. As excavations were carried out in such limited areas, interpretation of the archaeological features was often difficult. The permanent waterlogging, coupled with the fact that the deposits of archaeomagnetic interest were found towards the bottom of these deep, narrow, steel-shored trenches, presented particular sampling difficulties.

Description of the deposits sampled in trench 2

Trench 2 measured 3.2m² and was positioned in the northern corner of the site (Fig. 3.3). After removal of the cinema foundations, the trench was excavated by hand and was found to contain a number of deposits and timber structures ranging in date from Anglo-Saxon to late Medieval. A series of layers of silty clay (Fig. 3.4) were found about 5m below the level of the Cinema foundations, underlying the archaeological horizons, and these were sampled for archaeomagnetic studies.

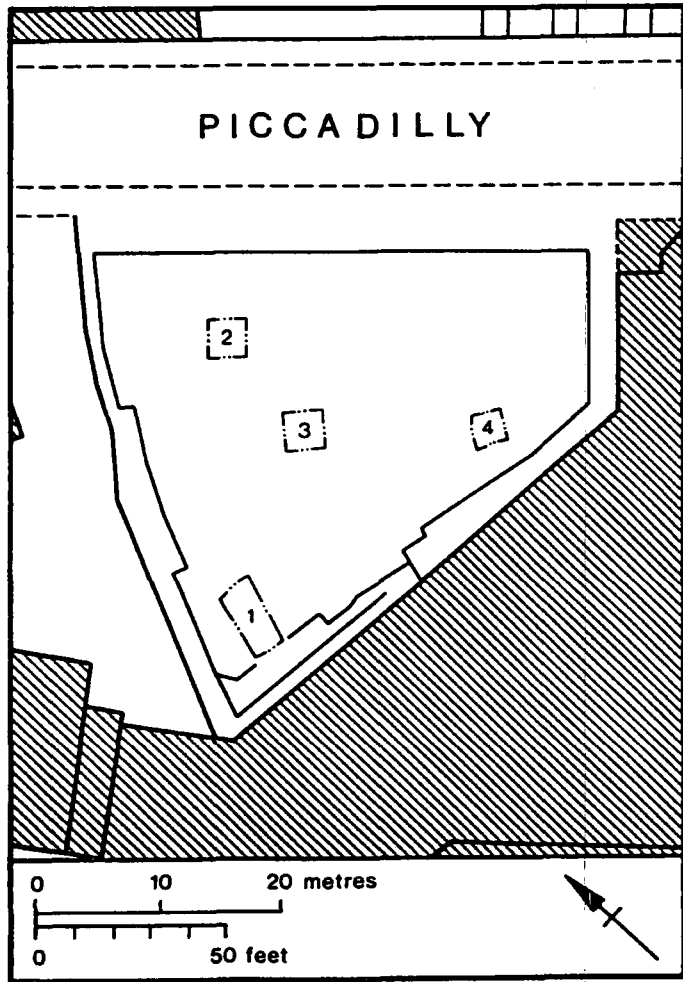


Figure 3.3: Site plan of A.B.C. Cinema, showing all the trenches excavated (provided by York Archaeological Trust).

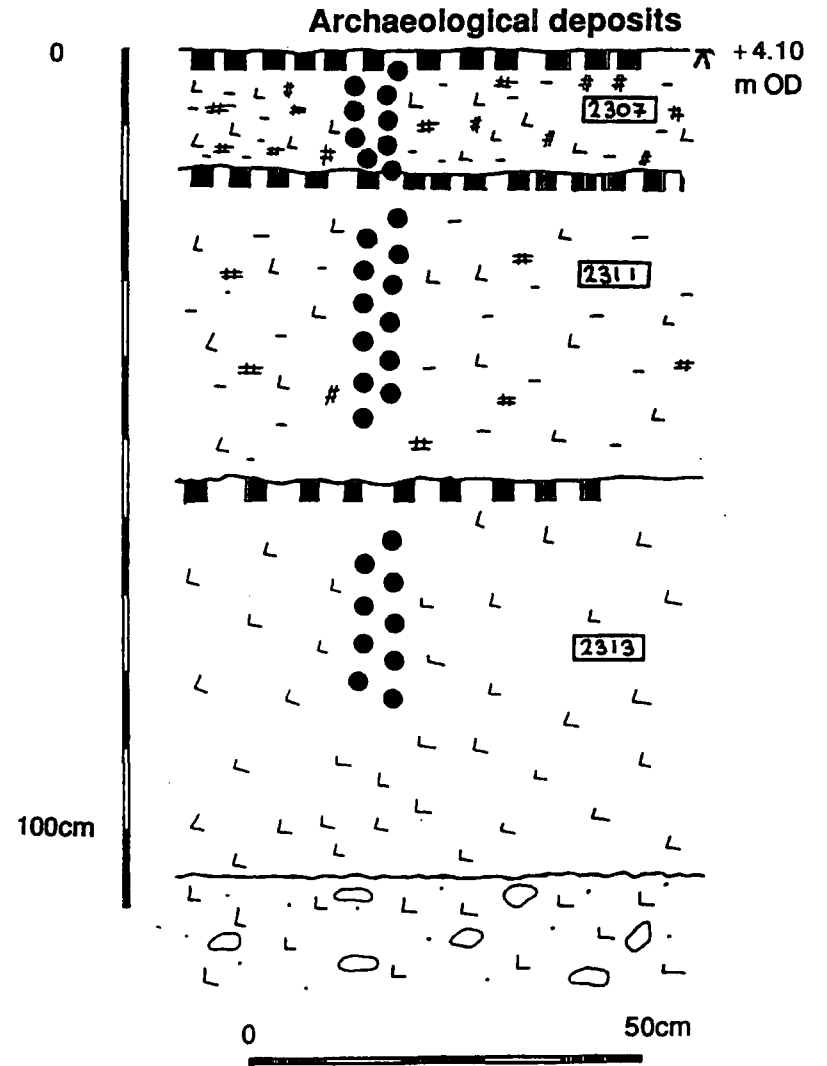


Figure 3.4: Vertical section drawing of contexts 2307, 2311 and 2313 at A.B.C. Cinema, showing sample locations.

Context No. 2307: This context consisted of a dark grey/brown (Munsell No. 10YR 4/1, 4/2) silty clay, covering the north-east part of the restricted area of excavation with a uniform thickness of 0.15m. It was overlain by site occupational deposits and sealed contexts 2311 and 2313 (Fig. 3.4) with an obvious and abrupt contact between the horizons. The material of the deposit was mainly a moist, silty clay, slightly gritty in texture, but still plastic. There was considerable (around 5-20% by volume) black charcoal mottling. A small quantity of bone was the only other organic material. There was no visible evidence of biological activity or sedimentary structures associated with deposition or post-depositional disturbance. The matrix contained occasional inclusions of pot, tile and shell fragments.

Context No. 2311: This context underlay 2307 and sealed 2313, with both boundaries being sharp and horizontal. It covered the entire area of excavation, at this stage 2.1m², in the north-east corner of the trench and was a uniform thickness of 0.4m. The deposit was a greyish brown (Munsell No. 10YR 5/2, 5/1) silty clay, lighter in colour than 2307 and without the same gritty texture. Occasional white flecks and charcoal mottling were visible, but there was little other organic matter and no evidence of biogenic activity or depositional sedimentary structures. Trowelling the deposit revealed occasional inclusions of bone, glass, charcoal and limestone fragments. A sump had been cut through the deposits close to the shoring to facilitate pumping and this area was avoided during sampling, as the sediments may have been disturbed.

Context No. 2313: This was the lowest deposit in the series under investigation, underlying 2307 and 2311 and overlying a sandy clay matrix containing large (up to 10cm diameter) rounded pebbles. 2313 consisted of a compact blue/grey clay (Munsell No. 7.5YR 5/0) which extended over the entire excavated area to a uniform depth of 0.5m. The clay was very smooth, plastic and sticky and contained no stones or gritty inclusions. There were no roots, burrows or other evidence of bioturbation, neither were there any visible sedimentary structures nor were any cultural artefacts retrieved on excavation.

All the deposits were soft and therefore easily sampled by the tube method (Section 2.1.3), which created little visible disturbance to the sediment surface. For each of the three contexts a horizontal shelf was cut into the top and holders were pushed vertically into it. A continuous sequence of samples was also taken down a vertical section through all three contexts. In all 65 were taken, the locations of which are shown in Fig. 3.4. Orientation was carried out by transferring a site line, related to the site grid, to the samples with a theodolite, as shoring prevented the use of a magnetic compass and lack of sun made a sun-compass unusable.

Archaeological interpretation of deposits in trench 2

The archaeological evidence suggested that the deposits in trench 2 reflected their proximity to the River Foss and changes in the river's course (Finlayson & Pearson, 1988). Clays which may have been deposited by the river were found under horizons consistent with a flood plain, indicating gradual movement of the riverbank towards its present location. Timber posts from the upper layers of the trench were interpreted as fencing used to delineate boundaries and there were a number of linear features which appeared to be attempts to drain the area into the river. A series of wattle hurdles running parallel and at right angles to the river were excavated. These were not associated with floors or occupation deposits and were therefore not part of buildings, but rather appeared to be an attempt to prevent soil from slumping into the river, thus creating terraces (Finlayson & Pearson, 1988). Pottery associated with vegetational growth above the terracing was dated at 11th century AD. The lower contexts, those sampled for archaeomagnetic investigation, were interpreted as being riverlain sediments, suggesting that the area lay within the course or floodplain of the river, or a tributary to it, at this point in its history. A Roman pottery lamp, still containing a wick, was found immediately above the riverlain deposits (Finlayson, 1987) and provided a *terminus ante quem* for them. Pottery from context 2307 was late 1st or 2nd century AD and pottery from context 2311 was dated to AD160-220 (N. Pearson, pers. comm.). Context 2313 contained no datable cultural artefacts, but the underlying gravels may have been deposited by meltwater towards the end of the last Pleistocene glacial, about 11,000 years ago (A. Jones, pers. comm.).

Results of magnetic measurements: the horizontal shelf in context 2307

Natural remanent magnetisation

The intensity of NRM of samples ABC45-56 fell in the narrow range 35.7-48.1 $\mu\text{Am}^2\text{kg}^{-1}$ and the directions were closely grouped with one outlier (Fig. 3.5a). The α_{95} value, including the outlier, was 8.6°.

Demagnetisation

8 of the 12 samples were subjected to stepwise alternating field demagnetisation and the behaviour of a typical sample is shown in Fig. 3.6a. The stereographic projection indicated that little directional change occurred in the magnetisation up to a demagnetising field of 40mT. The linear behaviour of the vector end-point shown on the Zijderveld plot confirmed that the remanence comprised of a single stable component of magnetisation with a slight viscous overprint. The stable component was statistically well defined with a stability index of 4.1 (stable) over a range of 7.5 to 40mT. The plot of

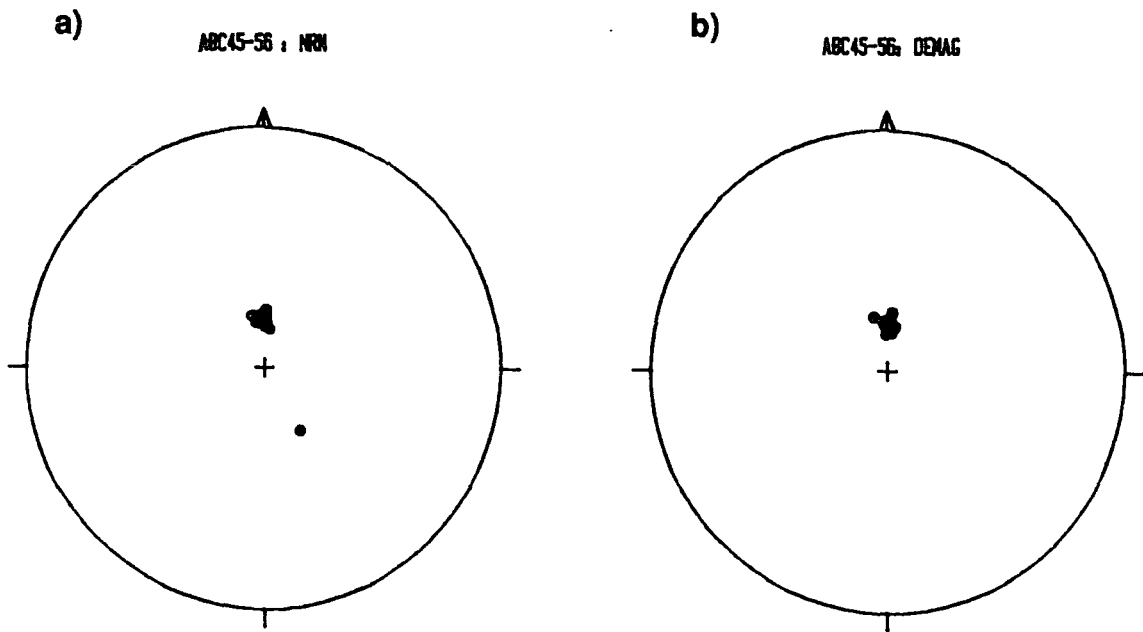


Figure 3.5: Stereographic plot of the directions of magnetisation of samples ABC 45-56 from context 2307 a) NRM values and b) after partial demagnetisation.

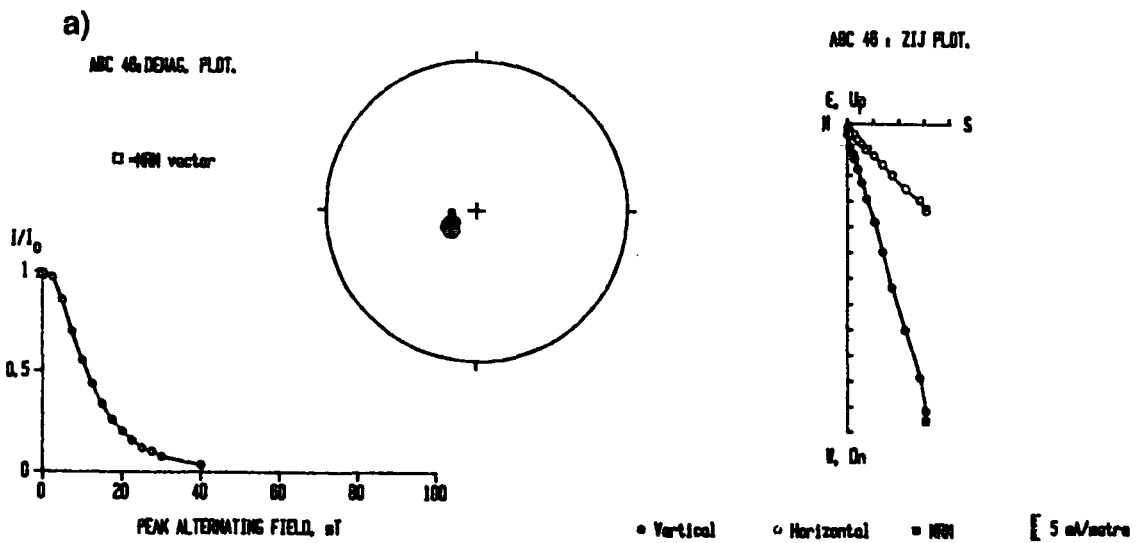


Figure 3.6 a): Stereographic, intensity and Zijderveld plots of the behaviour of a typical sample (ABC 46) from context 2307 on alternating field demagnetisation.

change in normalised intensity with increasing applied field fell smoothly and sharply, the intensity reducing to less than 5% of the original value after demagnetisation in fields of 40mT, with a low median destructive field of 10-12.5mT. These observations indicated that the magnetisation was soft but had a stable component. Demagnetisation of the outlier (ABC45) showed that its magnetisation consisted of at least three components, with the most stable having a magnetisation in a similar direction to the stable component found in the other samples (Fig. 3.6b). It seemed likely that the unusual direction of magnetisation of this sample was the result of a later, soft overprint and the stable component revealed in fields over 15mT was the primary magnetisation.

As the material was homogeneous and the pilot samples showed very similar behaviour on demagnetisation (with the exception of the outlier), the remaining samples were demagnetised in a field of 7.5mT to remove the small viscous component. This resulted in the convergence of the magnetic direction of the outlying sample with the others and an improved α_{95} of 2.0° (Fig. 3.5b).

Magnetic fabric

Specific susceptibility was in the range $39.7-55.8 \times 10^{-8} \text{m}^3 \text{kg}^{-1}$ and the magnetic fabric was found to be weak, with $h\%$ in the range 1.0-4.3%. All the q values fell in the range 0.12-0.51, characteristic of an undisturbed depositional fabric, with the exception of ABC45 which had $q=0.84$, possibly indicating a disturbance to the magnetic fabric of this sample. The minimum axes were fairly well grouped, indicating a near-horizontal magnetic foliation (Fig. 3.7), suggesting that the sediment had been deposited grain by grain. The maximum axes were also loosely grouped showing a lineation which was characteristic of a primary depositional fabric. The scatter in the principal axes may be partly attributed to the weakness of the fabric, and hence the difficulty of resolving it on the available instrument.

Magnetic mineralogy

Application of pulse fields of increasing intensity to a sample resulted in a sharp increase of induced IRM, followed by a very small further increase at higher fields (Fig. 3.8a). The SIRM value was $5.82 \text{mAm}^2 \text{kg}^{-1}$ and 99% of this value was reached in an applied field of 1T. $(B_0)_{\text{cr}}$ had a very low value of 15mT (Fig. 3.8b) and the S ratio was 1.0. The high S ratio and swift increase to saturation magnetisation suggested that the magnetic mineral carrying the remanence was predominantly magnetite, with virtually no contribution from harder magnetic minerals. The low value of $(B_0)_{\text{cr}}$ suggested that the magnetite was mainly in the form of larger, multidomain grains.

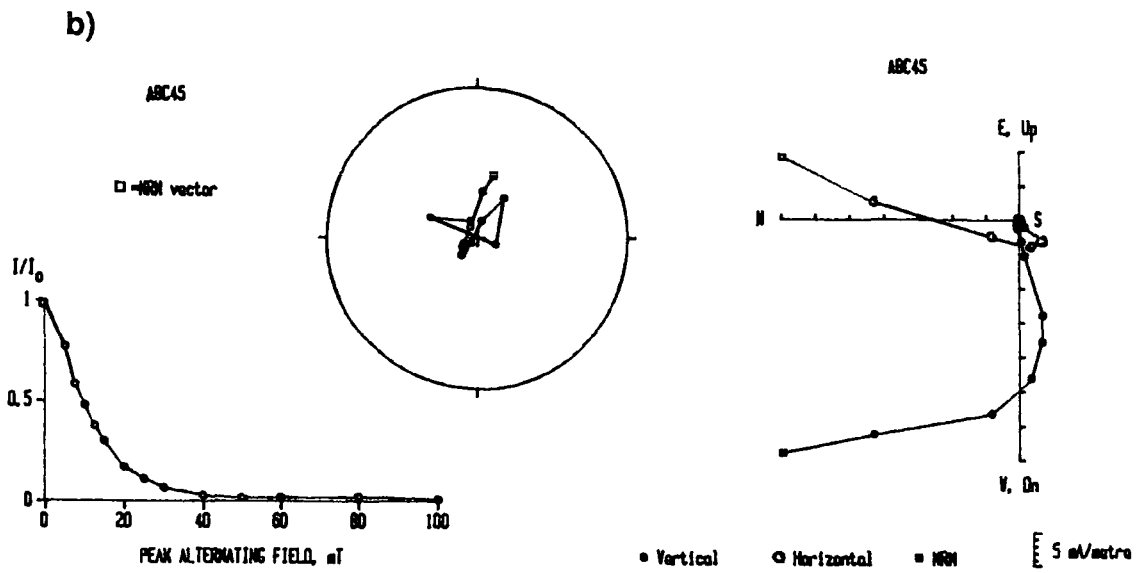


Figure 3.6 b): Stereographic, intensity and Zijdeveld plots of the behaviour of the outlying sample (ABC 45) on alternating field demagnetisation.

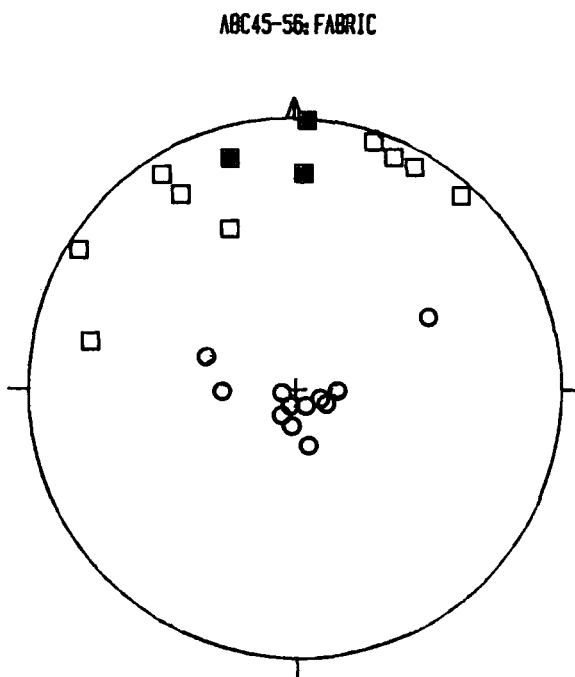


Figure 3.7: Magnetic fabric of samples ABC 45-56 from context 2307.

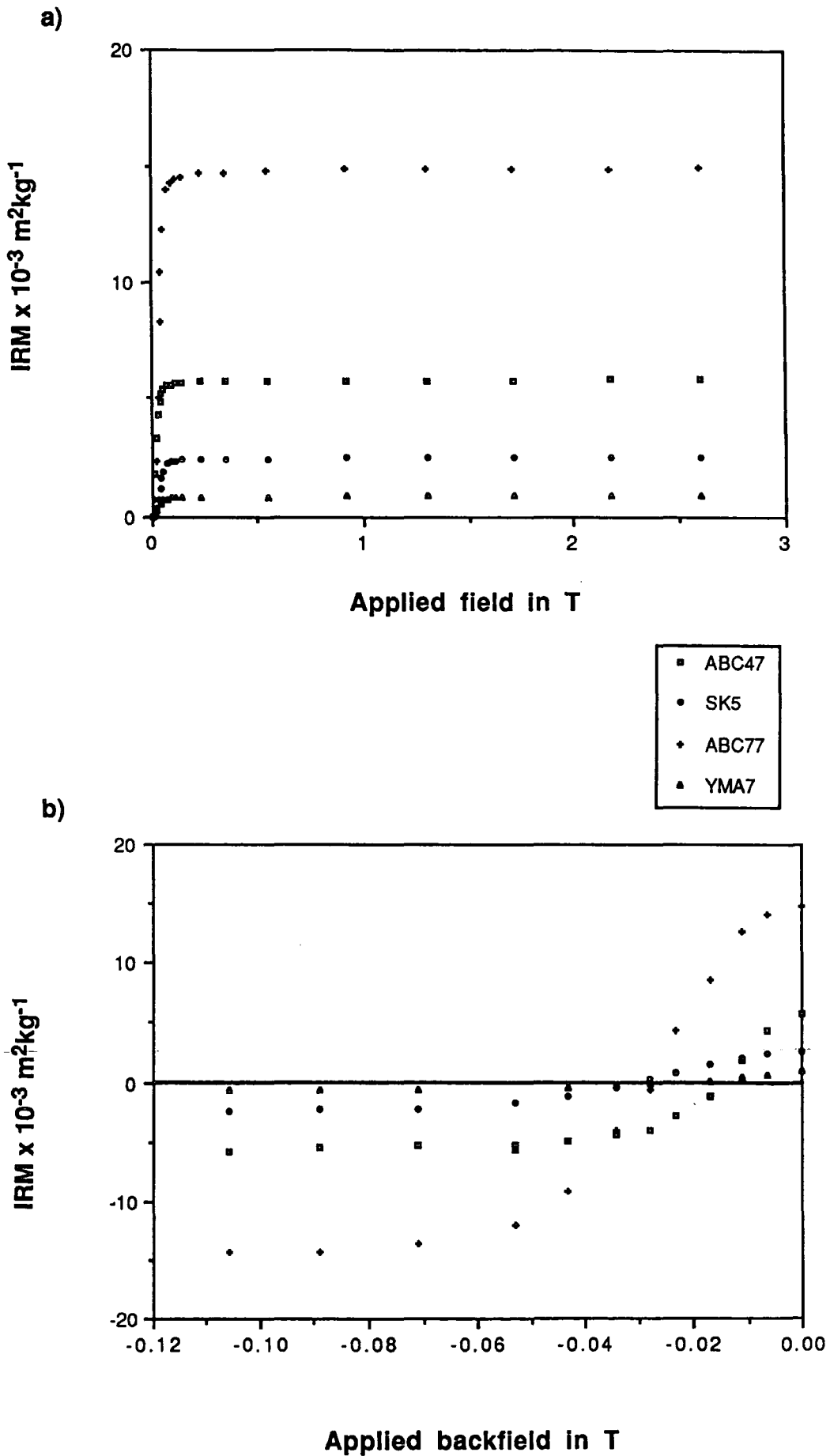


Figure 3.8 a: IRM build-up curve for samples ABC 46, ABC 77, SK 5 and YMA 7.
 b: Plot of back coercivity for samples ABC 46, ABC 77, SK 5 and YMA 7.

Results of magnetic measurements: the horizontal shelf in context 2311

Natural remanent magnetisation

The NRM intensity of samples ABC57-70 fell in the range $3.9\text{-}8.1\mu\text{Am}^2\text{kg}^{-1}$, slightly weaker than context 2307, but still well above the noise level of the magnetometer. The directions were generally well grouped (Fig. 3.9a), with an α_{95} value of 3.6° based on all 14 samples.

Demagnetisation

4 of the samples were subjected to stepwise demagnetisation in an alternating field (not shown). The behaviour was very similar to the samples from context 2307, with a single stable component of magnetisation with a stability index of 4.7 (stable) over the range 7.5 to 50mT and a slight, soft viscous overprint. The magnetisation of one outlying sample appeared to consist of several components, with no identifiable stable endpoint and it was therefore omitted from subsequent analysis. As the material was homogeneous and the remainder of the pilot samples showed very similar behaviour on demagnetisation, the other samples were demagnetised in a field of 7.5mT to remove the small viscous component. This resulted in a slightly improved grouping with an α_{95} of 3.3° (Fig 3.9b)

Magnetic fabric

Specific susceptibility was in the range $10.8\text{-}17.6\times 10^{-8}\text{m}^3\text{kg}^{-1}$, rather lower than that of context 2307, but the magnetic fabric was found to be generally slightly stronger, with $h\%$ in the range 1.7-4.7%. The q values fell between 0.14 and 1.02, 72% in the range characteristic of an undisturbed primary depositional fabric. The principal axes of susceptibility showed a similar distribution to those of context 2307 (Fig. 3.10), with the minimum axes closely grouped, indicating a well defined foliation plane and the maximum axes loosely grouped showing a lineation. The latter may be indicative of the action of an aligning force, such as a hydrodynamic or geomagnetic force, acting on the magnetic grains at the time of deposition.

Results of magnetic measurements: the horizontal shelf in context 2313

Natural remanent magnetisation

The intensity of NRM of samples ABC71-79 was in the range $74.0\text{-}125.8\mu\text{Am}^2\text{kg}^{-1}$, much stronger than the intensity of magnetisation of either context 2307 or 2311. The directions of magnetisation were very well grouped (Fig. 3.11a), with an α_{95} value of 1.2° based on all 9 samples.

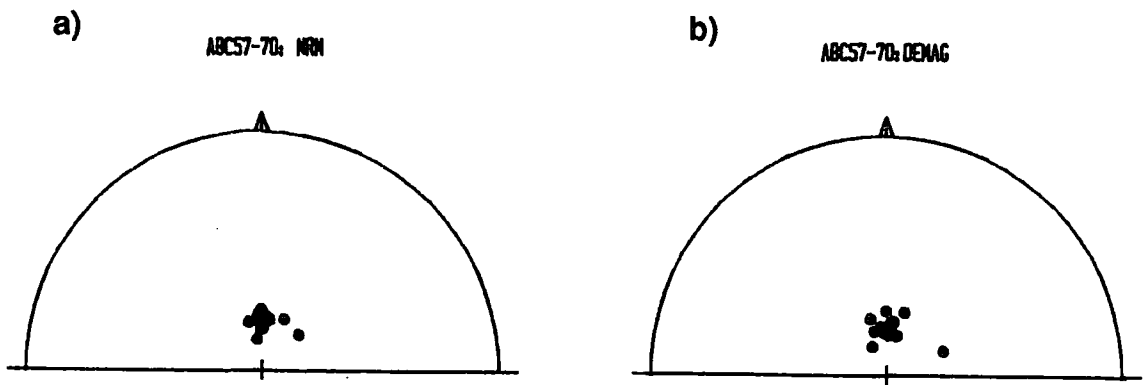


Figure 3.9: Stereographic plot of the directions of magnetisation of samples ABC 57-70 from context 2311 a) NRM values and b) after partial demagnetisation.

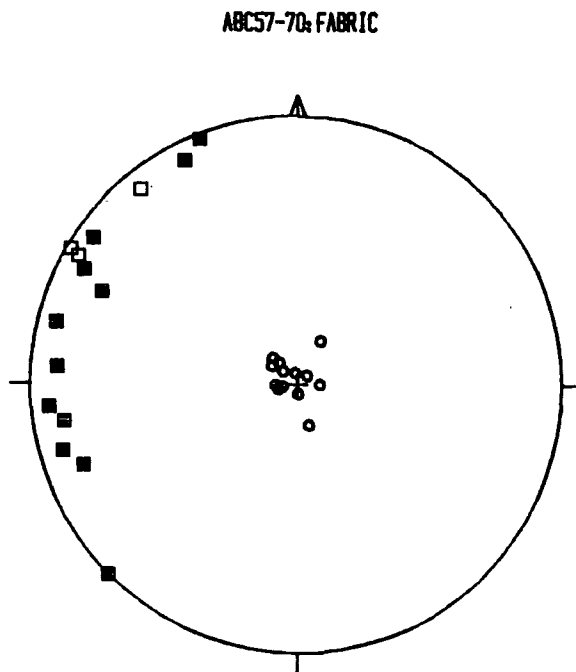


Figure 3.10: Magnetic fabric of samples ABC 57-70 from context 2311.

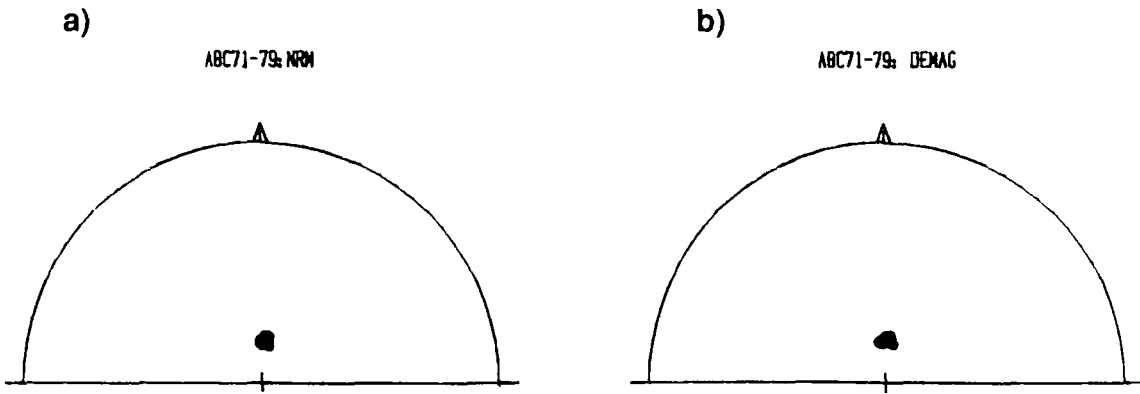


Figure 3.11: Stereographic plot of the directions of magnetisation of samples ABC 71-79 from context 2313 a) NRM values and b) after partial demagnetisation.

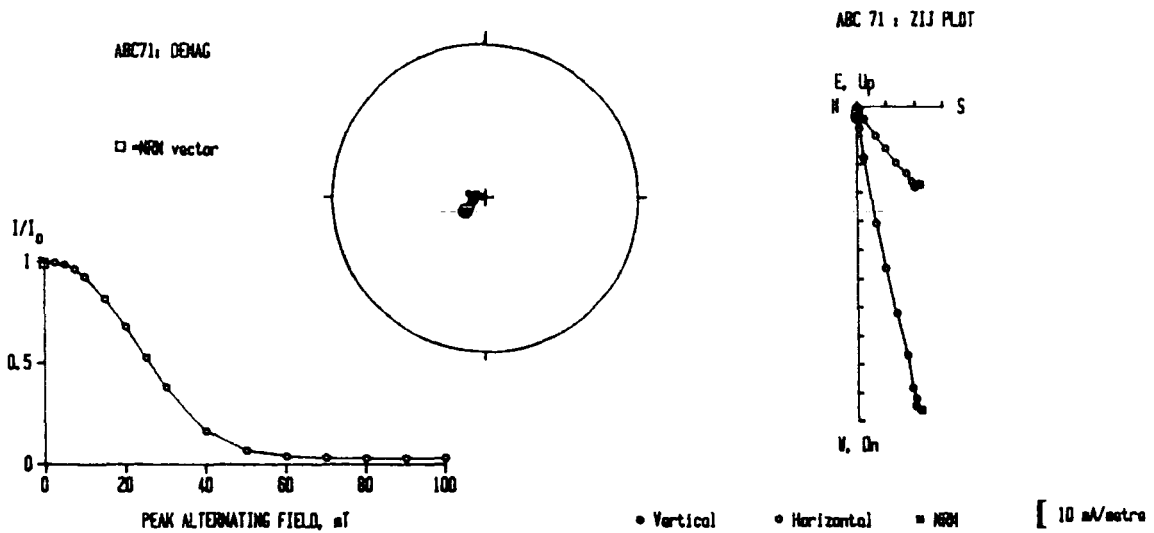


Figure 3.12 : Stereographic, intensity and Zijdeveld plots of the behaviour of a typical sample (ABC 71) from context 2313 on alternating field demagnetisation.

Demagnetisation

The 3 pilot samples showed similar behaviour on demagnetisation (e.g. Fig. 3.12). The Zijderveld plot and stereographic projection showed the remanence to consist of a single stable component with a slight viscous overprint. The stable component was statistically very well defined with a stability index of 22.5 (extremely stable) over the range 7.5 to 40mT. The intensity plot revealed the magnetisation to be harder than the previous two contexts, with over 6% of the original magnetisation remaining after demagnetisation at 60mT and a median destructive field of 25mT. There appeared to be a small, but very hard, component which remained undemagnetised in fields of 100mT, the peak demagnetising field available.

The remaining samples were demagnetised in a field of 7.5mT to remove the small soft component (Fig. 3.11b), resulting in a slightly increased dispersion with an α_{95} of 1.5° , which was attributed to random errors, rather than systematic changes in magnetic direction.

Magnetic fabric

Specific susceptibility was in the range $16.2\text{-}35.4 \times 10^{-8} \text{m}^3 \text{kg}^{-1}$, intermediate between the susceptibility of contexts 2307 and 2311. The magnetic fabric was found to be generally very weak, less than that of samples from contexts 2307 and 2311, with $h\%$ in the range 0.5-3.1%. q values ranged from 0.18 to 1.83, with only 4 falling in the range characteristic of an undisturbed depositional fabric. Both the minimum and maximum axes of susceptibility were very scattered (Fig. 3.13), possibly indicating the inability of the instrument to accurately resolve the foliation plane in such a weak magnetic fabric. A secondary magnetic fabric might have arisen from mineral alteration, sampling disturbance or bioturbation, but the stability and consistency of the remanence directions would suggest that such post-depositional disturbance was unlikely.

Magnetic mineralogy

IRM acquisition showed a similar pattern to that of context 2307 (Fig.3.8a), with 98% of the SIRM being attained in a field of 1T, although the SIRM value was much higher, $1.49 \times 10^{-2} \text{Am}^2 \text{kg}^{-1}$. $(B_0)_{\text{cr}}$ was 28mT, higher than the value for context 2307 (Fig. 3.8b) and the S ratio of 0.96 indicated that the predominant remanence carrying mineral was easily saturated, and hence probably magnetite, but there was a small contribution from a harder magnetic mineral, possibly haematite or goethite, which remained unsaturated in the highest fields available.

ABC 71-79 : FABRIC

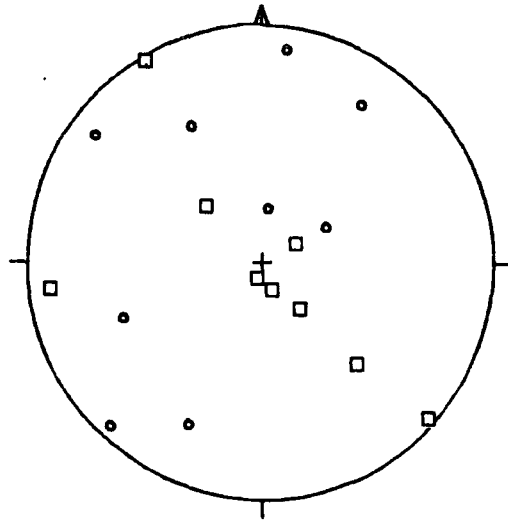


Figure 3.13: Magnetic fabric of samples ABC 71-79 from context 2313.

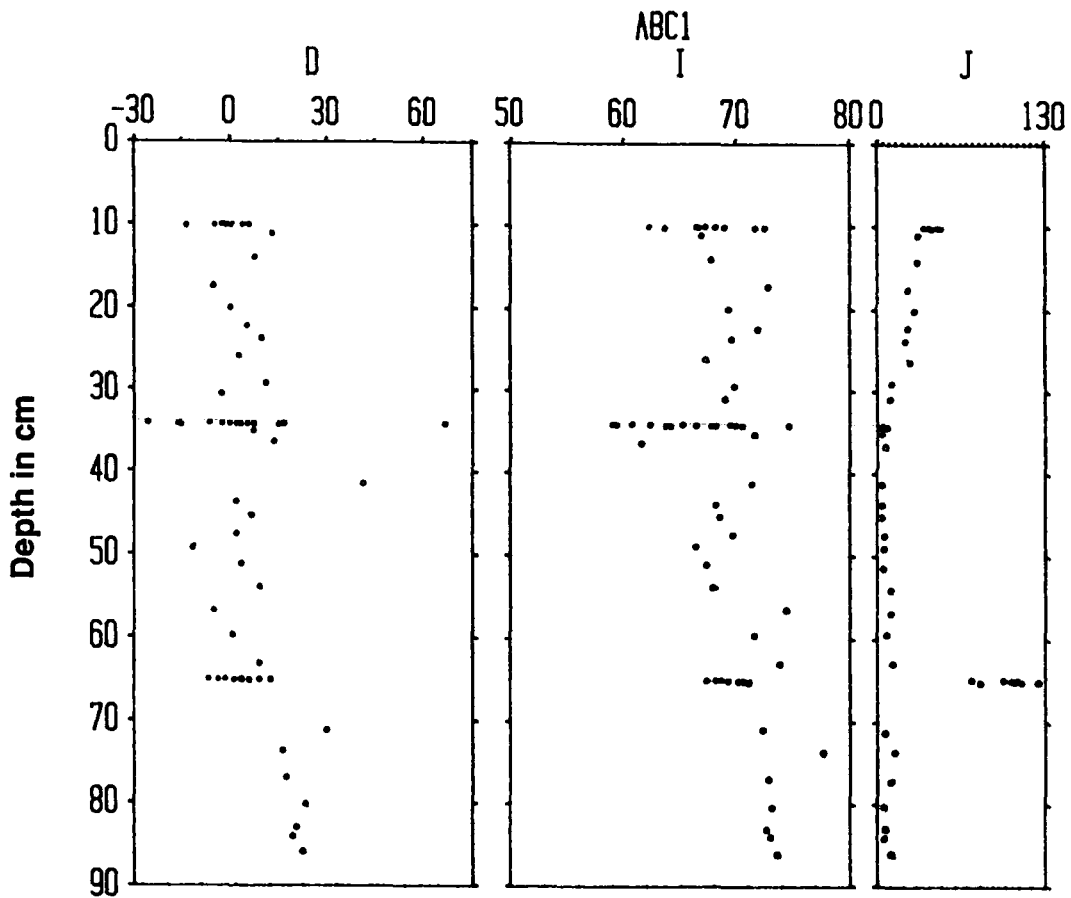


Figure 3.14: Plot of depth against declination (D) after demagnetisation (in degrees), inclination (I) after demagnetisation (in degrees) and intensity (J) ($\mu\text{Am}^2\text{kg}^{-1}$), from a vertical section through contexts 2307, 2311 and 2313. The plot also includes the results from the repeat horizons within each context.

Results of magnetic measurements: the vertical section

Natural remanent magnetisation

The intensity of NRM of samples at the top of the section was around $30\mu\text{Am}^2\text{kg}^{-1}$, comparable with that of ABC45-56, as anticipated (Fig. 3.14). The intensity decreased down the section to reach approximately $10\mu\text{Am}^2\text{kg}^{-1}$, at the boundary between contexts 2307 and 2311 at 35cm and remained largely unchanged until context 2313 at 65cm where it increased briefly to a range of intensities between 10.9 and $31.1\mu\text{Am}^2\text{kg}^{-1}$. The sudden increase in intensity implied a change in the magnetic mineralogy of the sediment. The directions were all very well grouped, falling within the α_{95} values of the magnetic directions of the horizontal groups of samples whose behaviour is described above. The directions showed little systematic change with depth, although no quantitative tests of trends were attempted because of the difficulties in their implementation, as discussed in Section 2.5.3.

Demagnetisation

Pilot samples from within each context were demagnetised and found to behave in a similar way to those taken from the horizontal sections within the same context. The remainder were demagnetised at a peak alternating field of 7.5mT which resulted in little change to declination or inclination values. It is interesting to note that at the bottom of the section, from 70cm to 87cm, both declination and inclination appeared to increase, but there were too few samples to draw definitive conclusions given the limitations of quantitative tests (Section 2.5.3).

General conclusions

The magnetic studies for contexts 2307, 2311 and 2313 indicated that the material in all three contexts retained a stable remanence, with a slight viscous overprint. The stable remanence appeared to be depositional or post-depositional in origin. The magnetic fabric was generally weak, in some cases too weak to be measured. Where it was measurable, the distribution of the principal axes was characteristic of a primary depositional fabric, with no clear indications of the direction of any current flow acting at the time of deposition. Thus, the magnetic fabric results suggested that deposition took place in slow moving or static water conditions, which is supported by the small grain size of the materials. IRM tests indicated that the remanence was primarily carried by a soft magnetic mineral, almost certainly magnetite. In context 2307 the magnetite appeared to be in the form of large, single domain grains and in context 2313 there was a small contribution to the remanence by a harder magnetic mineral, probably haematite or goethite.

The mean magnetic directions and their associated α_{95} values for each of the three contexts were converted to Meriden (Section 5.5) and compared with the calibration curve (Table 1C; Fig. 3.15) Thus, by visual inspection, context 2307 was dated to between AD50 and AD150, context 2311 to AD40-AD180 and context 2313 dated to AD20-AD100 (all at a 95% level of confidence). These dates corresponded well with the dates obtained from a study of the pottery types (see above). However, as discussed in Section 2.5.3, there are a number of inadequacies in this dating procedure and the dates obtained are reconsidered in Section 5.6.4 in the light of developments of the calibration curve in Chapter 5. No deductions could be made concerning rates of deposition, as there is no evidence to indicate whether deposition was at a constant or varying rate or even whether it had been interrupted. If the variation in magnetic direction indicated by the magnetic measurements from the bottom 20cm of the sediment section was reliable, it would appear that context 2313 was deposited over a period of time from around 500BC to around AD100, possibly at a much slower rate, but there were insufficient samples to draw any firm conclusions (Section 2.5.3). All the magnetic measurements provided results consistent with sediment being river-deposited in the early Roman period, possibly in the course of the River Foss, a tributary to it, or its floodplain.

Description of the deposits sampled in trench 4

Trench 4 measured 2.8m x 2.6 m and was situated in the south-east area of the site, nearest to the present day River Foss (Fig. 3.3). The upper deposits were contaminated by oil and were removed mechanically, but continued oil seepage made it difficult to distinguish contexts at lower levels. 5m of deposits were excavated, from the modern cinema foundations, through layers containing material from late Medieval to Roman periods, down to the lower levels which were considered to be river sediments.

Context No. 4006: This context was situated above a series of build up or dump deposits and under the area removed mechanically. It consisted of a moist, compact, medium brown (Munsell No. 10YR 4/3) silty clay, with occasional horizontal lenses of organic material and darker brown (Munsell No. 10YR 3/3) silt (Fig. 3.16). The deposit extended over the whole of the trench with a uniform thickness of approximately 1m. There was a large quantity of well preserved wood in the matrix (approximately 10% by volume) and small inclusions of bone, oyster shell, tile and pot fragments. No bioturbation was visible.

Samples were taken by the tube method from a baulk of material in the north-west corner of the trench. 9 samples were taken from a shelf cut at the top and a further

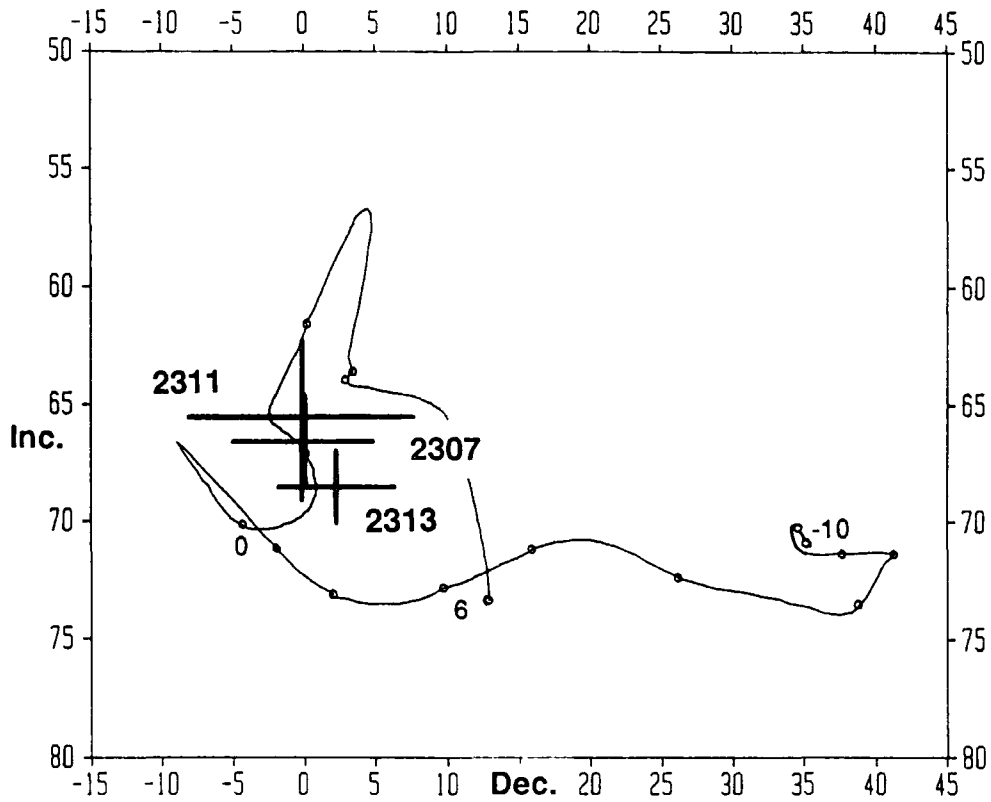


Figure 3.15: Mean magnetic directions after demagnetisation from contexts 2307, 2311 and 2313 with errors at 95% confidence, corrected to Meriden and fitted to the British calibration curve covering 1000BC-AD600. The calibration curve was digitised from that of Clark *et al.* (1988); declination (Dec) and inclination (Inc) are both in degrees, circles indicate centuries and the figures along the curve are 100's of years.

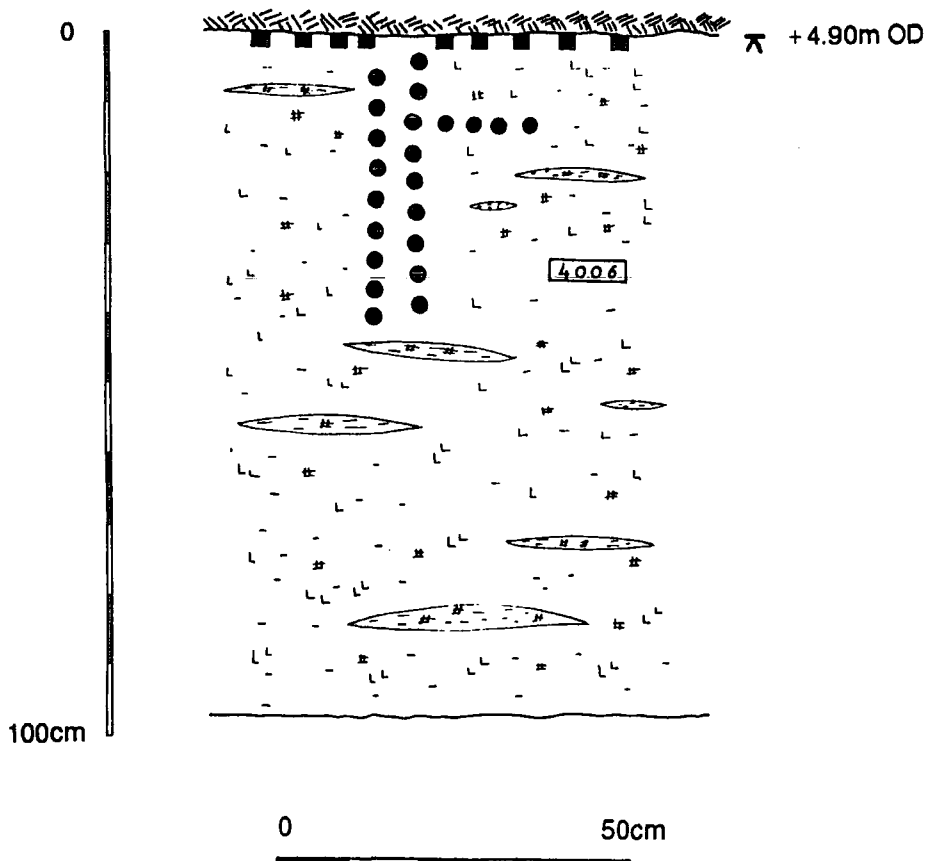


Figure 3.16: Vertical section drawing of ABC Cinema context 4006 showing sample locations.

22 from a vertical section down the baulk (Fig. 3.16). Orientation was carried out by transferring a site line with a theodolite; steel shoring and lack of sun made other methods inoperable.

Archaeological interpretation of the deposits in trench 4

Trench 4 appeared to contain a number of build-up or dump deposits of varied composition, including flood-derived detritus and vegetational growth, suggesting that the area was possibly in the flood-plain or in shallow, slow-moving water (Finlayson & Pearson, 1988). Context 4006 was dated to 11th or 12th century AD on the basis of its pottery, which is consistent with the deposit being associated with the King's Fishpool (see above).

Results of magnetic measurements: Context 4006

Natural remanent magnetisation

The NRM intensity of samples ABC1-31 fell in the range 1.0-10.8 $\mu\text{Am}^2\text{kg}^{-1}$, generally lower than the other samples examined from the A.B.C. Cinema site, but still measurable above the noise level of the magnetometer. The directions of magnetisation were widely dispersed (Fig. 3.17), with the 9 samples taken from the same horizon having an α_{95} of 9.0°.

Demagnetisation

The 8 samples with the highest intensity of magnetisation were demagnetised and their behaviour varied greatly from sample to sample. For example, ABC17 (Fig. 3.18) had a soft magnetisation, with a median destructive field of 15mT and only 6% of the magnetisation remaining after demagnetisation in a field of 40mT. The Zijderveld plot showed at least two components of magnetisation and did not appear to indicate a stable vector. Other samples showed a variety of demagnetisation behaviour, some having a number of different components of magnetisation and others appearing to behave in a random fashion. The remaining samples were demagnetised in a field of 15mT, in an attempt to see if grouping was improved by the removal of lower stability components, but this was not the case and dispersion within the repeat horizon increased to $\alpha_{95}=11.7^\circ$, with accompanying changes in declination and inclination (Fig. 3.17).

Magnetic fabric

Specific susceptibility was in the range 3.8-31.4 $\times 10^{-8}\text{m}^3\text{kg}^{-1}$, showing a general increase down the section (Fig. 3.17). The strength of the magnetic fabric of the samples

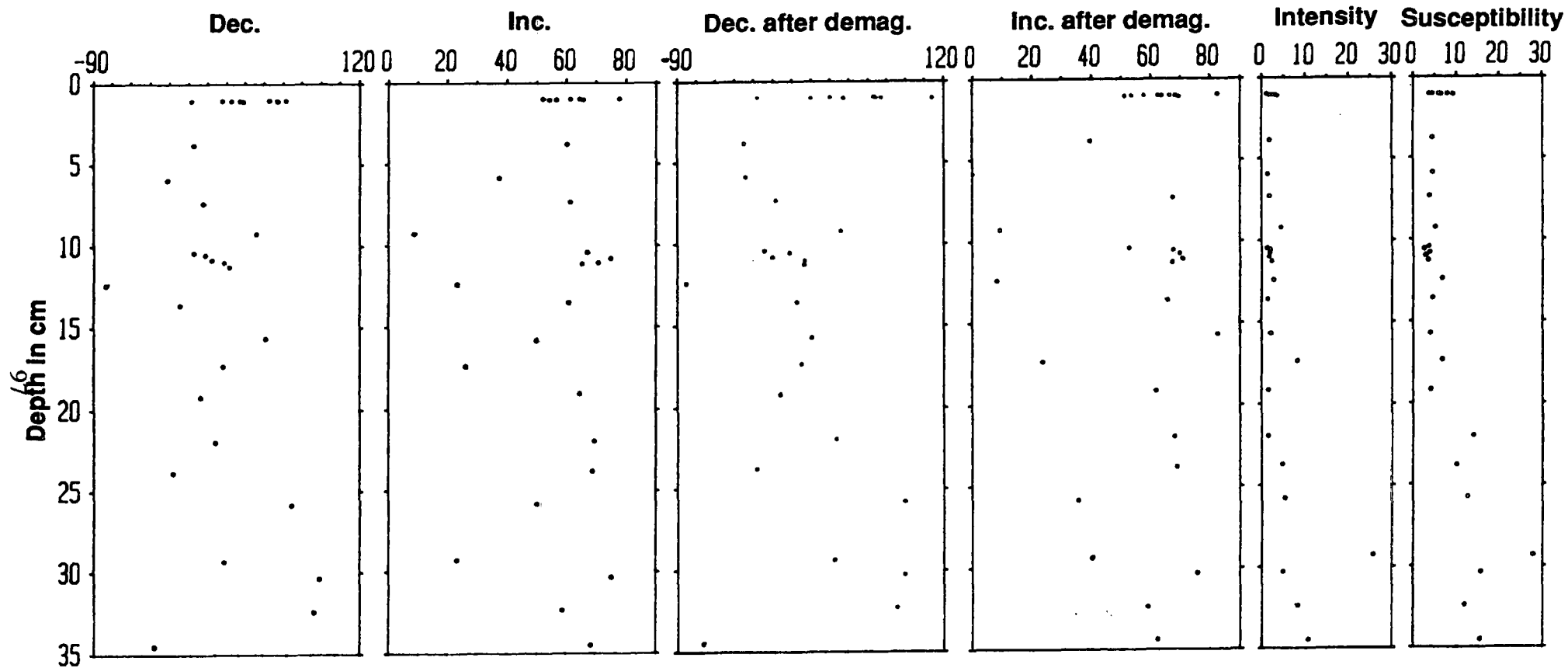


Figure 3.17: Plot of depth against NRM declination (Dec.), NRM inclination (Inc.), declination after demagnetisation, inclination after demagnetisation (all in degrees) and intensity (in $\mu\text{Am}^2\text{kg}^{-1}$) and susceptibility ($\times 10^{-8}\text{m}^3\text{kg}^{-1}$) from horizontal and vertical sections within context 4006.

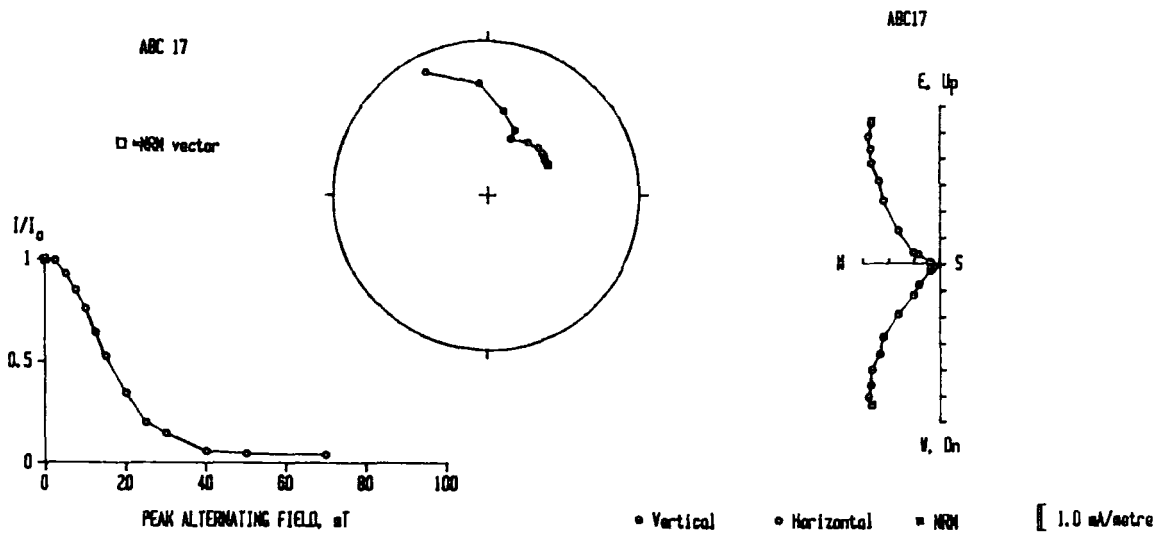


Figure 3.18 Stereographic, intensity and Zijdeveld plots of the behaviour of sample ABC 17 from context 4006 on alternating field demagnetisation.

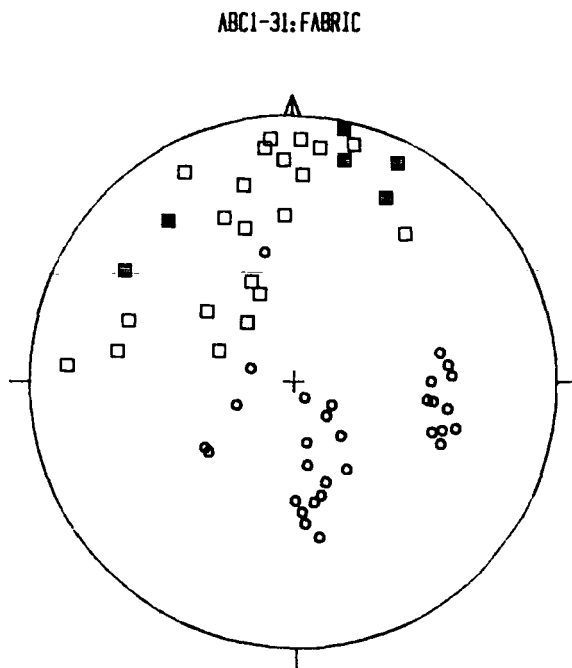


Figure 3.19: Magnetic fabric of samples ABC 1-31 from context 4006.

covered a much wider range than samples from the other A.B.C. Cinema contexts, including some extremely high values, with $h\%$ in the range 3.0-23.1%. The q values were between 0.05 and 1.4, with 26% falling outside of the range expected for an undisturbed depositional fabric. Both maximum and minimum axes of susceptibility appeared scattered (Fig. 3.19), but it was possible that the groups of maximum and minimum axes were displaced to the south-east, a phenomenon associated with deposition of a sediment on a slope (Rees, 1966), although the axes were too scattered to be convincing.

Magnetic mineralogy

Samples also showed a variety of behaviour in IRM acquisition tests, but the SIRM and S value were generally lower than those encountered for the other A.B.C. Cinema sediments (Table 1B), suggesting that magnetite was not the only magnetic mineral contributing to the remanence.

General conclusions

The archaeomagnetic investigation of context 4006 suggested that magnetic grains capable of carrying a remanence did exist in the matrix, but that they had either not been aligned during or after deposition or that their alignment had been subsequently disturbed. The wide variety of behaviour on demagnetisation and IRM experiments indicated that the magnetic minerals within the sediment were a variety of sizes and composition and that their distribution varied from sample to sample. The magnetic fabric appeared to show that the sediment might have been deposited on a slope, but the scatter of the principal axes made it difficult to draw firm conclusions. No slope was visible on excavation but sedimentary structures were difficult to discern, given the limited area under excavation. The archaeomagnetic results were consistent with post-depositional disturbance of the sediment, which might suggest that it had been deposited in shallow water or on the flood-plain and therefore subject to bioturbation. Unfortunately, such a disturbance of the sediment meant that the context could not be dated by archaeomagnetic methods. Dissection of the samples revealed a high content of organic material and no ceramic fragments or small stones.

3.4.2 Stakis Hotel Excavations, Wellington Row, York (O.S. Grid Ref. SE 6030 5183)

Site description

Excavations were carried out by York Archaeological Trust on the site formerly occupied by Leedham's Garage and the Armstrong Oiler factory on the south-west bank of the River Ouse (Fig. 3.2) between May 1988 and August 1989. The area was to be developed as a hotel by Stakis Land and Estates and had been the scene of small scale trial excavations in 1987 (Frere, 1988; Ottaway, 1987). Situated less than 20m from the present course of the River Ouse and within the Roman Colonia area of York (Section 3.4.1; Ottaway, 1984), it was hoped that the site would provide information on the Roman and Medieval town and possibly locate the Roman road running from York to the south-west.

A number of narrow trenches were excavated (Fig. 3.20); trenches 5 and 6 transected the site, running at right angles to the river, in an attempt to uncover the early waterfront and trench 4 was located across the course suggested for the Roman road by earlier excavations (Ottaway, 1984). Interpretation of the deposits from narrow trenches is often difficult and so a large area excavation (trench 7) was also undertaken at the south-east end of the site. This trench measured 21x15m and was the largest single trench excavated by York Archaeological Trust on the south-west bank of the Ouse, exploiting excavation opportunities that are unlikely to arise again in the foreseeable future. As always in rescue excavations, little time was available and so the upper 1.5m of deposits were removed mechanically and excavations commenced with the 12th and 13th century AD horizons. Even so, the deposits were so deep that material undisturbed by human activity was only reached on parts of the site (Ottaway, 1988)

Description of the deposits sampled in trench 4

Trench 4 was positioned at the south-east end of the site (Fig. 3.20) with the aim of locating the Roman road as it passed through the civilian town and crossed the river, probably by a bridge, into the legionary fortress on the north-east bank. The most recent levels had been removed by the construction of a Victorian cellar but further excavations revealed a road surface of crushed limestone and pebbles with a row of large limestone blocks running along its south-eastern side. Under this were a series of remetallings, situated on a substantial mound of large cobbles, up to 0.6m thick. Deeper excavations revealed a silt layer covering the whole trench and sealing what appeared to be an earlier

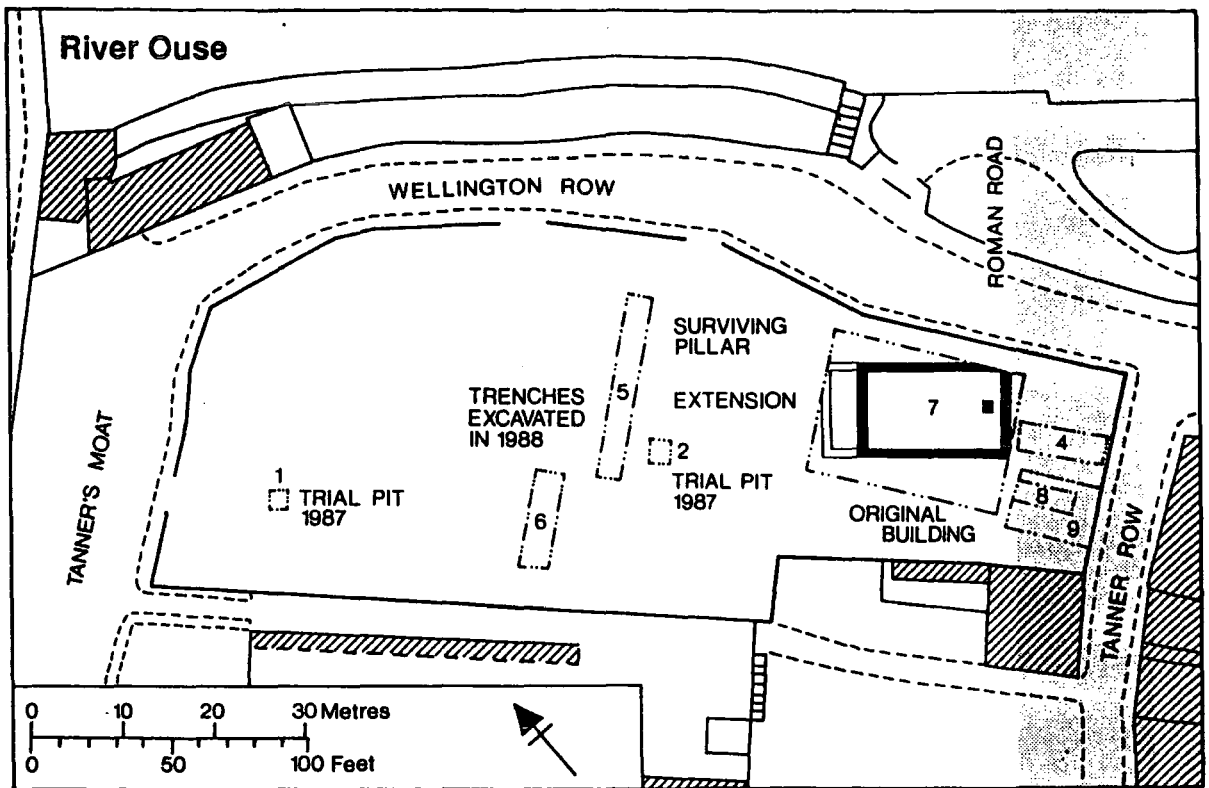


Figure 3.20: Plan of Stakis Hotel site showing all trenches excavated in 1987, 1988 and 1989 (provided by York Archaeological Trust).

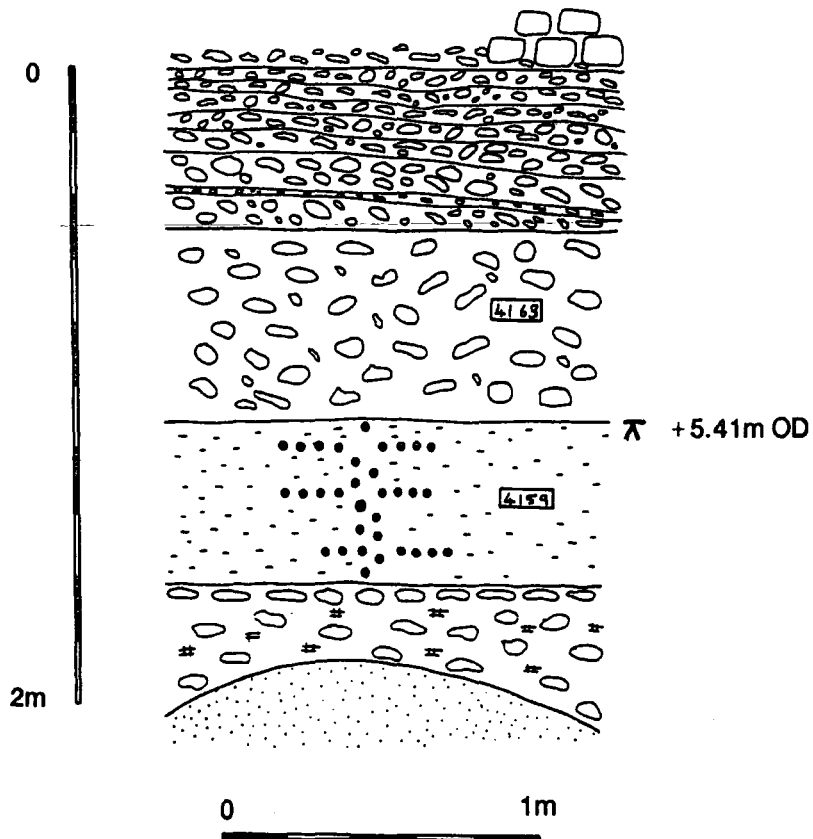


Figure 3.21: Section drawing through the road trench (trench 4), showing location of samples.



road consisting of layers of brushwood and cobbles, overlain with rough cobbles and built up with sandy material to give a camber (Fig. 3.21; Ottaway, 1988).

Context No. 4159: This context consisted the grey brown (Munsell No. 10YR 5/2) silt situated under the mound of large cobbles (Context no. 4163) and over a gravel road surface (Fig. 3.21). The silt was 0.5m thick and extended over the whole trench in an approximately horizontal layer, with very sharp contacts between it and the horizons above and below. It was wet, plastic and a uniform colour, with some lighter sandy brown patches, but no clear evidence of structures arising from deposition or compaction by the road above. There were no archaeological finds from the context.

Samples were taken by the tube method from a sump cut into the silt on the north-west side of the road and were collected in three horizontal groups and a vertical section (Fig. 3.21).

Archaeological interpretation of deposits in trench 4

It seems clear that the lower deposits in trench 4, 4m thick in all, represented various stages in the construction of the Roman road. This commenced with a raft of brushwood and cobbles to create a stable foundation on marshy ground and was followed by various episodes of resurfacing (Frere, 1990; Ottaway, 1988). Of particular interest in this study was the silt layer, which was interpreted as being the result of sediment from river flooding covering the road. The response to this seems to have been to construct a mound of cobbles on which subsequent road surfaces were built. Pottery found in the lower road surfaces, under the silt layer, consisted of a few sherds of Ebor ware, a red earthenware often found with the earliest Roman pottery assemblages in York (P. Ottaway, pers. comm.). This suggested that the earliest road dated from late 1st century AD, possibly contemporaneous with the founding of the legionary fortress in AD71 (Royal Commission on Historical Monuments, 1962 p6). Pottery in the cobbled layer, overlying the silt, suggested a late 1st or early 2nd century AD date for this horizon and the pottery associated with the crushed limestone uppermost surface was late 2nd century AD. It is interesting to note that this final surface is of magnesian limestone from the Tadcaster area, rather than the shelly oolitic limestone common in the buildings of the Roman town. Magnesian limestone was extensively used in the Roman fortress and it has been suggested that the quarry may have been under army control, indicating a military involvement in the building of the road (Ottaway, 1988). The streets and buildings excavated elsewhere in the civilian settlement in York, for example General Accident, Tanner Row (Pearson, 1983, 1984a & 1984b) and 5 Rougier Street (Ottaway, 1981 & 1982) appear to follow a rectilinear layout, aligned with the Roman road.

Excavations in trenches 5 and 6 reached Roman levels without finding evidence of the waterfront itself, but did locate a rubble and cobble surface at the riverward end. This may have been a riverside road or hardstanding and dated to the late 2nd century AD. A succession of later Roman roads and buildings were also located further from the river. Trench 7 revealed a late 2nd century AD stone structure, aligned with the road and still standing up to 2m high in places. Evidence of considerable internal alterations and fire damage were found and a complex history of use, possibly including a religious function, has been postulated (Ottaway, 1988).

Results of magnetic measurements: Context 4159

Natural remanent magnetisation

The intensity of NRM of samples SK1-33 were in the range 4.1–43.5 $\mu\text{Am}^2\text{kg}^{-1}$, comparable with the intensity of magnetisation of the A.B.C. Cinema samples (Section 3.4.1). The directions of magnetisation were very well grouped and the horizontal groups were indistinguishable from each other (Fig. 3.22a), so an α_{95} value of 1.5^o was calculated, based on all 33 samples.

Demagnetisation

5 samples were subjected to stepwise alternating field demagnetisation (Fig. 3.23). The Zijderveld plot and stereographic projection appeared to show that the remanence might consist of two stable components. The first was close to the NRM direction and the second was a small, hard component, revealed by the movement of the vector along a great circle path as demagnetisation proceeded, but which was not demagnetised completely, even in fields of 100mT. It seemed likely that the harder component was a later, possibly chemical, overprint and so the first component revealed was taken to be the one associated with deposition. It had a stability index of 5.3 (very stable) over the range 5–20mT. The intensity plot revealed the magnetisation to be fairly hard, with over 10% of the original magnetisation remaining after demagnetisation at 60mT and a median destructive field of around 30mT.

As the material was homogeneous and the pilot samples showed virtually identical behaviour on demagnetisation, the remaining samples were demagnetised in a field of 7.5mT to remove any soft viscous components. The magnetic directions of the samples were indistinguishable both along the horizons and down the section, so they were combined to give an α_{95} of 1.3^o, based on all the samples (Fig. 3.22b).

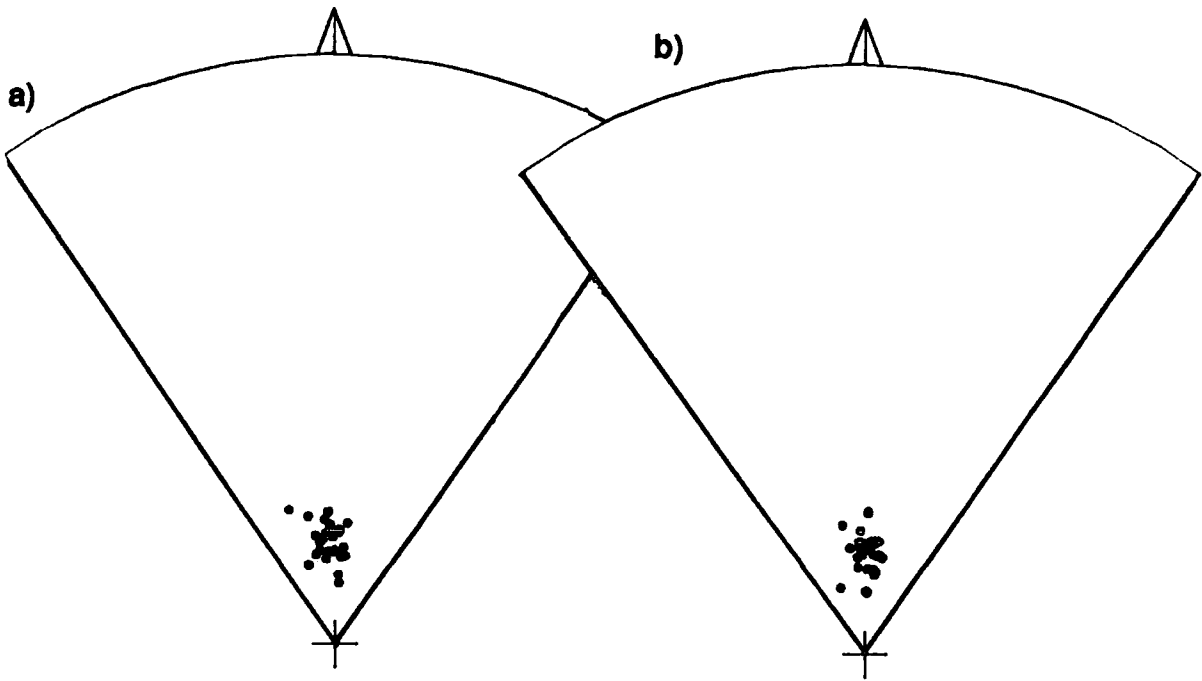


Figure 3.22: Stereographic plot of the directions of magnetisation of samples SK1-33 from context 4159 *a)* NRM values and *b)* after partial demagnetisation.

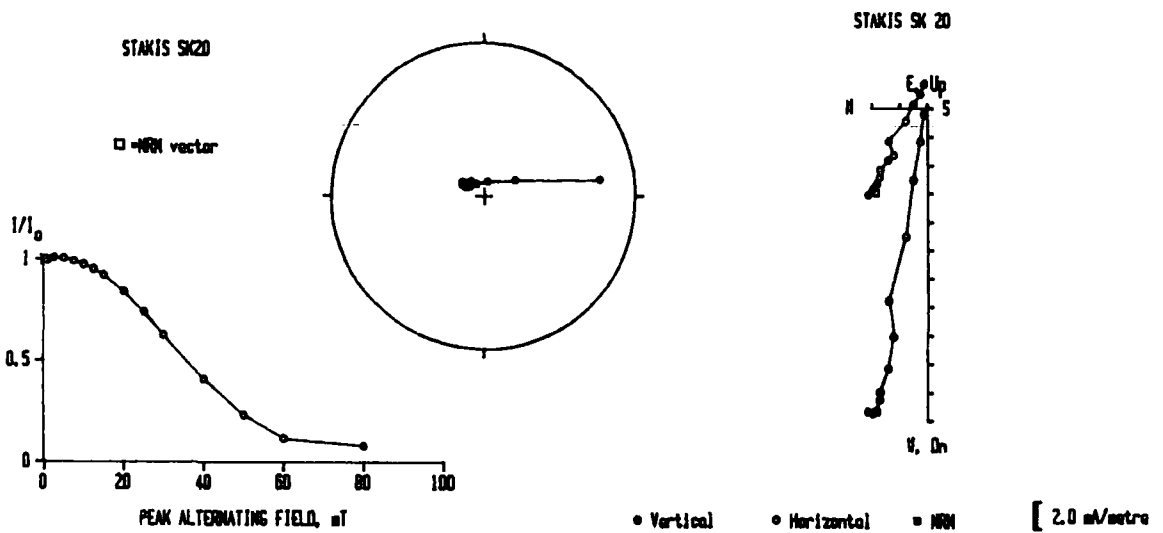


Figure 3.23: Stereographic, intensity and Zijderveld plots of the behaviour of a typical sample (SK 20) from context 4159 on alternating field demagnetisation.

Magnetic fabric

The specific susceptibility fell between 6.5 and $44.5 \times 10^{-8} \text{m}^3 \text{kg}^{-1}$ and the magnetic fabric was generally very weak, with $h\%$ in the range 0.8-3.0%. The q values ranged from 0.03 to 0.81, with 76% falling in the range characteristic of an undisturbed depositional fabric. The maximum axes were clustered (Fig. 3.24a), defining a magnetic lineation and the minimum axes were also closely grouped but at unusually shallow inclinations. The inclinations were much shallower than those observed in sediments under various conditions of fluid stress or slumping (Section 2.3.2.). Repeated measurements revealed little change in the distribution of axes and the position of the minimum axes was not consistent with any instrumentation error or with the fabric that might arise from grain rotation on sampling. It was possible that localised, post-depositional compaction of the material may have produced such a fabric, although there is no record of this in the available literature. Another possibility was that the fabric was dominated by the magnetisation of minerals that had formed post-depositionally. A further possibility was that the material had acquired its DRM from flowing or being squeezed over the road surface, leading to the unusual magnetic fabric. In order to draw detailed conclusions, more information would be necessary from reconstruction experiments of deposition on cobbled surfaces and from anisotropy of remanence experiments.

On the assumption that the alignment of the maximum axes was due to fluid stress and that the remanence had been acquired on deposition, the flow correction of Noel and Rudnicki (1988), outlined in Section 2.3.2, was applied to the Stakis Hotel results (Fig. 3.24b). This indicated a mean palaeoflow in the direction 17.7° north east, roughly at right-angles to, and towards, the Ouse. However, this conclusion must be treated with caution, given the uncertainties about the mode of deposition raised by the unusual magnetic fabric.

Magnetic mineralogy

IRM acquisition tests were carried out on two samples which showed similar behaviour (e.g. Fig. 3.8a), with 98% of the SIRM being attained in a field of 1T. $(B_0)_{cr}$ was 30-35mT (Fig. 3.8b), rather higher than the value for other sediments, indicating a smaller magnetic remanence carrier grain size or a contribution from a harder magnetic mineral. The S ratio of 0.92 indicated that whilst the predominant remanence carrying mineral was probably magnetite, there was a contribution from a harder magnetic mineral, possibly haematite or goethite. This might correspond to the small, hard component visible on demagnetisation in the higher fields.

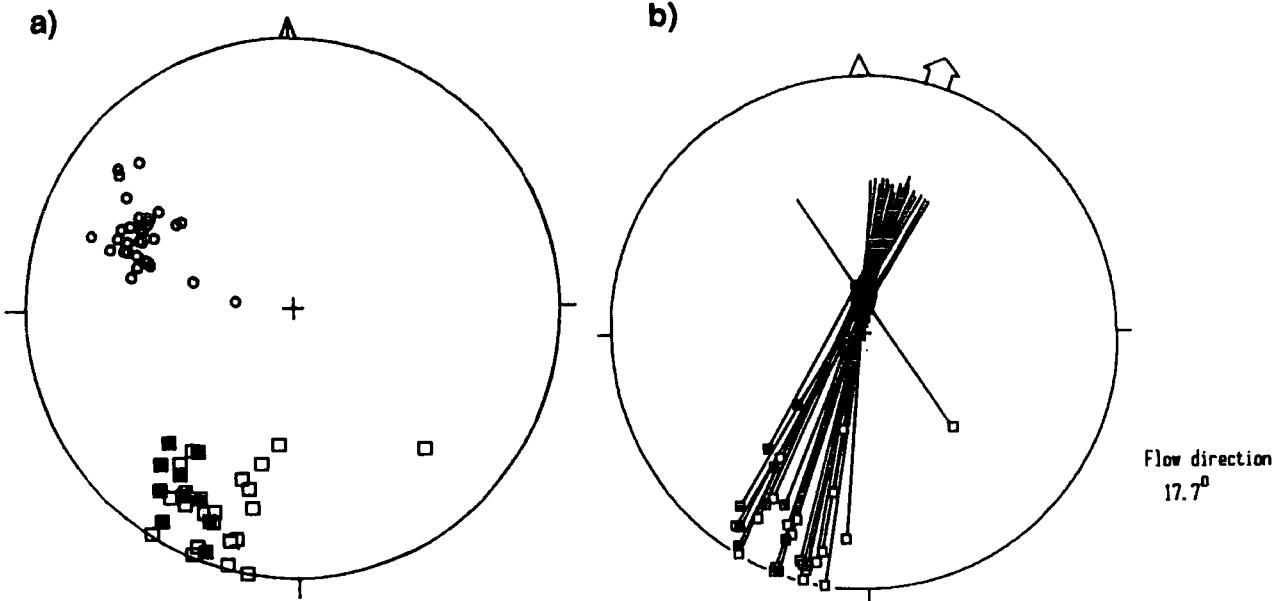


Figure 3.24 a: Magnetic fabric of samples SK 1-33 from context 4159.
 b: Determination of flow direction from magnetic fabric and NRM of samples SK 1-33 from context 4159. Arrow indicates mean flow direction.

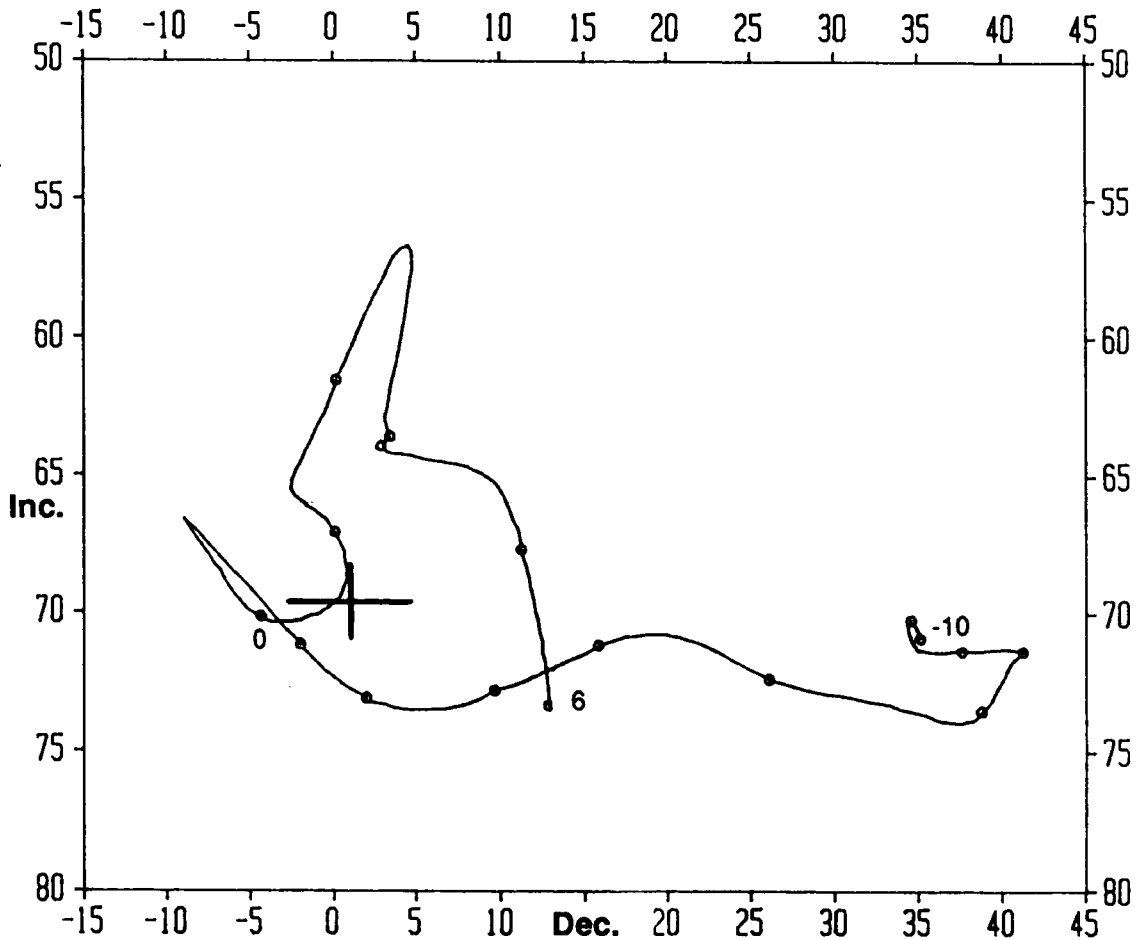


Figure 3.25: Mean magnetic directions after demagnetisation from context 4159 with errors at 95% confidence, corrected to Meriden and fitted to the British calibration curve covering 1000BC-AD600. The calibration curve was digitised from that of Clark *et al.* (1988); declination (Dec) and inclination (Inc) are in degrees, circles indicate centuries and the figures along the curve are 100's of years.

General conclusions

When the mean magnetic direction after demagnetisation and its associated α_{95} value, based on all 33 samples, were converted to Meriden and compared with the calibration curve (Fig. 3.25), a date in the range AD20 to AD80 was obtained (at a 95% level of confidence) by visual inspection. This date range was consistent with the archaeological evidence, which indicated that a date before AD71 was unlikely. However, as discussed in Section 2.5.3, there are a number of inadequacies in this dating procedure and the date obtained is reconsidered in Section 5.6.4 in the light of developments of the calibration curve in Chapter 5. The fact that such a small α_{95} value was obtained when considering samples from the whole of the deposit suggested that the silt unit making up context 4159 had all been deposited within the 60 year span, but of course it might have been laid down much more quickly, even in a single flood event. Magnetic fabric results were difficult to interpret and further work would be required before firm conclusions could be drawn. However, if it is assumed that the fabric is depositional in origin, (an assumption which is open to question) the maximum axes of susceptibility appeared to show a lineation which would be consistent with deposition occurring when the mean flow was back into the Ouse after flooding, a scenario which would be consistent with the small grain size of the material. The remanence would appear to be carried in magnetite grains, with a small but stable contribution from haematite, or another harder magnetic mineral such as goethite, becoming evident on demagnetisation in high fields and in IRM tests, perhaps indicating post-depositional chemical changes in the sediment.

3.4.3 Modern flood deposits, Bluebridge Lane, York

(O.S. Grid Ref. SE 607 510)

Site description

Flooding is a common occurrence in spring in York (Radley & Simms, 1971) and March 1991 was no exception. A combination of melting snow and heavy rain caused the Ouse to rise 16ft above its normal level and flood over the riverbanks and adjacent properties. Both the Ouse and the Foss were turbulent and fast-flowing, carrying a large quantity of sediment which was deposited on the flood-plain, as the waters receded. In many areas, particularly those that were paved, the flood-deposited silt was soon washed back into the river by further rain or was hosed away by council workmen, but some deposits remained undisturbed in sediment traps. An investigation of the riverbanks revealed a number of such environments and two were selected for sampling, in order to compare the archaeomagnetic properties of such sediments with their archaeological equivalents.

The sites chosen were situated approximately 10m downstream of the confluence the Rivers Foss and Ouse (+4.8m OD), in a grassy area close to the riverbank (Fig. 3.2). A number of riverside benches had been erected on the east bank, but flood deposited sediments had raised the ground level and the benches were situated in hollows where previous sediments had been dug out. These hollows provided an ideal depositional environment, where water had been trapped as the river level fell. Excavation of these sediments revealed that they overlay a horizon of leaves, under which were a number of ice-cream and sweet wrappers on a gravel surface. These observations would be consistent with the upper deposit being the result of that spring's flooding. The two sediment traps which appeared deepest and least disturbed were selected and samples taken from a cleaned upper surface by pushing tubes vertically into the sediment.

Description of the deposits sampled

Samples YMA1-9 were taken from context 1, the sediment trap at the bench closest to the river and samples YMA11-21 were from context 2, further from the river (Fig. 3.26).

Context No. 1: This context consisted of a dark yellowish brown (Munsell No. 10YR 4/4) fine sand, filling the depression in front of the bench to a maximum depth of 7cm. It had a lateral extent of about 2x0.5m and overlay a layer of fallen leaves and rubbish. The

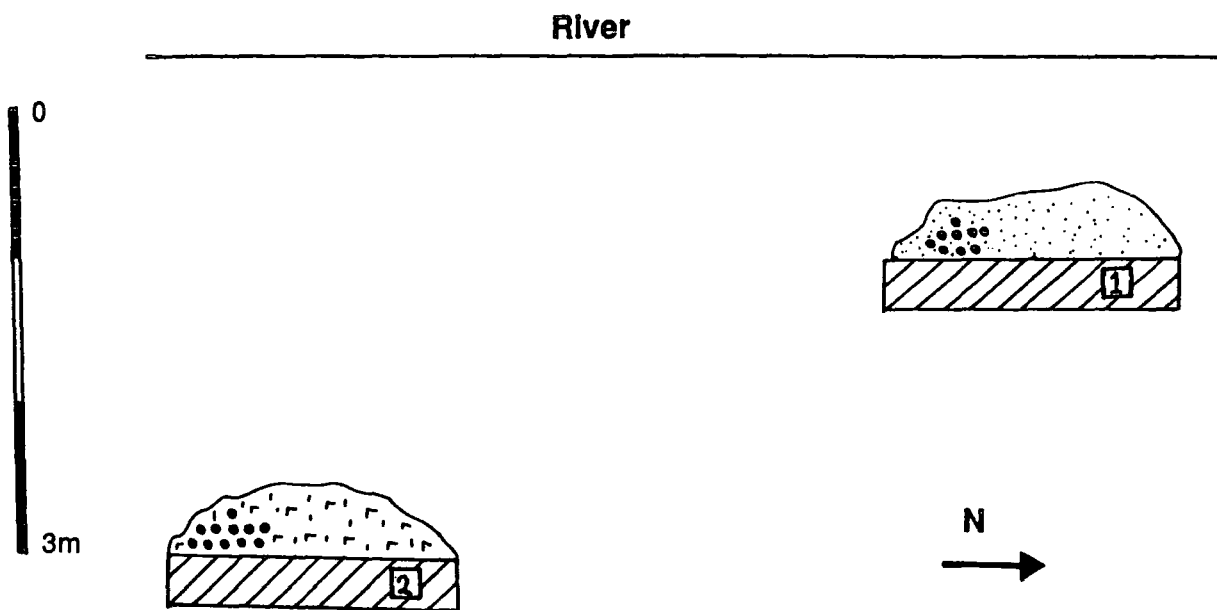


Figure 3.26: A plan view of the modern analogue environment at Bluebridge Lane, showing the location of samples.

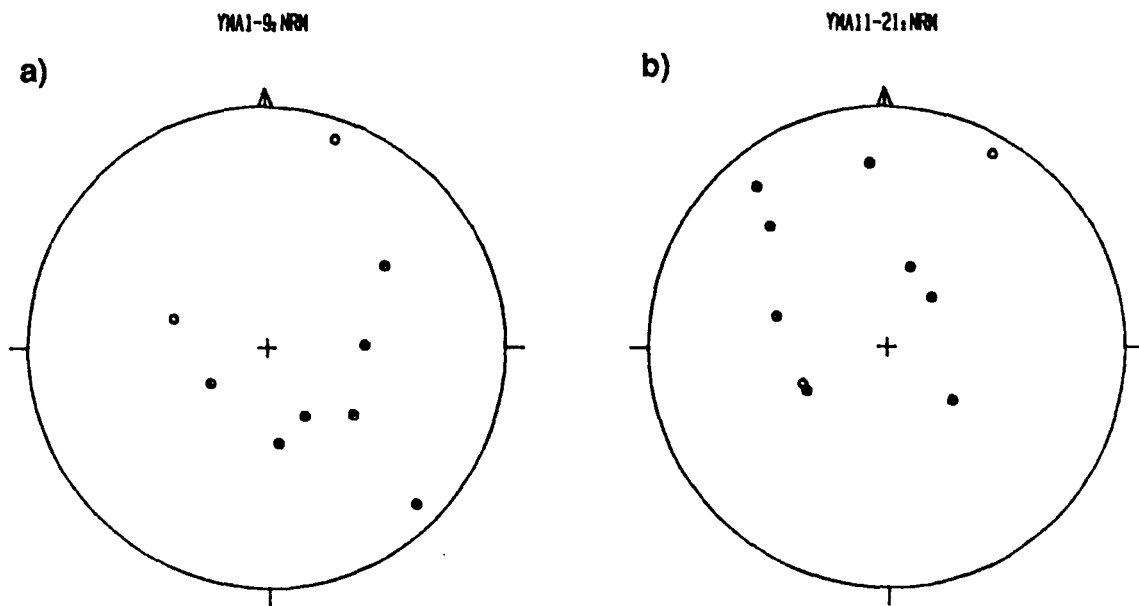


Figure 3.27: Stereographic plot of the directions of magnetisation of a) samples YMA from context 1 and b) samples YMA 11-21 from context 2.

material of the deposit was a very soft, wet, well-sorted, fine sand with occasional mottling of silty clay. The only inclusions were strands of organic material and there was no evidence of bioturbation.

Context No. 2: This deposit also covered an area of approximately 2m x 0.5m, with a maximum depth of 7cm. It was a wet, very dark brown (Munsell No. 10YR 2/2) silty clay, with occasional mottling of slightly siltier material. There were a few strands of organic matter in the matrix and the surface was pitted by rain. There was some evidence of disturbance by worms.

Both the deposits were soft and therefore easily sampled by the tube method, which created little visible disturbance to the sediment surface. Orientation was carried out using a magnetic compass.

Interpretation of deposits

A number of factors suggested that the deposits were the result of recent flooding of the River Ouse. They appeared very similar to the deposits left by the recent floods in York, the hollows were close to the river, the deposits were undisturbed although in a popular area for walking and the sediments were underlain by autumn leaves.

Results of magnetic measurements: Context 1

Natural remanent magnetisation

The NRM intensity of samples YMA 1-9 fell in the range 0.9-6.9 $\mu\text{Am}^2\text{kg}^{-1}$ and the directions were very dispersed, with two even having negative inclinations (Fig. 3.27a). The α_{95} value was 59.5°.

Demagnetisation

3 of the 9 samples were demagnetised and the behaviour of one of the samples with a negative inclination is shown (Fig. 3.28). The magnetic vector was shown to comprise of at least three components, the last of which (isolated in fields over 40mT) was normal in direction. The intensity fell smoothly in increasing applied fields, until demagnetising fields of 50mT were reached, when it began to rise slightly. The intensity reduced to less than 13% of the original value after demagnetisation in fields of 50mT and the median destructive field was 25mT.

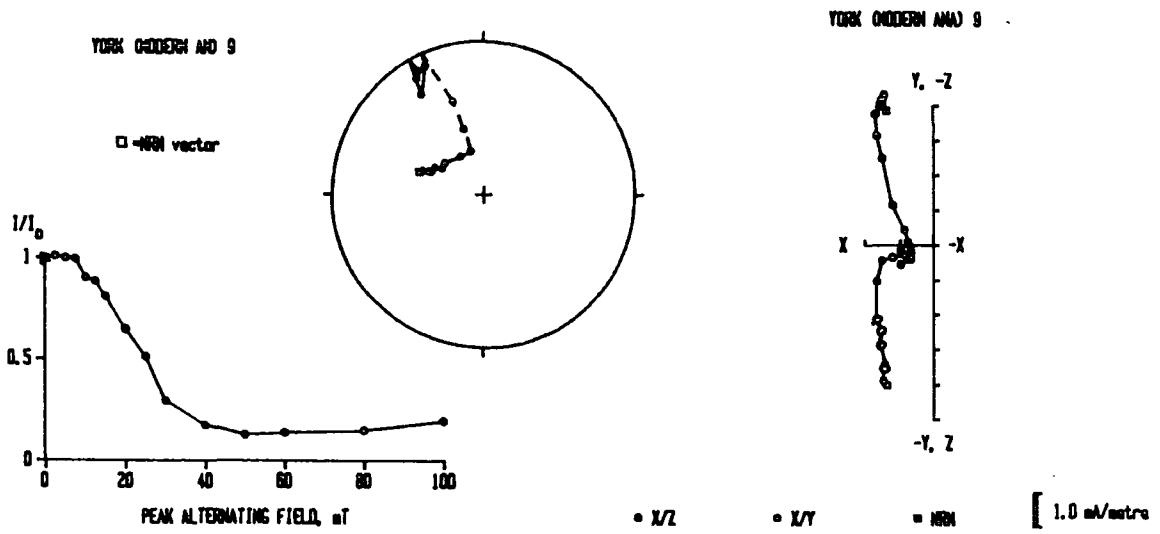


Figure 3.28: Stereographic, intensity and Zijdeveld plots of the behaviour of sample YMA 9 from context 1 on alternating field demagnetisation.

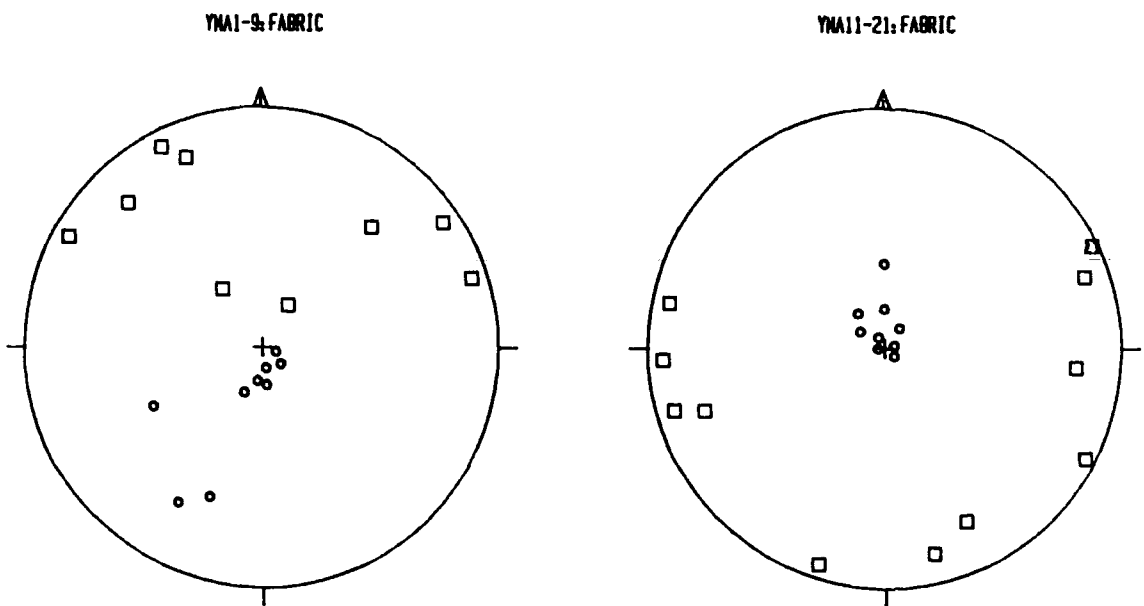


Figure 3.29 (left): Magnetic fabric of samples YMA 1-9 from context 1.

Figure 3.30 (right): Magnetic fabric of samples YMA 11-21 from context 2.

Although the sediment appeared homogeneous, the pilot demagnetisations all showed different behaviour, none of them isolating a stable component of magnetisation.

Magnetic fabric

Specific susceptibility was in the range $7.7\text{--}8.8 \times 10^{-8} \text{m}^3 \text{kg}^{-1}$ and the magnetic fabric was found to be fairly strong, with $h\%$ in the range 2.3–6.8%. q values fell in the range 0.17–0.73, 78% of them in the range characteristic of an undisturbed depositional fabric. The minimum axes were slightly scattered, but most appeared to be consistent with a magnetic foliation (Fig. 3.29), whereas the maximum axes were widely scattered, with no clear lineation. The lack of lineation suggested that the magnetic grains had not been aligned at the time of deposition by water currents, the geomagnetic field or grain interactions, or that the magnetic fabric had been disturbed subsequently.

Magnetic mineralogy

Application of pulse fields of increasing intensity to sample YMA7, which had a normal NRM, resulted in a rapid increase of induced IRM, followed by a very small further increase at higher fields (Fig. 3.8a). However, the SIRM value was $0.92 \text{mAm}^2 \text{kg}^{-1}$, much lower than that for the other York sediments, and 96% of this value was reached in an applied field of 1T. $(B_0)_{\text{CR}}$ was 22mT (Fig. 3.8b) and the S ratio was 0.77. The S ratio was much lower than the other York sediments, suggesting that, while the magnetic mineral carrying the remanence was predominantly magnetite, there was a larger contribution from a harder magnetic mineral, probably haematite or goethite, than had previously been the case.

Results of magnetic measurements: Context 2

Natural remanent magnetisation

The intensity of NRM of samples YMA 11–21 were in the wide range $0.9\text{--}522.6 \mu\text{Am}^2 \text{kg}^{-1}$. The directions of magnetisation were also widely dispersed, including some negative inclinations (Fig. 3.27b), with an α_{95} value of 48.3° based on 10 samples. One sample fell from its holder during transportation.

Demagnetisation

The 3 samples subjected to stepwise demagnetisation showed a wide variety of behaviour with none of them appearing to show a stable component of magnetisation, very similar to the demagnetisation behaviour of samples from context 1.

Magnetic fabric

Specific susceptibility was in a much wider range than that of context 1, $8.7\text{-}27.8 \times 10^{-8} \text{m}^3 \text{kg}^{-1}$, with high susceptibilities correlating with high intensities of NRM. The magnetic fabric was found to be generally slightly weaker than that of context 1, with $h\%$ in the range 2.5-6.3%, with the exception of sample YMA21 which had a very high $h\%$ value of 16.9%. The q values all fell in the range 0.08-0.88, 60% of them in the range characteristic of an undisturbed primary depositional fabric. The distribution of the principal axes of susceptibility (Fig. 3.30) was similar to that of context 1, with minimum axes loosely grouped indicating a near-horizontal foliation plane, but the maximum axes scattered, showing no clear lineation, implying that the fabric was oblate.

Magnetic mineralogy

IRM acquisition of sample YMA17 (not shown) followed a similar pattern to that of samples from context 1, with 95% of the SIRM being attained in a field of 1T and an SIRM value of $1.0 \text{mAm}^2 \text{kg}^{-1}$. $(B_0)_{\text{cr}}$ was 24mT and the S ratio of 0.79 indicated that the magnetic minerals were very similar to context 1, predominantly magnetite with some haematite or goethite contribution.

General conclusions

The results from the two modern analogue contexts were very different from their archaeological equivalents. IRM acquisition tests indicated that magnetic grains capable of carrying a remanence existed within the sediment matrix and that the magnetic mineralogy of the fine sand and the silty clay was very similar. However, the magnetic fabric study showed either that the magnetic grains had not been systematically oriented by current flow or the geomagnetic field, or that a pre-existing alignment had been destroyed. Extensive bioturbation was unlikely to have been the cause, as the deposits had only been in existence for a few days and there was little visible evidence of disturbance. The fact that the deposit was so shallow, compared with the archaeological contexts sampled, might have led to increased disturbance on deposition. However, it was also possible that insufficient time had elapsed for magnetic grains to orient themselves in the geomagnetic field and become fixed in the matrix, thus implying that any remanence acquired by sediments of this type is post-depositional in origin. The apparent lack of magnetised grains, shown by the low SIRM value suggested that any remanence acquired would be generally weaker than that of the other sediments. If sufficient material had been available, sediments could have been sampled over a period of time, to see if a post-depositional magnetisation was acquired. However, such experiments might not have been conclusive as the time scales involved are very short in comparison with the time archaeological sediments might take to acquire such a magnetisation.

3.4.4 Caldicot, near Newport, Gwent

(O.S. Grid Ref. ST 4873 8863)

Site description

Caldicot is located in the Nedern Valley, on the fringe of the Gwent Levels which are the most extensive ancient fenland in Wales, consisting of 100km² of coastal marshes, situated between the outskirts of Cardiff and the mouth of the River Wye at the Severn Bridge (Fig. 3.1). The geomorphology of the Levels has its origins in geological developments since the end of the last Pleistocene glacial, about 11,000 years ago. As the ice receded, the sea-level rose and the River Severn deposited a series of clay and silt layers, forming the Levels. The rate of sea-level rise was variable and, in periods of relative stability, plants colonised the land surface and localised peat horizons were formed. Thus an environment developed which varied from marine, through mudflat, saltmarsh, reedswamp and fen to dense forest. Clearly early humans exploited this environment, as some of the first evidence for agriculture in Wales has been found in the pollen record from nearby Goldcliff (Smith & Morgan, 1989). The environment at Caldicot and in the Nedern Valley also reflects these processes, with clays and silts having been deposited over the valley floor at a time when the lower Nedern Valley was on the estuary. The River Nedern has changed course over the centuries and the site investigated at Caldicot is situated in the bed of an earlier course of the river, which was subsequently filled with alluvium (Parry, 1988).

Excavations were carried out by Glamorgan-Gwent Archaeological Trust in the Caldicot Castle Country Park, in an area in the base of the Nedern Valley which was to be developed into an artificial lake. The excavation was situated on the edge of, and within, a filled channel of the previous course of the River Nedern. The initial excavations in Spring 1988 uncovered a number of ancient timbers, including a platform structure of timber and rounded uprights and a bronze chape (part of a scabbard), which was dated to 10th century BC on the basis of the metal-working style (Parry, 1988). Further excavations in 1988-9 concentrated on a limited part of the area to be covered by the new lake and revealed that the base of the river channel had been deliberately lined with limestone slabs to form a level surface (Parry, 1988; Parry & Parkhouse, 1989). Above the stone surface a large quantity of wood was found, including planks, posts, hurdles and artefacts. Some were unworked and possibly detrital, but others had clearly been deliberately positioned, for example lines of posts had been driven into the ground across the base of the channel. Many objects were unabraded suggesting that they had not been transported by the river (Parry, 1988). The finds also included flint tools, pottery fragments and bones of both domestic and wild animals and birds, such as horse,

cattle, sheep, red deer, brown hare, mallard and other wild fowl. The waterlogging of the site meant that wooden structures, artefacts and environmental evidence were well preserved, but also made excavation difficult. The wood was very soft, with a high water content, and so had to be sprayed and shaded to prevent it from drying out. Excavation was carried out from platforms suspended over the site to prevent crushing finds.

A second phase of excavation in 1989 elucidated the archaeological sequences (Fig. 3.31; Parry & Parkhouse, 1989). The dominant natural feature was a palaeochannel, approximately 20m wide, filled with laminated organic clays and containing the wooden and stone structures. When active, this channel cut through the finely laminated estuarine clay sequence and at some time after it filled with the organic clays, this major palaeochannel was dissected by at least one minor palaeochannel. The estuarine clay fill of the minor channel and its sinuous character suggested that it was part of the tidal creek system. Upper horizons of further estuarine and marine sedimentation have subsequently been subject to desiccation, resulting in iron redeposition and cracking (Parry, 1991). The most recent deposits had been destroyed by earth moving activities.

In Summer 1990, excavation of the two infilled palaeochannels within the estuarine clay uncovered a substantial plank fragment of a boat constructed from sewn oak planks, lying in the bottom of the major palaeochannel (Fig. 3.31; Parry, 1991). The plank was 3.5m long and probably formed part of the lowest strake of a plank boat. The strake is the plank or combination of planks which stretches from one end of the boat to the other (Wright, 1976). Analogies with vessels of similar construction from North Ferriby, Humberside (Wright, 1976; McGrail, 1987 p200) suggested that the Caldicot plank was probably part of a vessel up to 15m in length, powered by about a dozen paddlers (McGrail, 1987 p206) and capable of crossing the Severn. Sewing holes were clearly visible and evidence of stitching was found nearby, in the form of short lengths of root. The boat appeared to have been deliberately dismantled, possibly prior to winter storage (Parry, 1991). The plank was ideal for dating by dendrochronology as the sapwood was present and a date is awaited. The Ferriby boats were dated to mid to late 2nd century BC (Wright, 1976).

Description of the deposits sampled

The sequence of deposits sampled was rather complicated and is shown in simplified form in Fig. 3.31. The estuarine clay was cut by a major palaeochannel (Context No. 173), which was in turn cut by a minor palaeochannel (Context No. 174). The boat plank was lying on the interface between the major palaeochannel and the

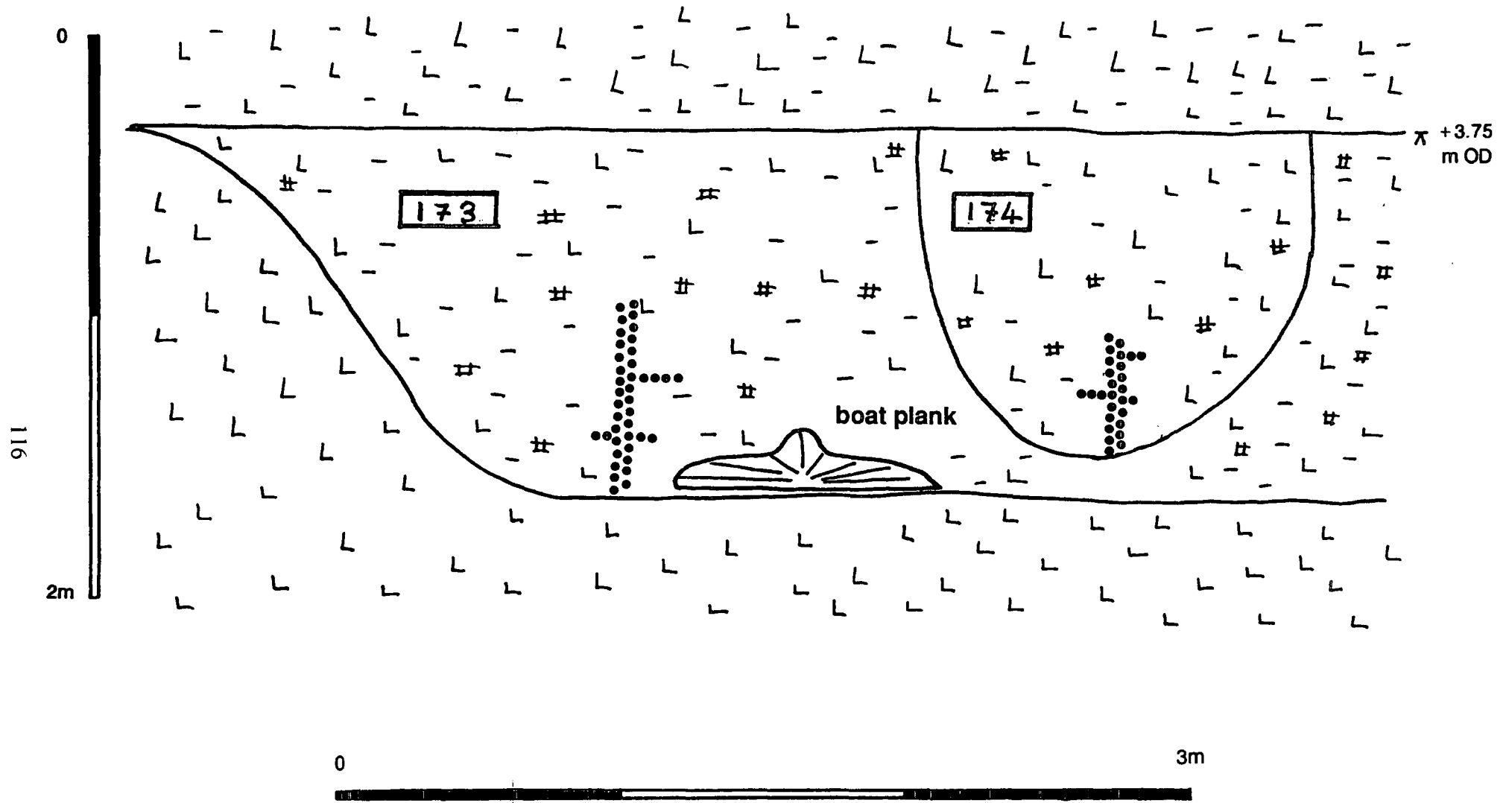


Figure 3.31: Schematic vertical section drawing of excavations at Caldicot, showing the location of samples.

estuarine clay, within the fill of the major palaeochannel. Samples were taken from two short columns, one at the deepest point of the minor palaeochannel and one at the deepest point of the deposits in the major palaeochannel (Fig. 3.31).

Context No. 174: This context consisted of a moist grey (Munsell No. 7.5YR 5/0) slightly silty clay, infilling a small channel which cut the major palaeochannel. In the section sampled the deposit had a uniform depth of 40cm tapering away at the sides. Overlying the context was a trackway of limestone blocks and wood, and it cut into context 173, the fill of the major palaeochannel, with an abrupt boundary. The silty clay was very uniform with no mottling, colour variations or visible sedimentary structures but contained a small quantity of organic material, mainly plant remains and charcoal. Archaeological excavation of the deposit revealed charcoal, worked wood and animal bones, providing evidence of human activity in the vicinity (Parry, 1991).

Context No. 173: This context was the fill of the major palaeochannel, cut into estuarine clays and containing the later, minor palaeochannel, with both boundaries being sharp and clearly defined. It was about 50cm deep at the section sampled and had a lateral extent of 5m. The deposit was a very dark grey (Munsell No. 5YR 3/1) silty clay, slightly siltier than the material in context 174. Frequent inclusions of organic matter, including leaves and plant stems, were visible and there were a number of horizontal charcoal lenses, less than 1cm thick. Archaeological excavation of this deposit revealed worked round wood, pottery, lithics and animal bone; in addition to the boat plank, timber structures and limestone blocks described above.

All the deposits were soft and therefore easily sampled by the tube method, which created little visible disturbance to the sediment surface. For both contexts a vertical section was cut and holders were pushed horizontally into it, in an overlapping sequence down the section, with repeat horizons. In all 61 samples were taken, the locations of which are shown in Fig. 3.31. Orientation was carried out using a line related to the site grid using the established site surveying system, and by magnetic compass (despite the presence of some steel shoring) to compare the orientations obtained from each method.

Archaeological interpretation of deposits

The archaeological evidence suggested that the major palaeochannel (context 173) cut into the estuarine clay sequence and a study of the molluscs within it indicated that the channel had been filled with moving, fresh water (Parry, 1991). In the light of the 1990 excavations, the wooden structures in the major palaeochannel were interpreted as a landing, close to the Late Bronze Age upstream tidal reach. The limestone blocks lining the channel would have allowed for the punting or quanting of boats on approach to the

landing (Parry, 1991; McGrail, 1987 p204). As the original tops of several of the bigger wooden uprights were preserved, Parry and Parkhouse (1989) suggested that the palaeochannel had been subjected to rapid infilling after the wooden structures had been built. The smaller palaeochannel (context 174) appeared to be part of the tidal creek system which cut through the earlier, silted-up channel.

Four radiocarbon dates for wood from the platform in the major palaeochannel have been obtained and all fall in the range 1260calBC-800calBC (radiocarbon ages in range 2650±50BP (RCD-33) to 2940±70BP (CAR-1214) with errors at 1σ from Parry (1991), calibrated using Pearson and Stuiver (1986)). The trackway sealing the later minor palaeochannel has been dated to 993calBC-837calBC (radiocarbon age 2750±60BP (CAR-1215) with errors at 1σ from Parry (1991), calibrated using Pearson and Stuiver (1986)). Earlier archaeomagnetic measurements on sediments from the major channel, just above the wooden uprights, suggested a date of 1850-1650BC at 68% confidence for this deposit, although the samples' magnetisation was weak and iron redeposition was evident in the section (A.J. Clark, pers. comm.).

Results of magnetic measurements: Context 174

Natural remanent magnetisation

The NRM intensity of samples CAL1-28 fell in the range 2.1-22.0μAm²kg⁻¹ and the directions appeared to follow a fairly smooth trend with similar directions ($\alpha_{95} = 4.5^\circ$) being obtained for samples taken from a single horizon (Fig. 3.32). The data were smoothed with a three-point running mean to reduce the noise but preserve low frequency secular variation more clearly. Quantitative statements about the trends were not attempted for the reasons given in Section 2.5.3.

Demagnetisation

6 pilot samples were selected from the 28 and demagnetised in an alternating field. The behaviour of a typical sample is shown in Fig. 3.33. The stereographic projection indicated that little directional change occurred in the magnetisation up to a demagnetising field of 40mT. The linear behaviour of the vector end-point shown on the Zijderveld plot confirmed that the remanence comprised of a single stable component of magnetisation with a slight viscous overprint. The stable component was statistically well defined with a stability index of 9.4 (very stable) over a range of 5-25mT. The plot of change in normalised intensity with increasing applied field fell smoothly and sharply, the intensity reducing to less than 12% of the original value after demagnetisation in fields of 40mT, with a low median destructive field of 20mT. These observations indicated that the magnetisation was soft, but stable. Demagnetisation in fields over 40mT also

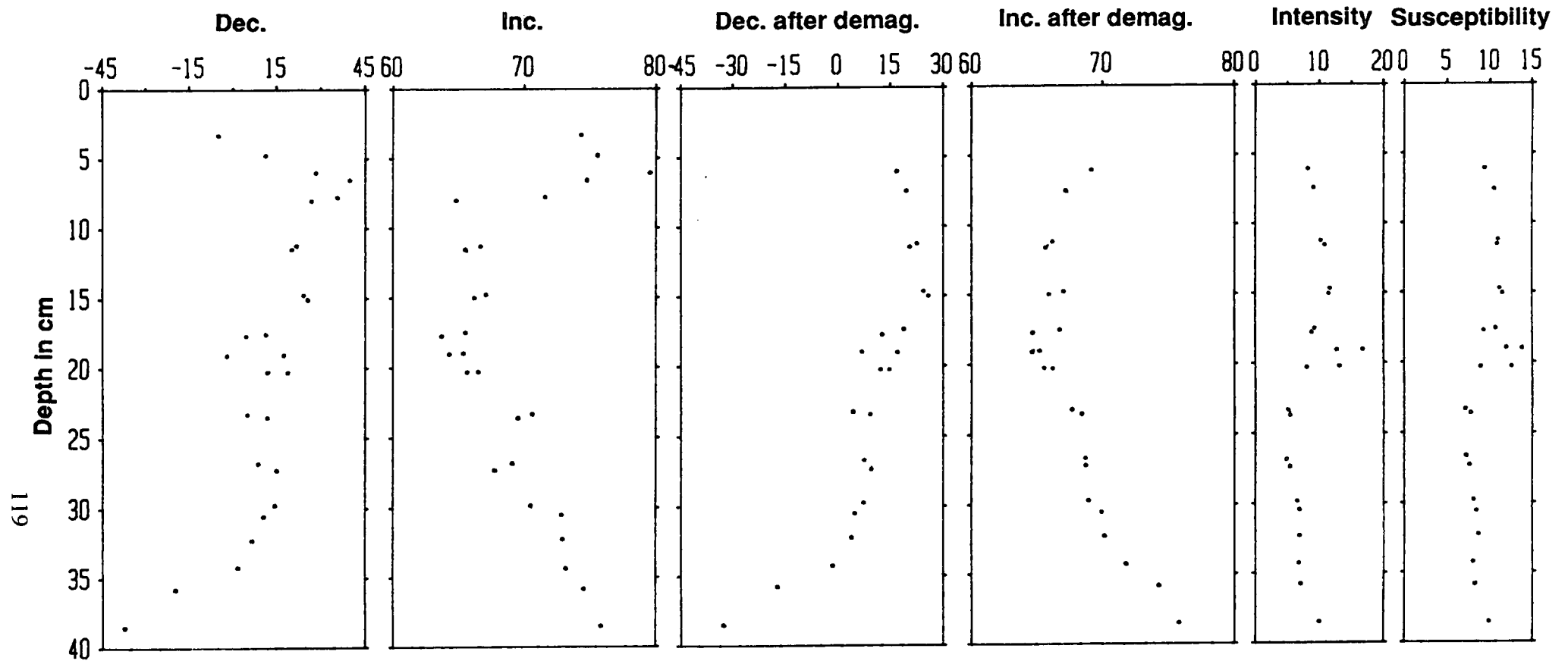


Figure 3.32: Plot of depth against NRM declination (Dec.), NRM inclination (Inc.), declination after demagnetisation, inclination after demagnetisation (all in degrees) and intensity (in $\mu\text{Am}^2\text{kg}^{-1}$) and susceptibility ($\times 10^{-8}\text{m}^3\text{kg}^{-1}$) from a vertical section through context 174, smoothed with 3 point running mean.

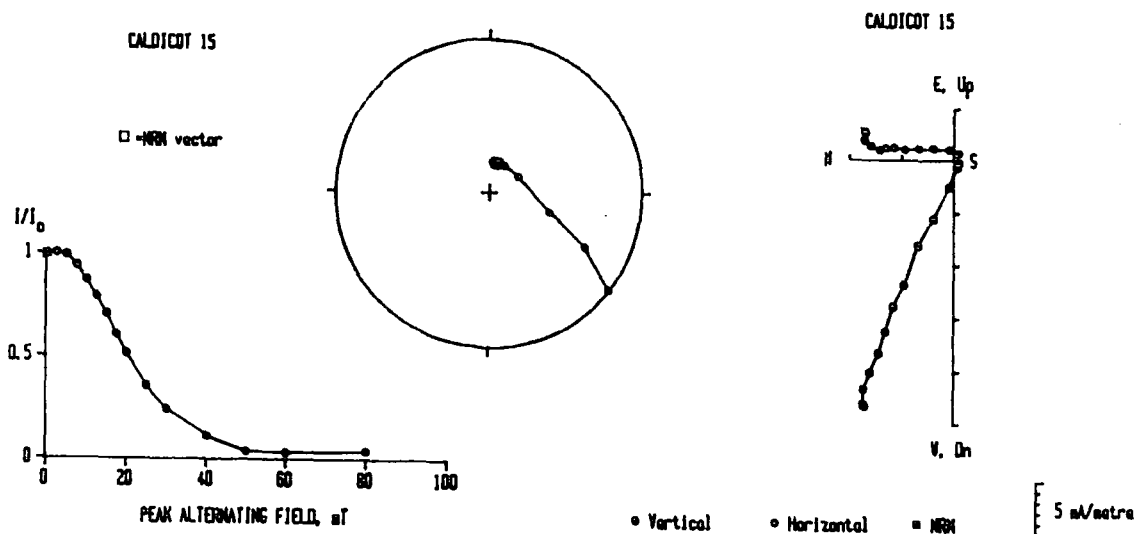


Figure 3.33: Stereographic, intensity and Zijdeveld plots of the behaviour of a typical sample (CAL 15) from context 174 on alternating field demagnetisation.

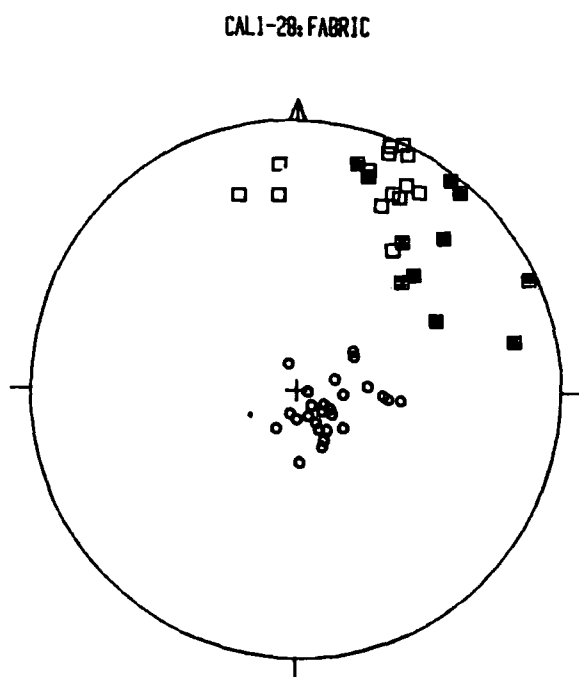


Figure 3.34: Magnetic fabric of samples CAL 1-28 from context 174.

suggested the existence of another stable component, which could not be isolated with this method.

As the material was homogeneous and the pilot samples showed very similar behaviour on demagnetisation, the remaining samples were demagnetised in a field of 10mT to remove the viscous component. This resulted in a slightly improved grouping of magnetic directions (α_{95} value for single horizon reduced to 4.2°) and the same smooth trends in declination and inclination were clearly visible (Fig. 3.32). Intensity and susceptibility records showed no significant changes through the section and the data were smoothed using a three-point running mean, which reduced the amplitude of the swings slightly, but made the trends down the section more clearly visible. As mentioned above, any quantitative description of these trends would have been very difficult (Section 2.5.3).

Magnetic fabric

Specific susceptibility was in the range $5.6\text{-}19.5 \times 10^{-8} \text{m}^3 \text{kg}^{-1}$ and appeared to show no systematic change through the section (Fig. 3.32). The magnetic fabric was found to be reasonably strong, with $h\%$ in the range 1.7-7.8%. q values all fell in the range 0.01-1.4, with 86% in the range characteristic of an undisturbed depositional fabric. The minimum axes of susceptibility were well grouped, defining a near-horizontal magnetic foliation plane (Fig. 3.34), indicative of grain by grain deposition. The maximum axes were also clustered showing a lineation, which suggested that the long axes of elongated grains had been aligned on deposition, possibly by current flow in the north-east to south-west direction.

Magnetic mineralogy

Application of pulse fields of increasing intensity to a number of samples resulted in a sharp increase of induced IRM, followed by a very small further increase at higher fields (e.g. Fig. 3.35a). Typical SIRM values were around $0.81 \text{mAm}^2 \text{kg}^{-1}$, with 99% of this value being reached in an applied field of 1T. $(B_0)_{\text{cr}}$ was 25mT (Fig. 3.35b) and the S ratio was 0.9. These parameters suggested that the magnetic mineral carrying the remanence was predominantly magnetite with very little contribution from harder magnetic minerals, as shown by the high S ratio.

Results of magnetic measurements: Context 173

Natural remanent magnetisation

The intensity of NRM of samples CAL30-63 fell in the range $2.4\text{-}17.5 \mu\text{Am}^2 \text{kg}^{-1}$, slightly weaker than context 174, but still well above the noise level

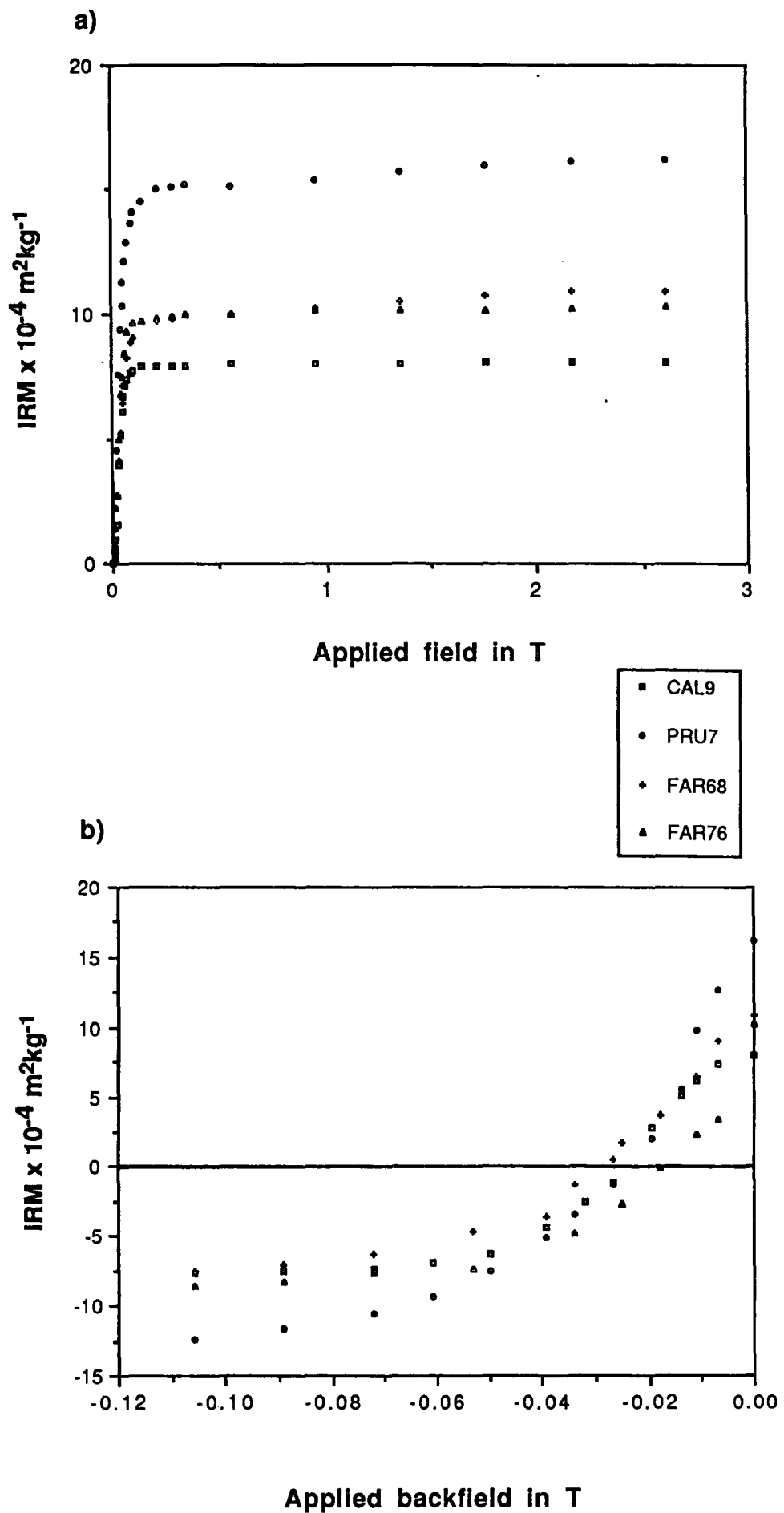


Figure 3.35 a: IRM build-up curve for samples CAL 9, PRU 7, FAR 68 and FAR 76.
 b: Plot of back coercivity for samples CAL 9, PRU 7, FAR 68 and FAR 76.

of the magnetometer. The directions were generally rather more dispersed than the previous sequence, but still appeared to be consistent within a single horizon, with an α_{95} value of 5° (Fig. 3.36).

Demagnetisation

6 of the 33 samples were subjected to stepwise demagnetisation (e.g. Fig. 3.37). The stereographic projection shows slight movement of the vector on demagnetisation but with a stable component with a stability index of 9.9 (very stable) over the range 5 to 30mT. The linear vector behaviour shown on the Zijderveld plot confirms that the remanence comprises of a single stable component, up to a demagnetising field of about 40mT, with a slight viscous overprint. The plot of change in normalised intensity with applied field fell smoothly and sharply, reducing to less than 15% of the original value after demagnetisation at 40mT, with a low median destructive field of 20-25mT. These observations indicated the remanence of samples from context 173 was very similar to that of samples from context 174, with a stable remanence being isolated in fields between 5 and 40mT and the possibility of another stable remanence existing at much higher fields.

The remaining samples were demagnetised in a field of 10mT to remove the small viscous component. This resulted a slight increase in the dispersion of magnetic directions (α_{95} value of the single horizon decreased to 4.8° ; Fig 3.36). After the application of a 3 point running mean, some general trends were visible, although as above no statistical tests were made. Also revealed was a change in magnetic directions for a horizon from 17-23cm which also had unusually high intensity and susceptibility. These samples were taken from an organic lens and were apparently disturbed and were therefore omitted from the subsequent analysis.

Magnetic fabric

Specific susceptibility was in the range $5.2-18.3 \times 10^{-8} \text{m}^3 \text{kg}^{-1}$, generally slightly less than for the first group of samples but still showing little variation down the section (Fig. 3.36), apart from the disturbed horizon discussed above. The magnetic fabric was found to be similar to that of context 174, with $h\%$ in the wide range 1.6-10.0%. The q values fell in the range 0.05-1.51 and only 55% were in the range characteristic of an undisturbed primary depositional fabric. The minimum and maximum axes were both well grouped, showing a similar distribution to those in the first section (Fig. 3.38), suggesting that a similar depositional conditions were in operation.

Magnetic mineralogy

The behaviour of pilot samples in SIRM tests (not shown) was very similar to the behaviour of samples from context 174, with typical SIRM values around

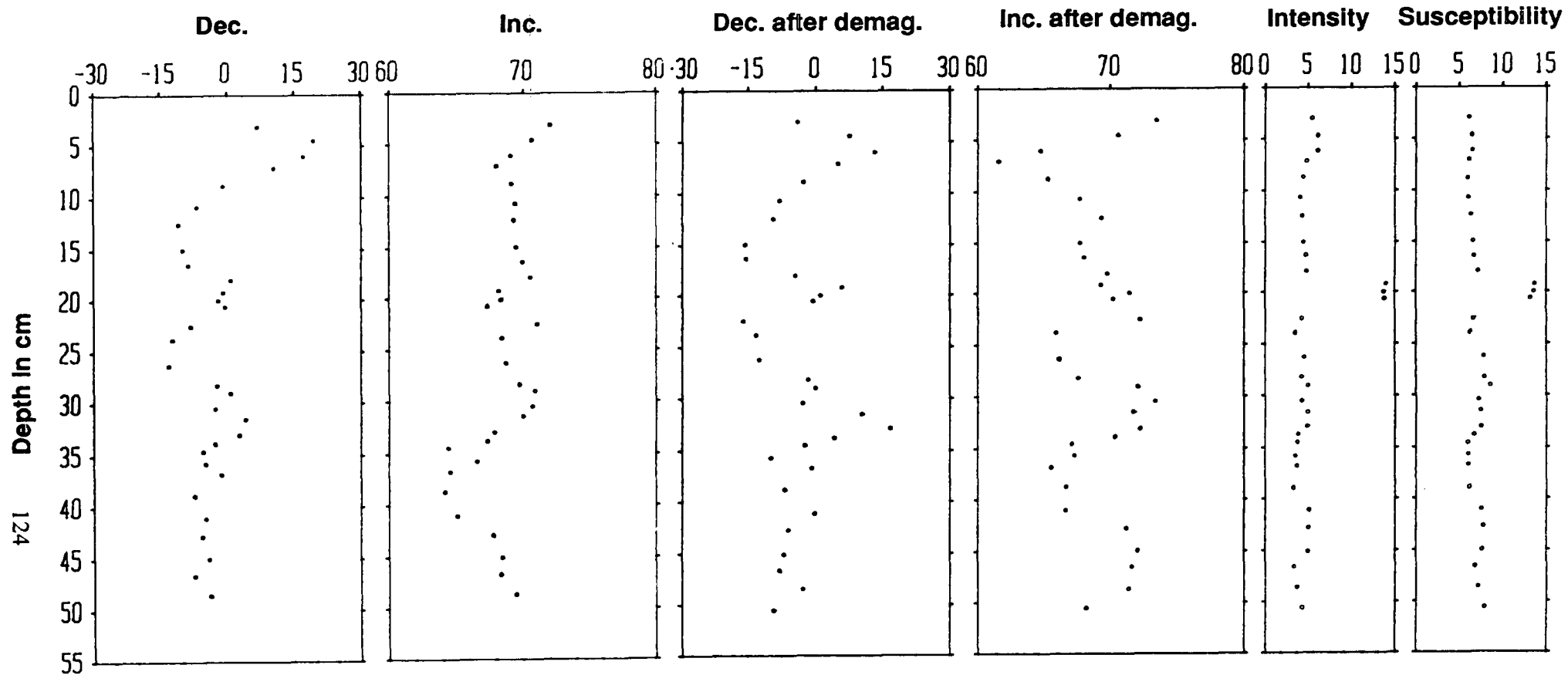


Figure 3.36: Plot of depth against NRM declination (Dec.), NRM inclination (Inc.), declination after demagnetisation, inclination after demagnetisation (all in degrees) and intensity (in $\mu\text{Am}^2\text{kg}^{-1}$) and susceptibility ($\times 10^{-8}\text{m}^3\text{kg}^{-1}$) from a vertical section through context 173, smoothed with 3 point running mean.

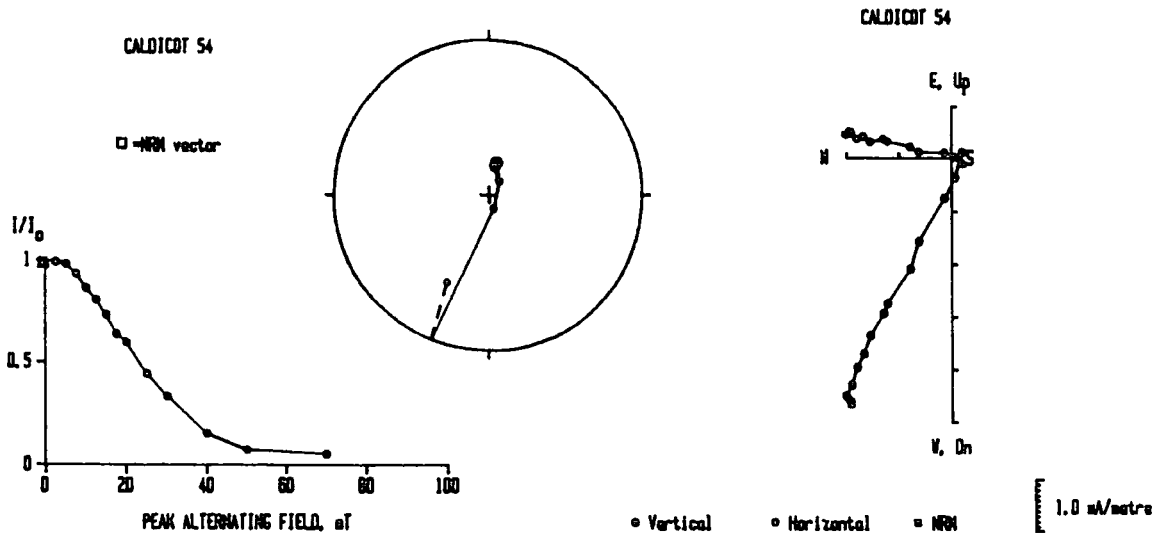


Figure 3.37: Stereographic, intensity and Zijdeveld plots of the behaviour of a typical sample (CAL 54) from context 173 on alternating field demagnetisation.

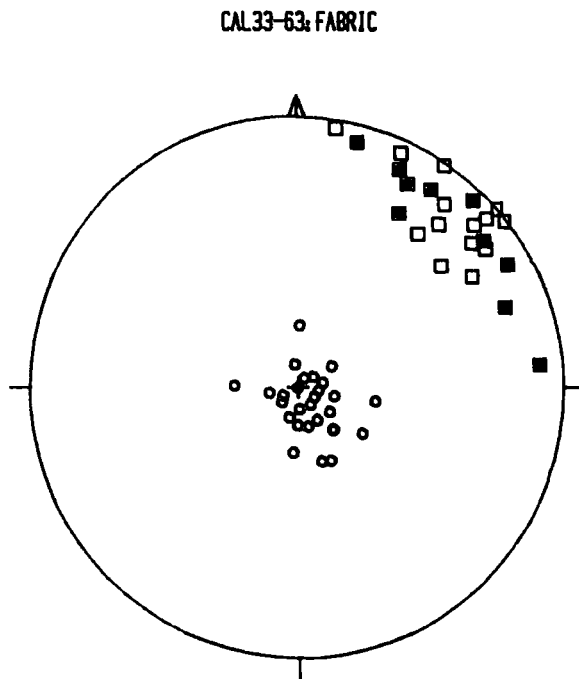


Figure 3.38: Magnetic fabric of samples CAL 30-63 from context 173.

0.72mAm²kg⁻¹, 99% of this value being reached in an applied field of 1T. $(B_0)_{cr}$ was 25mT and the S ratio was 0.9. These parameters suggested that the magnetic mineral carrying the remanence was predominantly magnetite with very little contribution from harder magnetic minerals, as shown by the high S ratio. The close correspondence between these results and those from context 174 suggested that the remanence in both cases was due to magnetic carriers with a very similar mineralogy and grain size.

General conclusions

The magnetic investigations of the sediments from Caldicot indicated that in both context 173 and 174 a stable remanent magnetisation was recorded in magnetite grains within the sediment. This remanence appeared to reflect secular variations of the geomagnetic field at, or shortly after, deposition of the sediments. The study did not reveal any subsequent chemical changes to the sediment and the similarity of the behaviour of both sediments in IRM and demagnetisation tests led to the conclusion that the magnetic carriers in both cases were very similar. This might be expected if the material of two sediments had the same source. The magnetic fabric in both cases was indicative of deposition under conditions of laminar flow. The fabric of context 173 was rather more scattered than that of context 174, as were the magnetic directions. This was attributed to increased depositional disturbance, due to the higher organic content of context 173. The differences between the NRM values obtained with the two orientation methods was always less than 2° and therefore not considered to be significant.

Both sections showed systematic variations of declination and inclination with depth through the sediment and good repeatability of magnetic direction within horizontal groups of samples (Figs. 3.32 and 3.36) although magnetic directions were more dispersed where there was a higher organic content. There were too few samples from the organic material to demonstrate the increase in dispersion using Fisher statistics but it is clearly shown on the depth plot of Fig. 3.36. The increase might be attributed to greater biological activity or an influx of non-detrital material containing the organic matter.

The trends in magnetic direction through either section did not appear to correspond to variations represented in the current archaeomagnetic calibration curve. However, when the directions from the minor palaeochannel (context 174) were compared visually to the lake sediment curve (Fig. 3.39), there appeared to be correspondence in both declination and inclination between the two records from 350calBC to 1950calBC. The Caldicot inclination record was slightly shallower than the lake record, which might be attributable to their spatial separation. The Caldicot

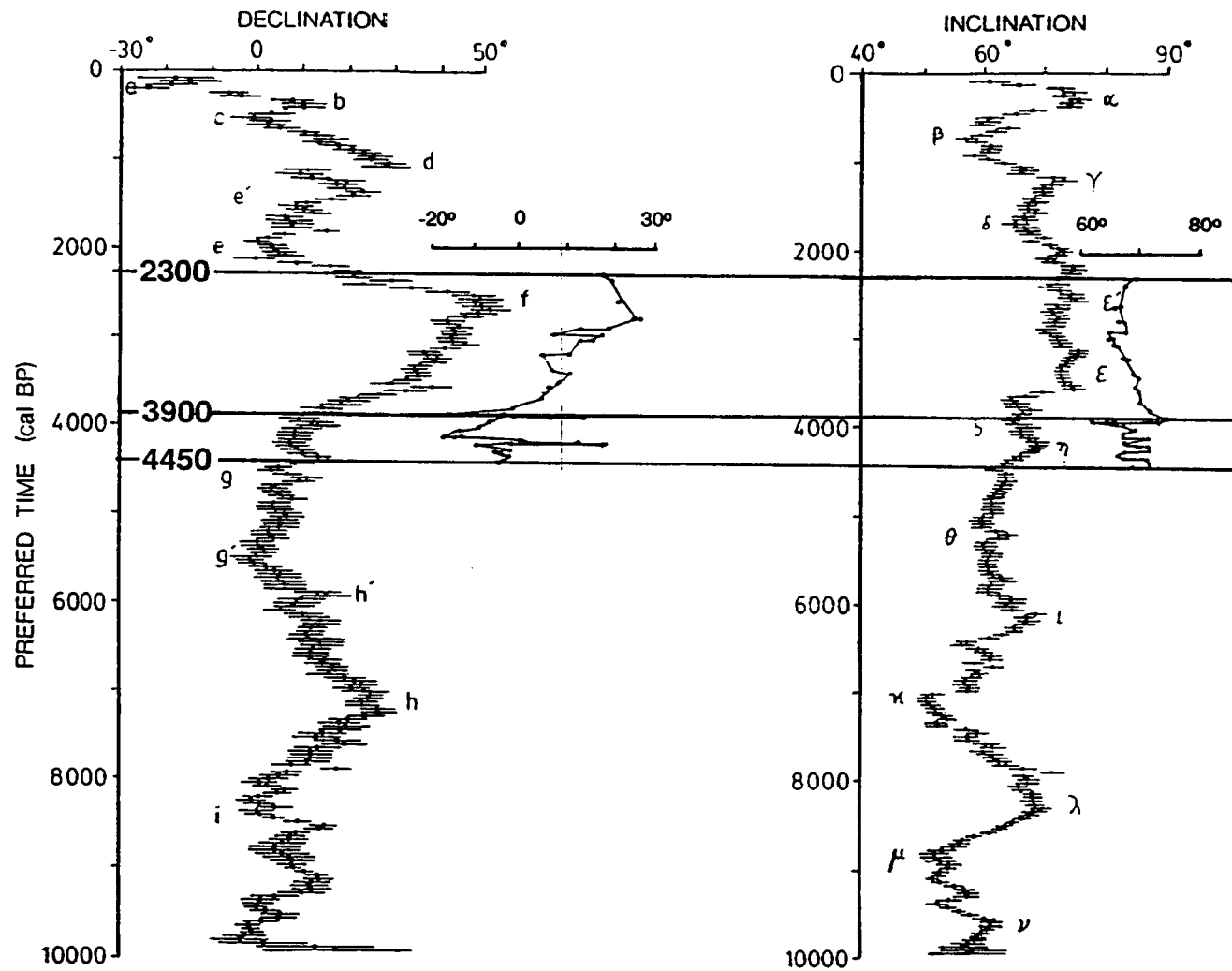


Figure 3.39: Comparison of the secular variation obtained from the two sections at Caldicot with the lake sediment secular variation curve of Turner and Thompson (1982).

declination record was rather more westerly than expected but showed a very similar form to the lake sediment curve. This observation is similar to the results from earlier sediment archaeomagnetism (Section 3.3), which also suggested that the declination of the lake sediment curve was too far east. These dates implied that deposition might have been very slow, averaging 0.025cm per year. The magnetic directions from the major palaeochannel fill, context 173, were rather more scattered and difficult to match with the lake sediment curve. However, they seemed to correspond best to the curve between 1950calBC and 2500calBC (Fig. 3.39), which would give an average rate of deposition of 0.1cm per year. In both cases, the average rate of deposition depends upon deposition being at a uniform, uninterrupted rate. The dates for the fill of the major palaeochannel were consistent with it being filled before deposition commenced in the minor palaeochannel and corresponded reasonably well with the previous archaeomagnetic dates. If, as the magnetic measurements indicated, the palaeochannel sediment provided a reasonably accurate record of secular variations of the geomagnetic field, this would suggest that the boat had been deposited before 2500calBC. This is considerably earlier than the date expected based on the artefactual evidence (J. Parkhouse, pers. comm.) and the radiocarbon dates. The origin and stability of the secular variation record was well established, but discussion of the validity of the dates obtained will have to wait until information is available from another source, such as radiocarbon or dendrochronology on the boat's timbers. No attempt was made to compare the magnetic directions to the revised calibration curve presented in Chapter 5, as the sections were expected to date to a period before the commencement of this curve.

It must be noted that any comparisons with the lake sediment curve of this type are extremely tentative, especially as no statistical method was used (Section 2.5.3). The deposition rate at Caldicot is not known and must be assumed to be constant and uninterrupted, high frequency changes in secular variation may have been removed from either or both the records during their mathematical smoothing and the visual comparison of the two records is extremely subjective. In this case such a comparison was only possible because of the distinctive swing of declination recorded in the Caldicot sediments.

3.4.5 Low Prudhoe, Northumberland

(O.S. Grid Ref. NZ 088 637)

Site description

Low Prudhoe is situated in the lower Tyne Valley, 15km west of Newcastle-upon-Tyne (Fig. 3.1), on the floodplain of the River Tyne and to the north of Prudhoe (Fig. 3.40). In August 1986 a major flood eroded the bank at Low Prudhoe and revealed sections of the floodplain consisting of 2-3m of finely laminated sands and silts, overlying 2m of sandy gravels. Chemical and granulometric properties of sands from the upper alluvial unit were similar to those of the sands deposited overbank by the 1986 flood, suggesting that the exposed sediments might be a result of recent floods in the Tyne Valley (Macklin & Dowsett, 1989). Macklin *et al.* (in press b) used historical documentation of flood events in the area, along with sedimentological and geochemical analysis of the deposits, to construct a record of the floods of the Tyne over the last 100 years. The alluvium exposed at Low Prudhoe proved ideal for such an investigation, as there was considerable (up to 3m) vertical accretion of well-bedded sands and silts arising from overbank flood deposits and the high average sedimentation rates (2.37cm per annum) made it possible to recognise individual flood events. Extensive archive reports of floods in the Tyne Basin exist and it was possible to relate flood deposits to mining activity upstream by examining trace metal concentrations (Macklin *et al.*, in press b). It was hoped to correlate the archaeomagnetic information derived from the deposits with this information.

The River Tyne is fed by two major tributaries, the River North Tyne which drains Bewcastle Fell and the southern Cheviots, and the River South Tyne, fed from the Northern Pennines. Both catchment areas are predominantly underlain by sandstones, limestones and shales and so there is a large sand component in the flood sediments, as well as fine-grained sediments from the uplands (Macklin & Dowsett, 1989). Tributaries of the River South Tyne pass through the North Pennine ore field, once the most productive metalliferous region in Great Britain (Dunham, 1944). The principal metal minerals found there were galena (PbS) and sphalerite (ZnS), with significant concentrations of trace metals such as cadmium, copper and silver (Young *et al.*, 1987). Both lead and silver have been mined in the area, probably since Roman times (Raistrick & Jennings, 1975 pp1-22) and from AD1650 the North Pennines was Britain's leading producer of lead and zinc (Schnellmann & Scott, 1970). Maximum lead output occurred between AD1815 and AD1880 and then declined, with a revival between AD1920 and the outbreak of World War II (Dunham, 1944). The peak period of zinc production was between AD1880 and AD1920 and the last major metal mine in the Tyne Basin closed in

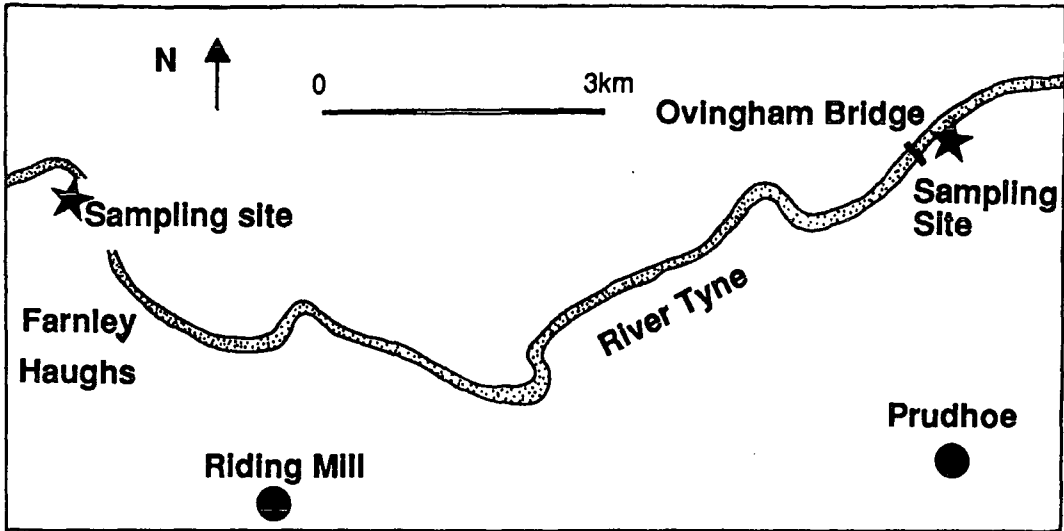


Figure 3.40: Map of Tyne basin showing sampling sites at Prudhoe and Farnley.

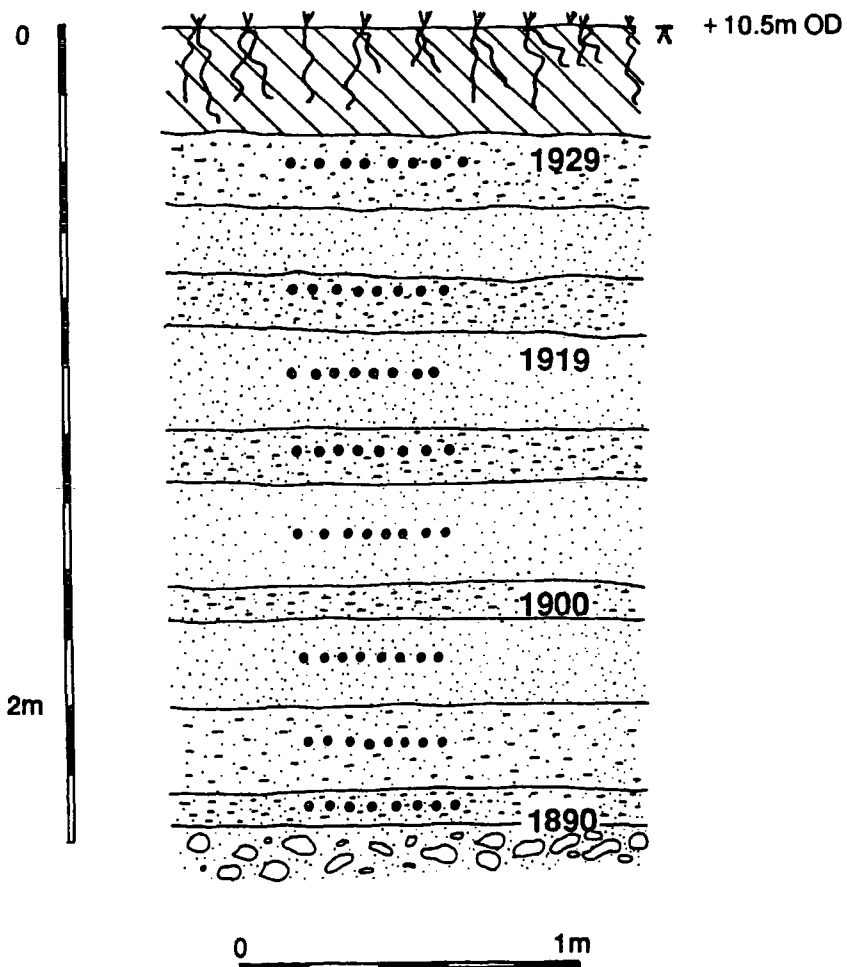


Figure 3.41: Vertical section drawing of Prudhoe section, showing the sample locations. Samples PRU1-8 were taken from the uppermost horizon and 8 samples were taken from each horizon indicated down to PRU57-64, from the base of the section.

the early 1950's. Extraction and processing of lead and zinc resulted in the release of large quantities of fine-grained, metal-rich waste into the Tyne, providing a distinctive source of sediment that can be linked to the development of metal mining and used as stratigraphic markers.

By measuring trace metal concentrations in the flood deposits and relating them to changes in metal mining activity, Macklin *et al.* (in press b) suggested that the major part of the alluvial sequence found at Low Prudhoe had been developed over a comparatively short time, between AD1890 and AD1950. Assigning the more prominent sand units to the major documented floods led to more refined dating of the sequence and showed that changes in the riverbed and floodplain sedimentation levels had controlled the magnitude and frequency of the floods represented in the sedimentary record.

Description of the deposits sampled

A section was prepared close to the sequence investigated by Macklin *et al.* (in press b) on the south bank of the River Tyne at Low Prudhoe, by Ovingham Bridge (Fig. 3.40). The primary sand units associated with major flood events could be easily identified and provided dated horizons. The section was approximately 2.5m deep (Fig. 3.41), commencing with an extensively bioturbated sandy topsoil, followed by a sequence of horizontal laminations (approximately 10cm thick on average), overlying sandy gravels. The laminations consisted of very fine, yellowish brown (10 YR 3/4) silty sand horizons, interspersed with coarser medium and fine sands, lighter in colour (10 YR 5/4). The upper 50cm contained a large number of very fine rootlets and the occasional small burrow but there was no other evidence of bioturbation. The sediments were generally dry and rather loose, with very few visible organic inclusions.

All the deposits were soft and therefore could be sampled by the tube method, but great care was necessary as the material was inclined to crumble. 8 samples were taken from each of 8 horizons by pushing tubes horizontally into the cleaned section (Fig. 3.41). 5 groups of samples were taken from the more silty material and 3 from sandy material. Orientation was carried out using a magnetic compass.

Archaeological interpretation of deposits sampled

As the Tyne channel at Low Prudhoe does not appear to have moved appreciably over the last 130 years (Macklin *et al.*, in press b), the sediments sampled were likely to be a build-up of material from overbank flood events. The section sampled was dated to

between AD1890 and AD1929 using geochemical markers and documentary flood records. Two of the horizons were dated to within a year and the remainder to within at least 20 years (Macklin *et al.*, in press b). It was possible that each pair of medium sand/silty sand laminations represented a single flood event, with the coarser material being deposited as the flood rose and at peak flow and finer material settling as the flood fell. Rapid water recession would lead to a lack of fine material in the flood record and a weak flow might not be able to carry suspended sand, leading to the lack of coarser grained material and hence causing irregularities in the sequence.

Results of magnetic measurements:

Natural remanent magnetisation

The intensity of NRM of all 64 samples (PRU1-64) was very low, falling in the range $0.6\text{-}2.4\mu\text{Am}^2\text{kg}^{-1}$, and was generally slightly higher in the silty horizons. There was considerable dispersion in the directions of magnetisation within the horizons (Fig. 3.42), with α_{95} values varying from 6.5° for the uppermost horizon to 47.4° for the samples taken at 190cm. The α_{95} values were slightly smaller for the siltier horizons but no clear distinction could be made. Although the NRM intensity was low, repeated measurements of the same sample gave magnetic directions that were within 2° (95% confidence), a variation which was attributed to random errors in measurement. This demonstrated that the samples' magnetisation could still be measured above the noise level of the magnetometer and so the dispersion of results was taken as an accurate representation of the dispersion of directions of magnetisation in the sediment.

Demagnetisation

12 of the 64 samples were subjected to stepwise demagnetisation in an alternating field and the behaviour of a typical sample is shown in Fig. 3.43. As the intensity of magnetisation of the samples was so low each demagnetisation step was repeated three times. The resulting plots clearly showed that the measurement of direction and intensity was repeatable until the intensity dropped below $0.3\mu\text{Am}^2\text{kg}^{-1}$. The stereographic projection indicated that there was little change in the direction of magnetisation to a demagnetising field of 10mT and the linear behaviour of the vector end-point, shown on the Zijderveld plot, confirmed that the remanence appeared to comprise largely of a single stable component of magnetisation, after the removal of a small, very soft component. The stable component was statistically well defined over a short range with a stability index of 2.5 (stable) over a range of 0 to 10mT. The plot of change in normalised intensity with increasing applied field fell very sharply, the intensity reducing to less than 11% of the original value after demagnetisation in fields of 40mT, with a very low median destructive field of 7.5mT. These observations indicated that the

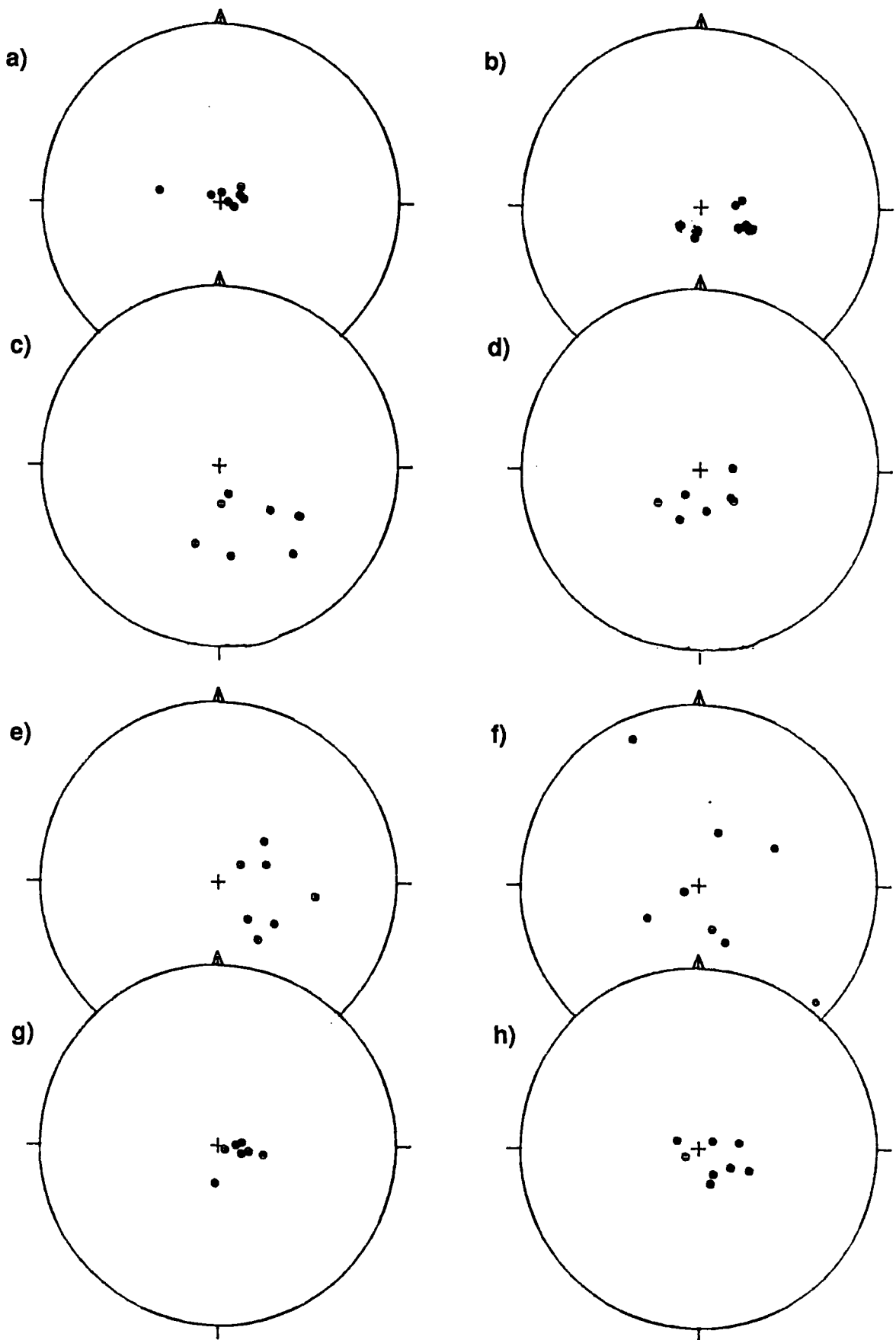


Figure 3.42: Stereographic plot of the NRM directions of magnetisation of samples *a)* PRU 1-8, *b)* PRU 9-16, *c)* PRU 17-24, *d)* PRU 25-32, *e)* PRU 33-40, *f)* PRU 41-48, *g)* PRU 49-56 and *h)* PRU 57-64.

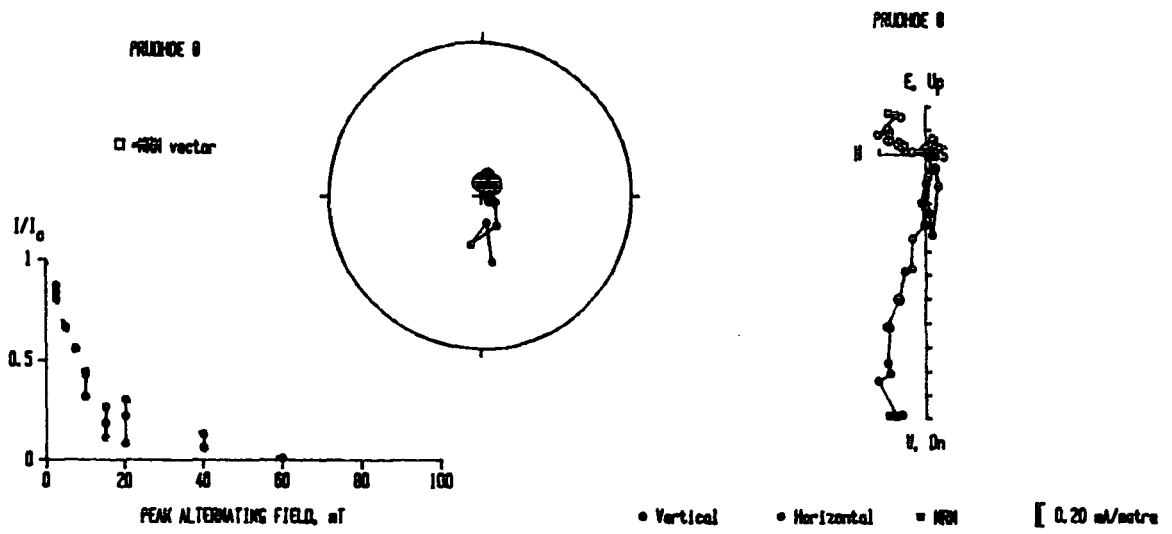


Figure 3.43: Stereographic, intensity and Zijderveld plots of the behaviour of a typical sample (PRU 8) on alternating field demagnetisation.

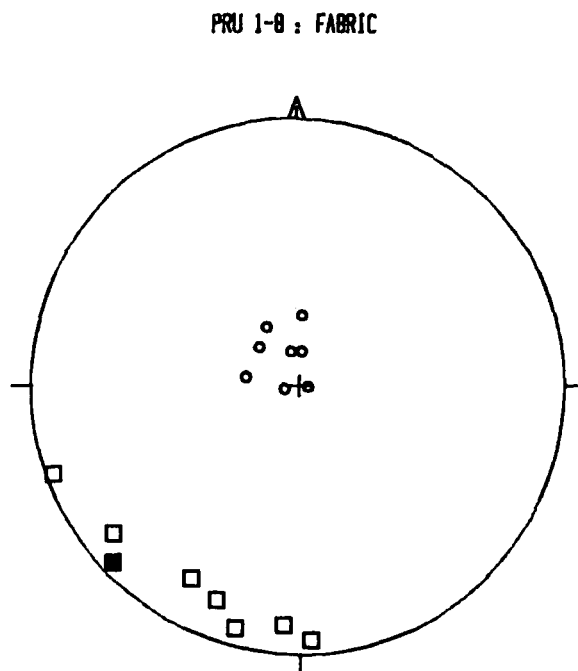


Figure 3.45: Magnetic fabric of samples PRU 1-8.

magnetisation was very soft but a stable component could be isolated between the viscous overprint and the noise level of the instrument, although the samples were rather weak for this to be measured accurately.

All the pilot samples, both from the sand and from the silts, showed very similar behaviour on demagnetisation, with median destructive fields in the range 7.5-15mT. The remaining samples were demagnetised in a field of 5mT to remove the small viscous component. This resulted in an increased dispersion in magnetic directions in all groups of samples giving α_{95} values ranging from 9.3° to 90° (Fig. 3.44).

Magnetic fabric

Specific susceptibility was in the range $10.0-17.5 \times 10^{-8} \text{m}^3 \text{kg}^{-1}$ and was systematically lower in the sandier horizons. The magnetic fabric was found to be fairly weak, with $h\%$ in the range 1.4-5.7%. The q values fell in a wide range 0.1-1.8, with more from the silty horizons than from the sandy horizons falling in the range characteristic of an undisturbed depositional fabric. The distribution of susceptibility axes for each horizon were very similar (e.g. Fig. 3.45). In all cases the maximum axes were well grouped showing a lineation. The minimum axes were also fairly well grouped demonstrating a magnetic foliation. These AMS results suggest that deposition of the sediment has been grain by grain and that a force has acted to align elongated grains roughly parallel with the river course and directed downstream.

Magnetic mineralogy

IRM acquisition tests were carried out on 4 samples; 2 from the silt and 2 from the sand horizons (e.g. Fig. 3.35a). For all the samples the SIRM values were in the range $1.2-1.6 \text{mAm}^2 \text{kg}^{-1}$ and 95% of this value was reached in an applied field of 1T. $(B_o)_{cr}$ was in the range 25-26mT (e.g. Fig. 3.35b) and the S ratio was 0.8. These parameters suggested that the magnetic mineral carrying the remanence was predominantly magnetite with a contribution from harder magnetic minerals, unsaturated in 1T, which was most likely to be haematite or possibly goethite. The value of $(B_o)_{cr}$ was slightly higher than usual, probably reflecting the contribution of the harder magnetic mineral. Despite the difference in appearance of the sand and silt horizons, the remanence carrier in both cases appeared to be very similar, both in mineralogy and in grain size.

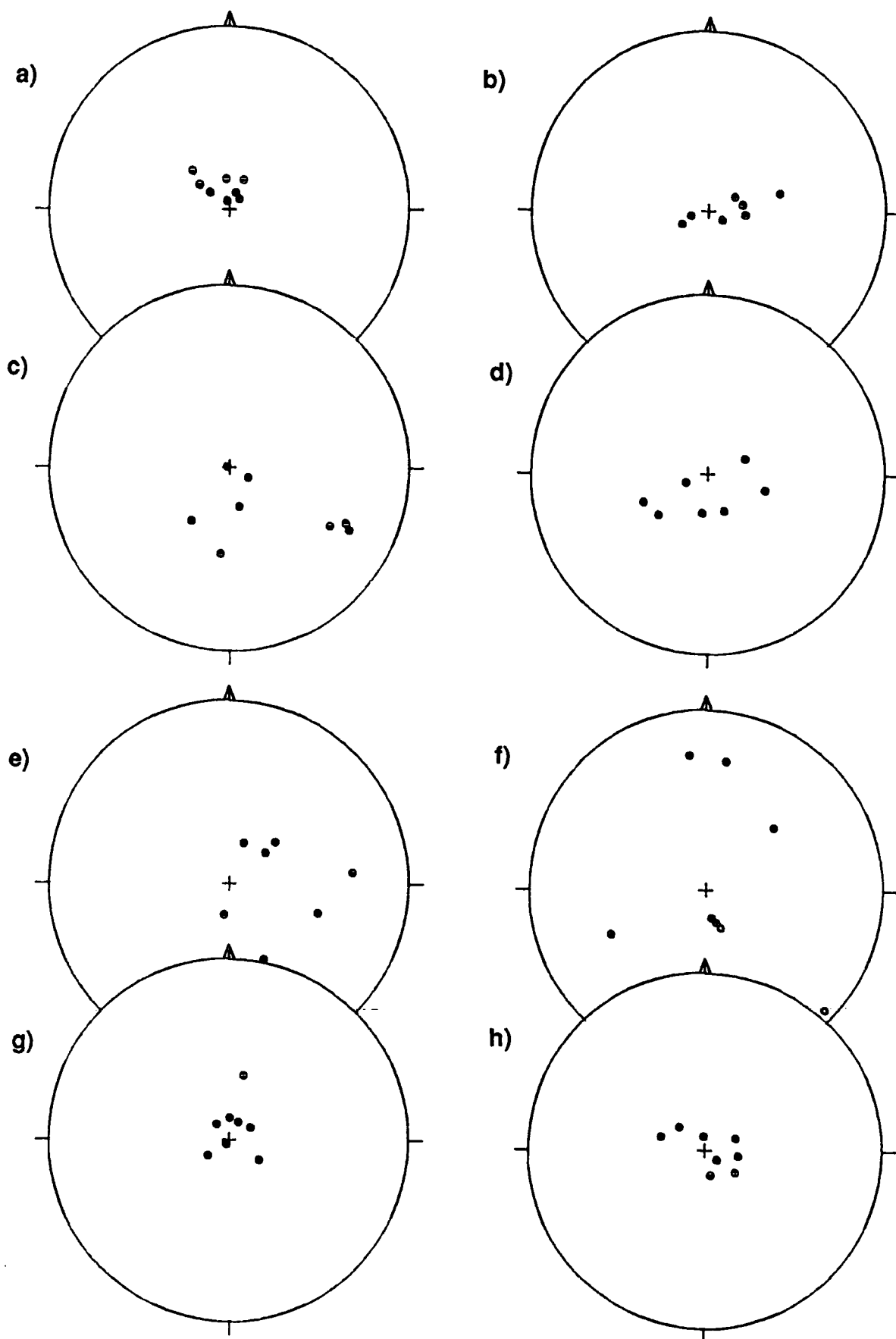


Figure 3.44: Stereographic plot of the directions of magnetisation after partial demagnetisation of samples *a)* PRU 1-8, *b)* PRU 9-16, *c)* PRU 17-24, *d)* PRU 25-32, *e)* PRU 33-40, *f)* PRU 41-48, *g)* PRU 49-56 and *h)* PRU 57-64.

General conclusions

The overbank flood deposits sampled at Prudhoe were potentially ideal for archaeomagnetic investigations as they consisted of thick, horizontal laminations of known date. However, their NRM was very low in intensity and, although stepwise demagnetisation revealed a stable component, it was difficult to isolate above the noise level of the instrument. Removal of what appeared to be viscous components of magnetisation merely increased the dispersion. This may have been due to the resulting reduction in intensity or attributable to the removal of a later, viscous magnetisation which masked an essentially random distribution of primary magnetic directions. However, the fabric results suggested that the magnetic grains had been preferentially aligned and IRM acquisition tests demonstrated that remanence-carrying grains, both magnetite and haematite or goethite, were present in the matrix in significant concentrations. Thus it must be concluded that there was a general alignment of grains, possibly by current stresses, and this alignment was retained to the present day, but that remanence carrying grains within the sediment were not to be aligned. One possible explanation is that they were small enough to move freely in the pore spaces in the sediment matrix and were disturbed by water movement subsequent to deposition. Hence any depositional or post-depositional remanence was not preserved and the material was not datable by archaeomagnetic means. Despite the lack of success in dating these particular sediments, sediments from similar depositional environments but with a different mineralogy may be suitable. Macklin and Lewin (in press) describe a number of dated flood deposits associated with British rivers which might prove a valuable resource for future archaeomagnetic investigations.

3.4.6 Farnley Haughs, Northumberland

(O.S. Grid Ref. NZ 065 632)

Site description

Farnley Haughs is situated in the lower Tyne Valley, on the south bank of the River Tyne, between Riding Mill and Corbridge, approximately 9km upstream of Prudhoe (Section 3.4.5; Fig. 3.40) and 10km downstream of the confluence of the North and South Tyne rivers. The area consists of a series of flat terraces on the inner curve of a bend in the River Tyne (Fig. 3.40). Alluvial gravel extraction has cut through the terraces to a depth of over 10m, revealing laminated deposits which appear to be the result of over-bank flooding. The river channel has moved northwards, leaving behind it a series of terraces, possibly representing floods of different ages. At the time of the site visit, in March 1990, deposits from that winter's flooding could be seen adjacent to the river channel. The sedimentary units appeared similar to those exposed at Prudhoe, but were much thicker. As yet, trace metal investigations have not been carried out and hence the deposits cannot be dated or their sources identified by this means, but such studies are in progress (M. Macklin, pers. comm.)

Gravel extraction has exposed a continuous 300m section across the Holocene valley floor, from the junction with the Late Pleistocene coarse grained alluvium on the south side of the valley to the present river channel on the north (Macklin *et al.*, in press a). Four holocene alluvial units have been identified, truncating older fills and covered by younger fluvial deposits. The units all comprise of sandy gravels overlain by flat-bedded sands and silts, the form of deposits expected from meandering rivers (Section 3.2.1). The coarse material represents riverbed or bar material and the fine material is a result of flood plain or channel fill of sediments from overbank or static water deposition (Macklin *et al.*, in press a).

Description of the deposits sampled

A 1m deep section was cut into the oldest Holocene terrace, known as the Willy Wood unit (Macklin *et al.*, in press a; Fig. 3.46). The sequence commenced with an extensively bioturbated, sandy topsoil; followed by a series of wide (about 10cm), horizontal, well-bedded laminated silty sands and overlying sandy gravels. The laminations consisted of very fine, red/brown (5 YR 3/4) silty sand horizons, alternating with coarser medium and fine sands, lighter brown in colour (10 YR 6/3). The upper 50cm contained a large number of very fine rootlets and the occasional small burrow, but

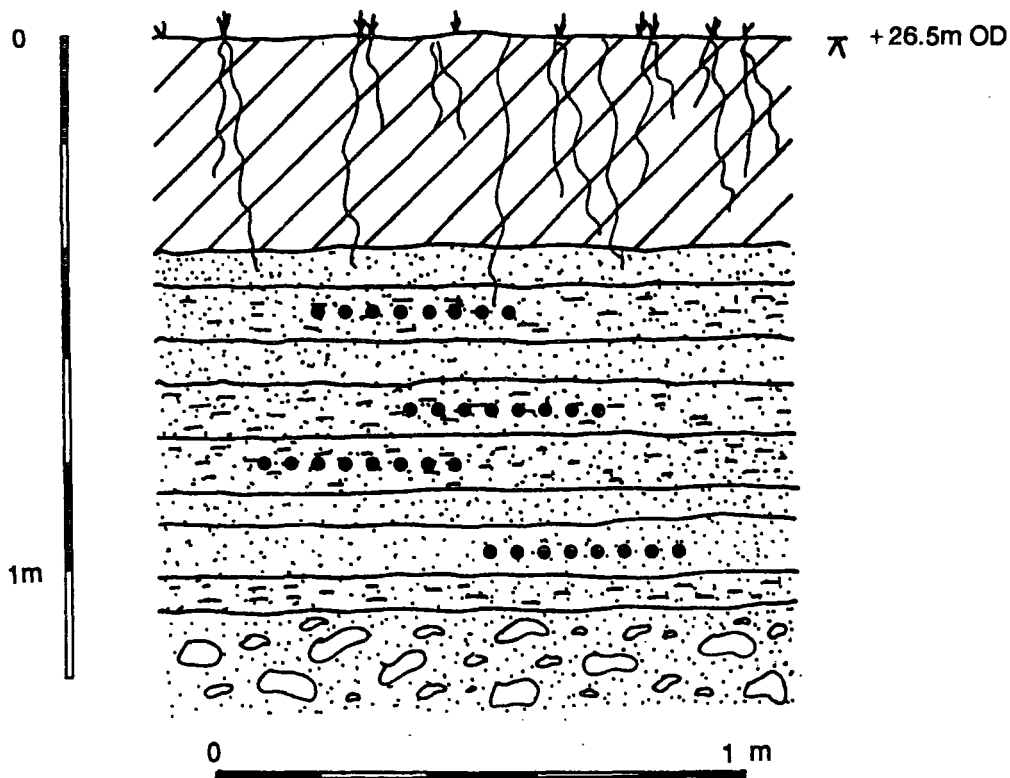


Figure 3.46: Vertical section drawing of Farnley section cut in the Willy Wood unit, showing the location of samples. FAR50-56 in the upper horizon, then FAR57-64 and FAR65-72, with FAR73-79 in the lowest horizon.

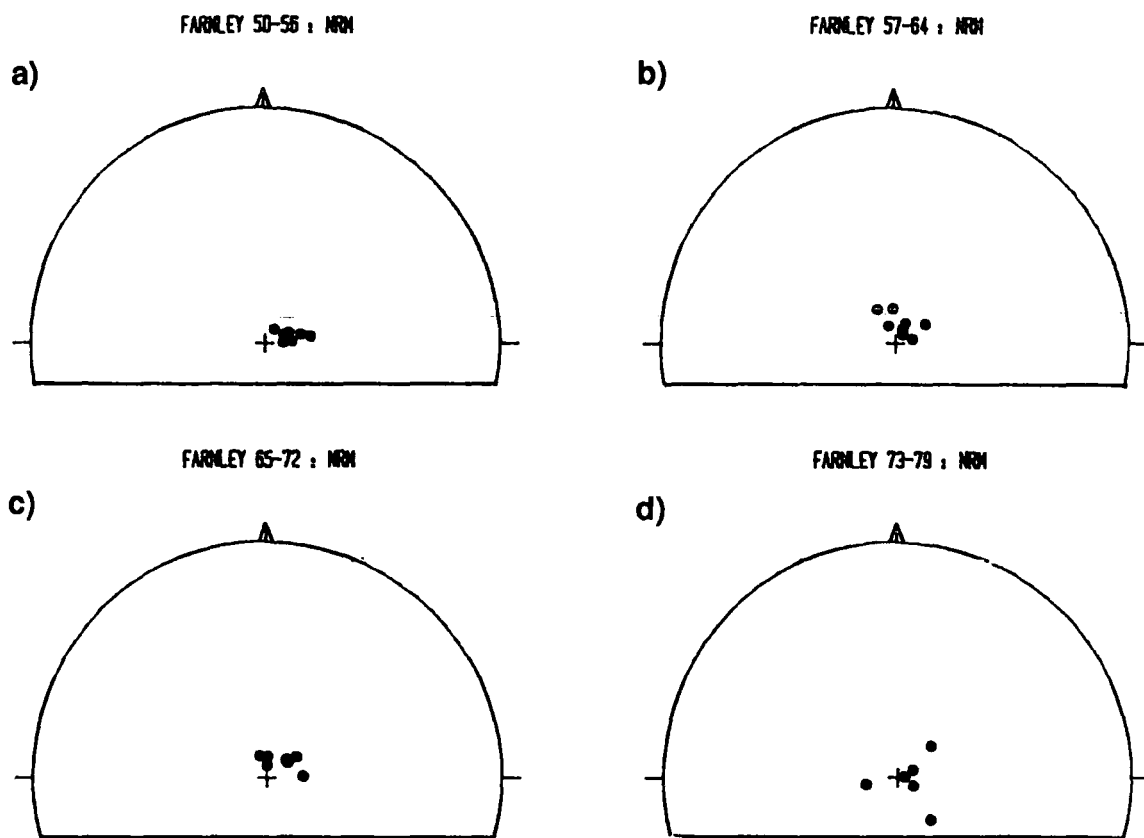


Figure 3.47: Stereographic plot of the NRM directions of magnetisation of samples a) FAR 50-56, b) FAR 57-64 c) FAR 65-72 and d) FAR 73-79.

there was no evidence of bioturbation in the lower horizons. The sediments were generally dry and rather loose, with very few visible organic inclusions and appeared very similar to those sampled at Prudhoe.

The section was cleaned well back from the original surface to remove weathered material and, as the deposits were soft, they were sampled using tubes, taking great care as the material was inclined to crumble. 8 samples were taken from each of 4 horizons by pushing tubes horizontally into the cleaned section (Fig. 3.46). 3 horizons were in the siltier material and one, the lowest, was in the sandy material. Orientation was carried out using a magnetic compass. Unfortunately the samples were very fragile and three did not survive transportation.

Archaeological interpretation of deposits sampled

The proximity of the deposits to the River Tyne, their sedimentary structure and their similarity in appearance to recent flood deposited sediments in the same area, suggested that they were a build-up of material resulting from over-bank flooding. At the time of writing, the section sampled had not been dated using geochemical markers and documentary flood records, as described for Prudhoe. However, an oak tree uncovered in the underlying gravel beneath the terrace was dated by radiocarbon to 4600cal BC-4940calBC (details of calibration and radiocarbon age in Macklin *et al.*, in press a). It is possible that the medium sand/silty sand laminations represent a sequence of annual floods or that the section records only the major floods over a much longer period of time.

Results of magnetic measurements

Natural remanent magnetisation

The intensity of NRM of all 29 samples (FAR 50-79) was very low, falling in the narrow range $1.1-2.7\mu\text{Am}^2\text{kg}^{-1}$, showing no marked differences between the horizons. The magnetic directions from samples in the silt horizons were slightly dispersed, with α_{95} values varying from 4.6° to 6.1° , whereas the magnetic directions of samples from the sandy horizon were considerably more dispersed with an α_{95} of 13.7° (Fig. 3.47). Although the NRM intensity was low, it was measurable above the noise level of the magnetometer.

Demagnetisation

8 samples were subjected to stepwise demagnetisation in an alternating field. The behaviour of a typical sample from the silt is shown in Fig. 3.48a. The repeatability of measurement of direction and intensity was good, despite the weakness of the magnetisation. The stereographic projection indicated that little directional change occurred in the magnetisation up to a demagnetising field of 80mT and the linear behaviour of the vector end-point, shown on the Zijderveld plot, confirmed that the remanence appeared to comprise of a single, stable component of magnetisation. The stable component was statistically well defined, with a stability index of 8.3 (very stable) over a range of 5 to 80mT. The plot of change in normalised intensity with increasing applied field fell gradually, revealing a sizeable hard component. In fact, more than 16% of the original value of intensity of magnetisation remained after demagnetisation in fields of 100mT. The median destructive field was 20-25mT. These observations indicated that there was a significant hard component of magnetisation, possibly due to haematite or goethite as suggested by the red colouring of the samples. In contrast, the magnetisation of the sandier samples was much softer (Fig. 3.48b) with a median destructive field of 7.5mT and only 2% of the original magnetisation remaining after demagnetisation in 30mT. The changes in direction of magnetisation did not reveal a stable component.

The remaining pilot samples showed similar behaviour to those described and were demagnetised in a field of 5mT to remove any soft, viscous components. This resulted in little change in the α_{95} of the silt samples, but considerably increased dispersion in magnetic directions of the sandy samples to an α_{95} value of 36.9° (Fig. 3.49).

Magnetic fabric

Specific susceptibility was in the range $9.4-12.9 \times 10^{-8} \text{m}^3 \text{kg}^{-1}$, with the sandy samples having susceptibilities towards the bottom of the range. The magnetic fabric was found to be weak, with $h\%$ in the range 0.6-4.5%. q values fell in a wide range 0.1-1.5, with more of the samples from the silt horizons than from the sand horizons falling in the range characteristic of an undisturbed depositional fabric. The principal axes of susceptibility for all the silt horizons showed a very similar distribution (e.g. Fig. 3.50). Both minimum and maximum axes were scattered, but showed some indications of a primary magnetic fabric. It seemed likely that the scatter was due to the low overall degree of anisotropy and hence difficulty of resolving the axes with the instrument available. The magnetic fabric results for the sand samples (not shown) appeared very scattered, but too few survived to draw any conclusions.

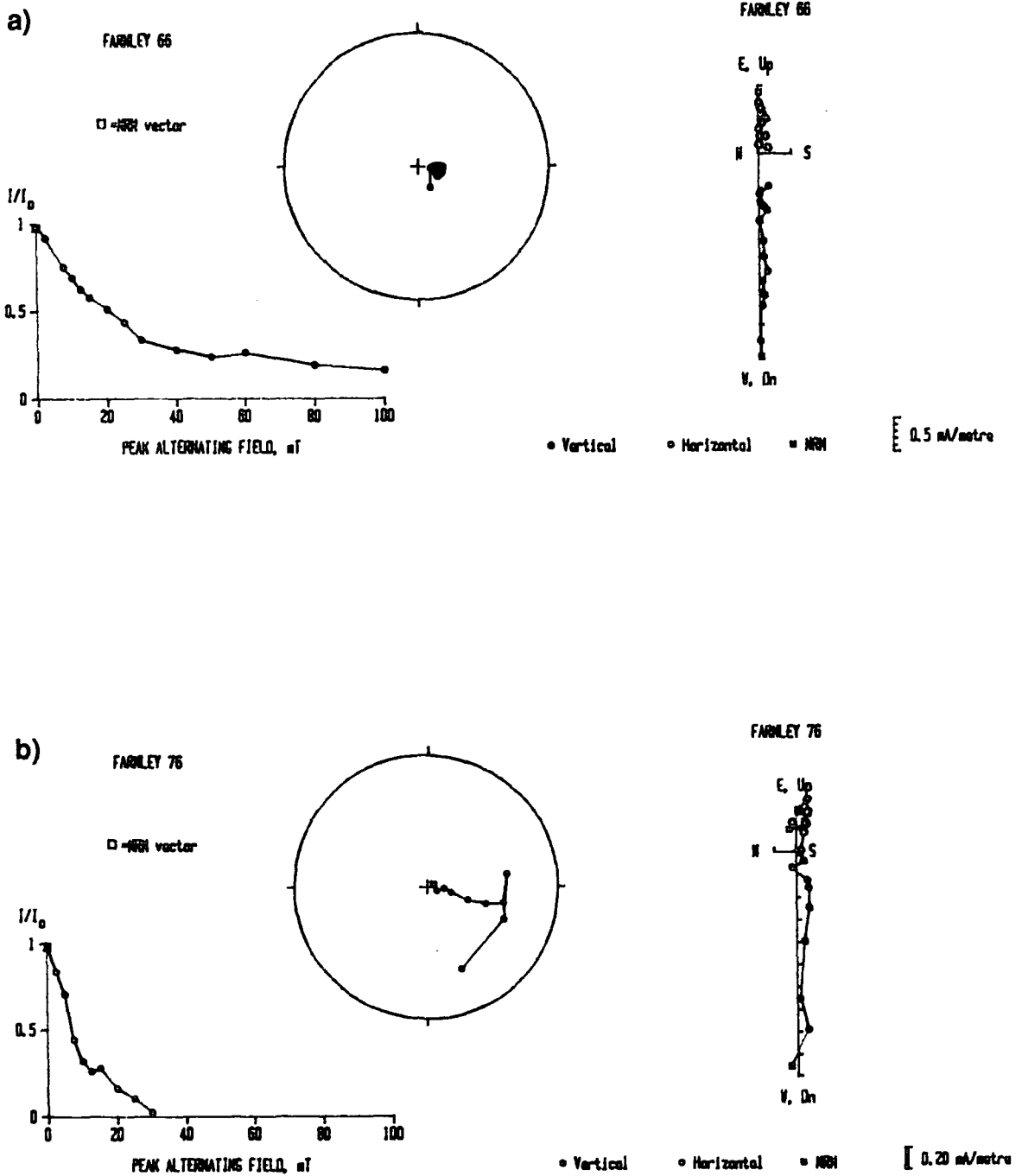


Figure 3.48: Stereographic, intensity and Zijdeveld plots of the behaviour of a typical sample *a)* from the silt (FAR 66) and *b)* from the sand (FAR 76) on alternating field demagnetisation.

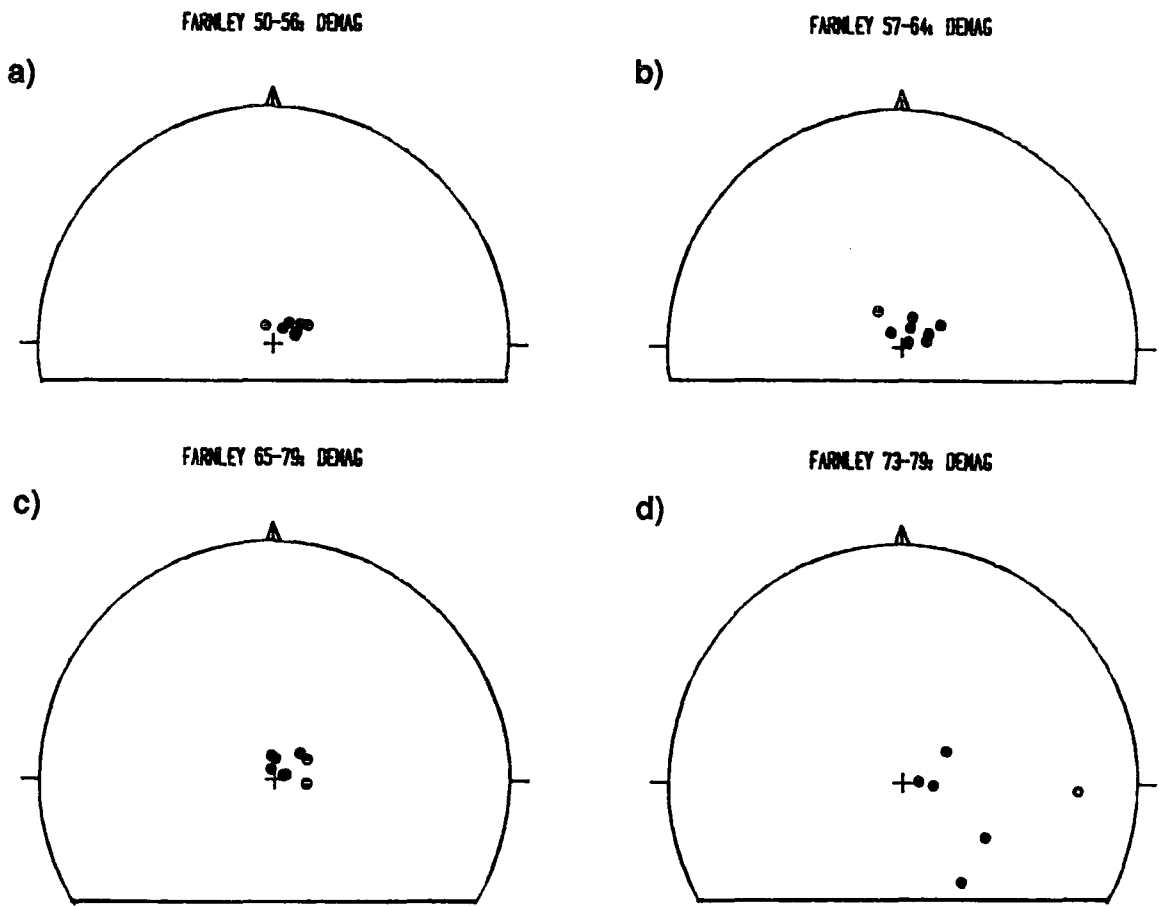


Figure 3.49: Stereographic plot of directions of magnetisation after partial demagnetisation of samples a) FAR 50-56, b) FAR 57-64 c) FAR 65-72 and d) FAR 73-79.

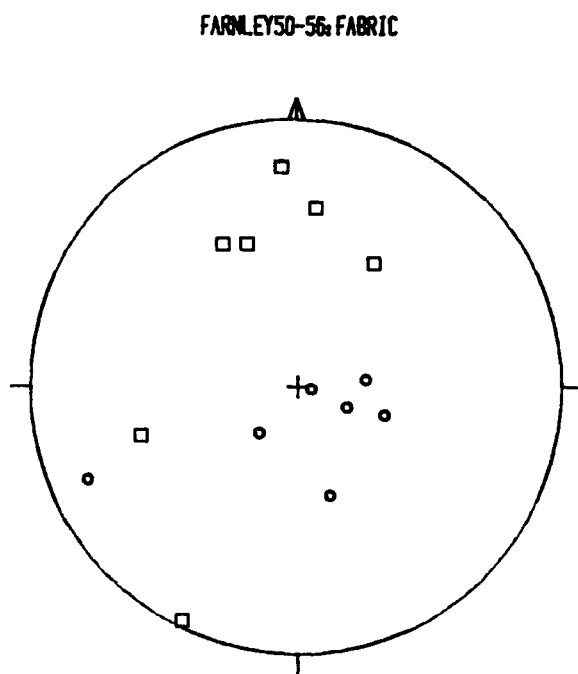


Figure 3.50: Magnetic fabric of samples FAR 50-56

Magnetic mineralogy

IRM acquisition tests were carried out on three samples; two from the silt and one from the sand (e.g. Fig. 3.35a). For the silt samples, the SIRM value was in the range $1.1\text{--}1.2\text{mAm}^2\text{kg}^{-1}$ and 94% of this value was reached in an applied field of 1T. $(B_0)_{\text{cr}}$ was 29-30mT (Fig. 3.35b) and the S ratio was 0.7. These parameters suggested that, while a soft magnetic mineral such as magnetite dominated the acquisition curves, there was also a significant contribution from harder magnetic minerals, such as haematite or goethite, indicated by the low S ratio. In contrast, although the sand sample had a similar SIRM value of $1.0\text{mAm}^2\text{kg}^{-1}$, 98% of this value was acquired in fields of less than 1T (Fig. 3.35a). $(B_0)_{\text{cr}}$ was very low, 15mT and the S ratio was 0.9 (Fig 3.35b), suggesting that the remanence carrying mineral was predominantly magnetite in the form of large, multidomain grains.

General conclusions

It appeared that the silt material had a stable magnetisation, preserved by a mixture of magnetite and haematite or goethite grains within the matrix. This magnetisation may have been depositional or post-depositional in origin, or be the result of the growth of a chemical remanence, in the orientation favoured by existing magnetic particles. The haematite may be detrital in origin, weathered from nearby Triassic tills, or be the result of a post-depositional chemical change. The goethite would arise from weathering processes. The stable magnetic directions obtained from the three silt horizons were indistinguishable, and so were combined to give an average direction of magnetisation for all three horizons. When this direction was compared to the archaeomagnetic calibration curve (Fig. 3.51), it fell closest to the section dated to before 500BC, although the error bars did not intersect with the calibration curve. As discussed in Section 2.5.4, there are a number of inadequacies in the present dating procedure and this magnetic direction is reconsidered in the light of developments of the calibration curve in Chapter 5 (Section 5.6.4).

Comparison of a single magnetic direction with the lake sediment curve of Turner and Thompson (1982) would normally be unjustifiable. However, in this case (Fig. 3.52) the high declination and inclination values meant that magnetic direction was only consistent with the direction of the Earth's field between 550calBC and 1850calBC. The error margins were large, partly because of the dispersion of magnetic directions, but also because the steep inclination led to high errors in declination. This suggested date range must be treated with great caution as comparison of a single magnetic direction with the lake sediment curve is rather dubious (Section 2.5.4). More certainty could be expressed if there had been some indication of secular variation through the sediment

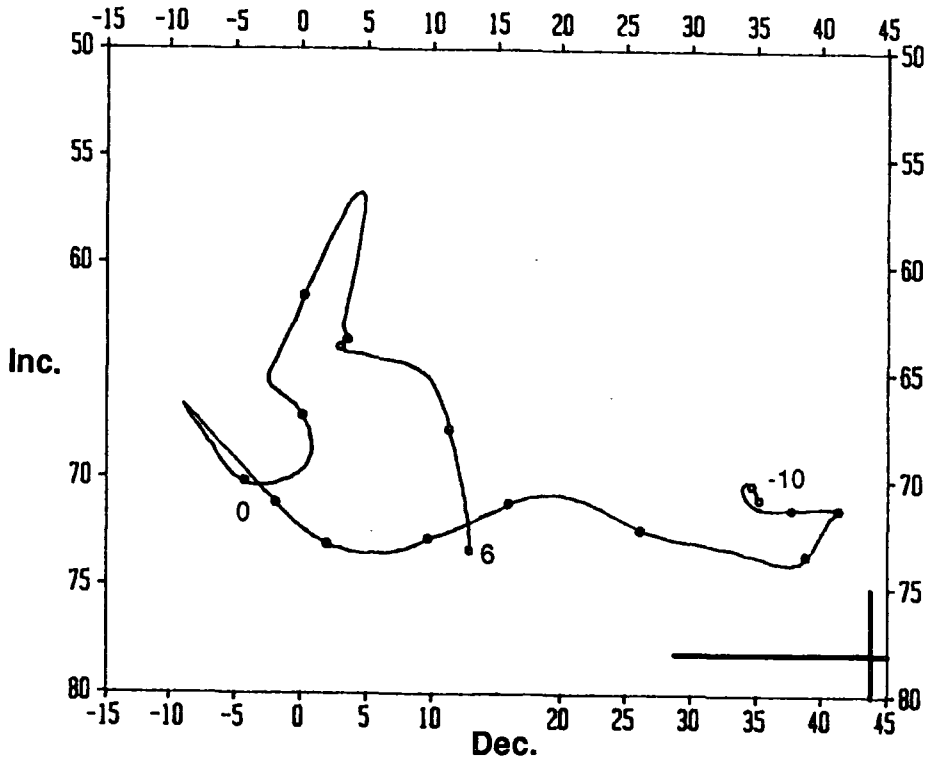


Figure 3.51: Mean magnetic direction after demagnetisation of all Farnley silt samples with errors at 95% confidence, corrected to Meriden and fitted to the British calibration curve covering 1000BC-AD600. The calibration curve was digitised from that of Clark *et al.* (1988); circles indicate centuries and the figures are 100's of years.

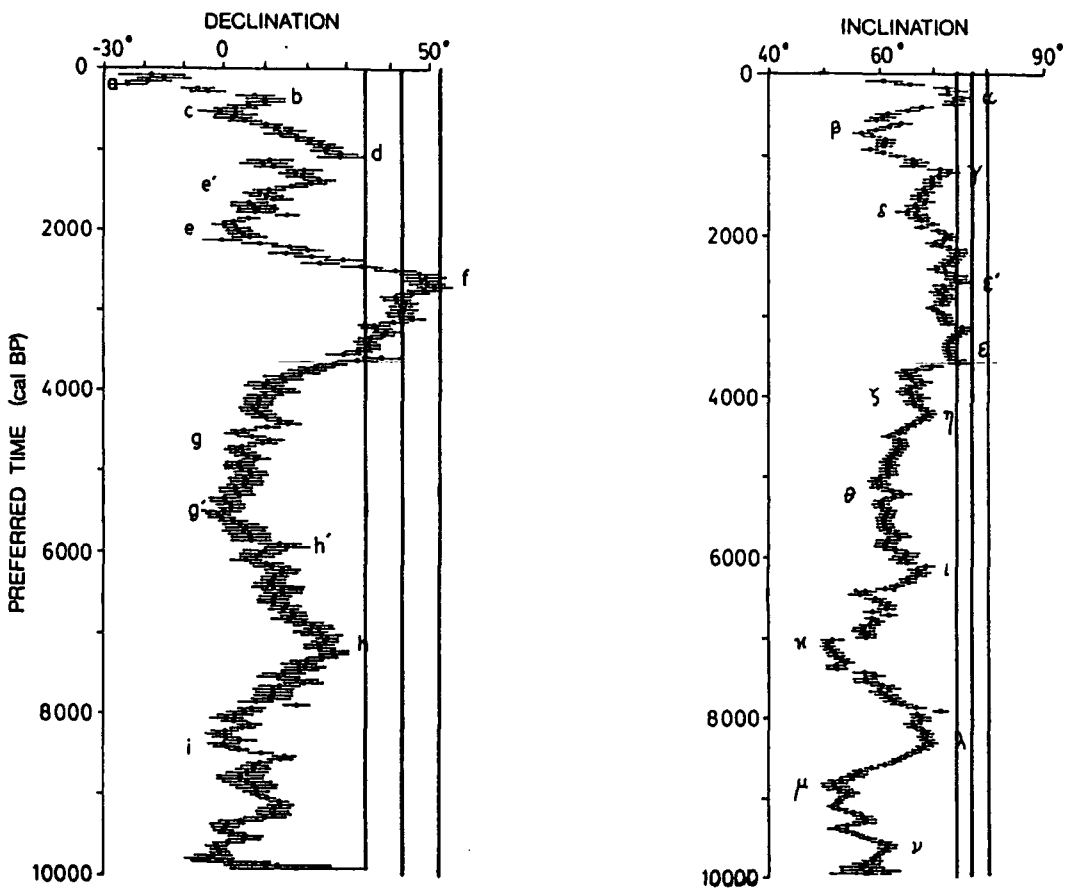


Figure 3.52: As above but with direction compared to lake sediment secular variation curve of Turner and Thompson (1982).

section. However, the date was consistent with the radiocarbon dates for the tree below the sequence and was supported by the existence of late/mid-Bronze Age standing stones in the vicinity, erected on what would appear to be the same sedimentary unit as that dated here (M. Macklin, pers. comm.). The date also corresponded to a period of climatic deterioration and incision in the middle and lower Tyne between 1350-550BC. During this period climatic records indicate a shift to colder and probably wetter conditions (Macklin *et al.*, in press a). The River Tyne appears to have adjusted to the larger and more frequent floods by accelerated overbank deposition and widening and deepening of the river channel.

The sand material did not retain a stable magnetisation, either as a result of never having acquired such a magnetisation or of it having been disturbed subsequent to deposition. Remanence carrying minerals, predominantly magnetite, did exist in the material but they had a very soft magnetisation, which did not appear to retain a record of the geomagnetic field at the time of deposition.

3.4.7 Redlands Farm Roman Villa, Nr. Stanwick, Northamptonshire (O.S. Grid Ref. SU 9583 7058)

Site description

Excavations were carried out by the Oxford Archaeological Unit at the site of the Roman villa near Stanwick in the summer of 1990 (Fig. 3.1). The site was situated within the area covered by the Raunds Area Project (Dix, 1987), where there have been a number of interesting archaeological excavations, ranging from Beaker burials to a Medieval hamlet (Windell *et al.*, 1990). The villa at Redland's Farm was in the floodplain of the River Nene, on what was probably originally a low island of sand (Keevill, 1990), and was under threat from gravel extraction. Excavations revealed a number of phases of development and abandonment of the structures, which were sufficiently important for the threat of destruction to be lifted.

In the 2nd century AD a two roomed building was constructed, consisting of living quarters and a cellar. The building was approached by two substantial stone lined aqueducts and has been interpreted as being a water mill (Keevill, 1990), although there was no indication of the location of the millstone. It is not known when the mill went out of use, but the building was then converted into a winged corridor villa by dividing part of the original building into two, constructing wings to the east and west and adding a single long room to join the wings. The cellar was converted into a hypocaust room and the floors of the villa were covered with tessellated and mosaic pavements. At a later stage, a corridor or verandah was built between the projected wings and a second storey was added to the east wing. The second storey is dramatically evident as the entire northern gable wall was deliberately toppled at a later date and fell intact, preserving its structure. Subsequent alterations to the villa included the subdivision of the wings and modifications to the hypocaust. The decline of the villa probably began in the late 4th century AD, when parts of the building gradually fell into disrepair, the hypocaust disintegrated and the patterned pavements were broken up. The two wings, including the northern gable wall, were deliberately demolished. They had been constructed on sloping ground, over the mill leat, and had probably become unsafe by the late 4th or early 5th century AD (Keevill, 1990).

To the south and east of the villa, excavations revealed a series of courtyards and associated buildings, including two Roman round houses and two rectangular barns (Fig. 3.53). Environmental evidence suggested that the round houses were occupied by humans and animals, indicating that the area was associated with farming. A threshing barn was discovered to the south and the fields to the east appeared to be prehistoric in

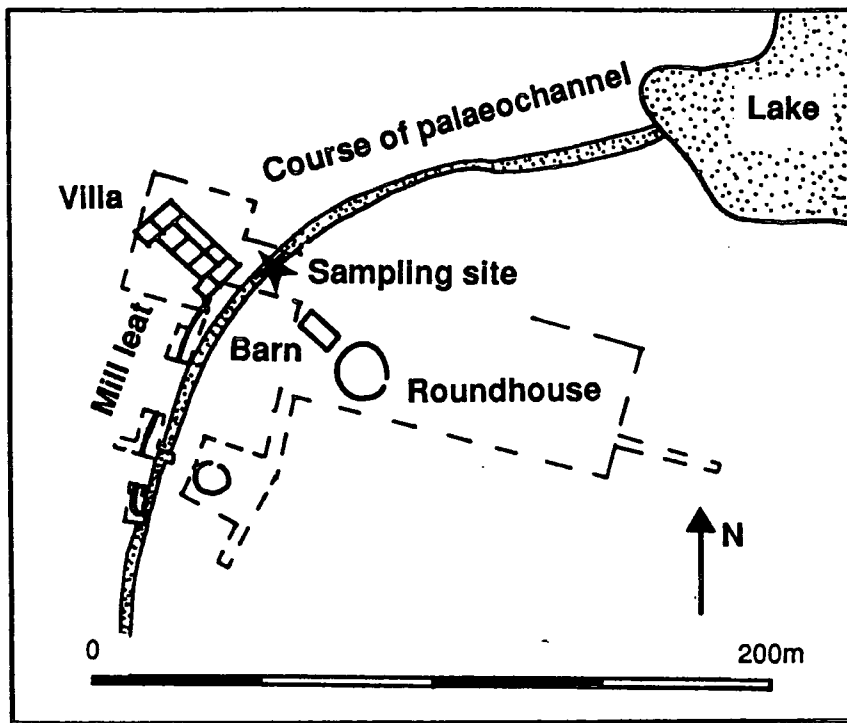


Figure 3.53: Plan of the Stanwick site (after Keevill, 1990). The dotted line indicates the area under excavation.

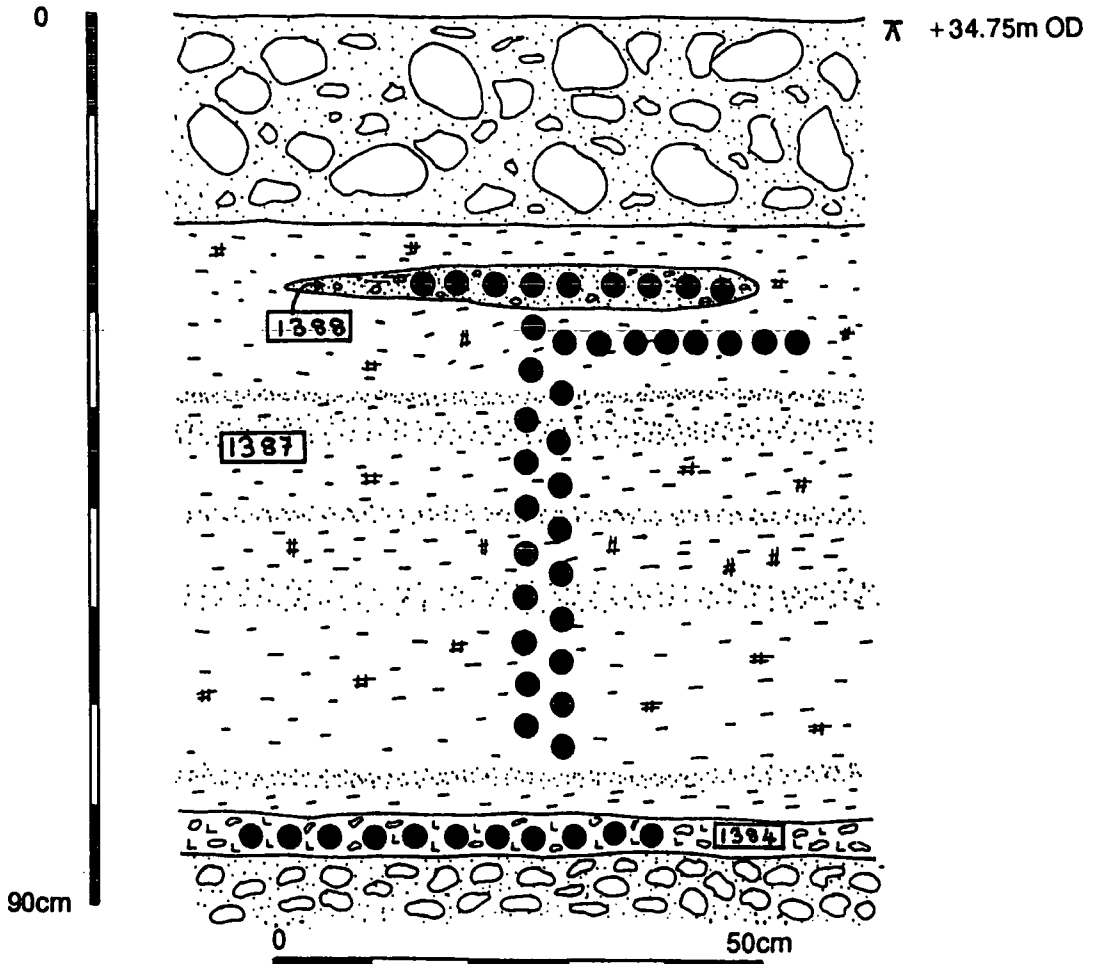


Figure 3.54: Vertical section drawing of Stanwick channel, showing the location of samples .

origin. Dividing the villa from the farm buildings was a palaeochannel which had been infilled with rubble (Fig. 3.53).

Description of the deposits sampled

Samples were taken from the fill of the palaeochannel with a view to attempting to date its construction, abandonment and infilling. The channel was situated between the villa and the farmstead (Fig. 3.53) and was approximately 5m wide, running south-west to north-east. It was infilled with a series of deposits, described in detail below. The channel was sealed by rubble and covered by a layer of alluvium (Fig. 3.54).

Context No. 1388: This context consisted of a light, yellowish brown (Munsell No. 10YR 5/4) sand lens, occurring within context 1387, 26cm below the top of the rubble surface. The lens was horizontal with a uniform thickness of 4cm and a lateral extent of 0.5m. The material of the deposit was a coarse, dry, loose packed sand comprising of large, poorly sorted angular grains. About 5% of the matrix was pebbles around 1cm in diameter. There were also inclusions of chalk and small patches (about 2-5cm in diameter) of dark brown silty mottling. There was no visible evidence of biological activity or any organic material, but there were some sedimentary structures associated with compaction.

Context No. 1387: This context underlay the rubble and sand layer, sealing the grey clay (context 1384) and contained the sand lens (context 1388), with both boundaries being sharp and horizontal. It extended from the centre of the trench, where it was truncated by a cut infilled with a grey clay, to the eastern edge of the channel where it thinned, having a greatest thickness of 60cm. The deposit was a dark grey (Munsell No. 10YR 3/1) silty loam, incorporating a number of yellowish brown (Munsell No. 10YR 5/4) sand laminations. The silty loam was moist, plastic and well sorted, containing no stones or roots. There was considerable organic matter in the matrix, including twigs and a relatively large quantity (about 2%) of charcoal. In contrast, the material making up the sand laminations was large grained and loose. These horizons were generally 1-2cm thick and horizontal.

Context No. 1384: This was the lowest deposit in the series under investigation, underlying context 1387 and overlying a sand and gravel mix containing large (up to 10cm) pebbles. It consisted of a compact, dark grey clay (Munsell No. 10YR 4/1), which extended from the edge of the trench towards the centre, where it was truncated by a cut infilled with grey/brown clay, but appeared again towards the far side of the trench. The layer was at a depth of 60cm beneath the rubble surface and had a uniform thickness of

approximately 5cm. The clay was dry and hard and contained a large quantity (about 50%) of irregularly shaped stones and pieces of chalk making sampling very difficult. There were no roots, burrows or other evidence of bioturbation, neither were there any visible sedimentary structures. A number of shells were retrieved on excavation.

All the deposits were sampled by the tube method, which created little visible disturbance to the sediment surface although care had to be taken when sampling the loose sands and to avoid stones. For each context, holders were pushed horizontally into the cleaned surface and a continuous sequence of samples was also taken down a vertical section through context 1387. In all 47 were taken, the locations of which are shown in Fig. 3.54. Orientation was carried out using a magnetic compass.

Archaeological interpretation of deposits

The archaeological evidence (G. Keevill, pers. comm.) suggested that the channel was cut into the natural gravels before the development of the Roman settlement. The water from it was deliberately diverted into the southern leat to provide the primary water supply for the early Roman mill. It would therefore be expected that in the Roman period the channel would contain very little water. In the later Roman period the channel may have become active again, although the leat was kept at least partially open to feed a man-made pond. The channel then appeared to have silted up over the years, until rubble was deliberately dumped over it, possibly still during the Roman period, to seal it off or perhaps to make the soft ground passable. The rubble was sealed by a thick layer of alluvium, which had been deposited by the early Medieval period and possibly as early as mid-Saxon times. At the time of writing, the post-excavation examination of the pottery and the environmental analyses had not been carried out, but it is hoped that these will help to complete the picture in the future.

Results of magnetic measurements: Context 1388

Natural remanent magnetisation

The intensity of NRM of samples from context 1388 fell in the wide range of 7.5-56.7 $\mu\text{Am}^2\text{kg}^{-1}$ and the magnetic directions were dispersed (Fig. 3.55), with an α_{95} value of 17.1°.

Demagnetisation

3 samples were subjected to stepwise, alternating field demagnetisation and the behaviour of a typical sample is shown in Fig. 3.56a. The stereographic projection

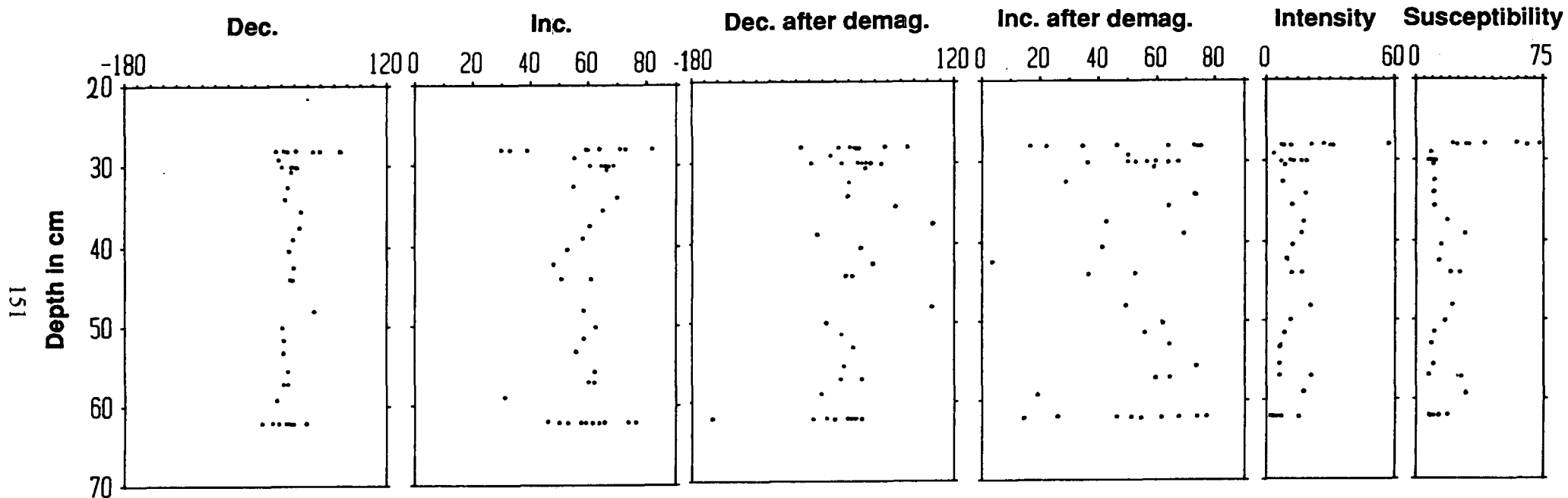


Figure 3.55: Plot of depth against NRM declination (Dec.), NRM inclination (Inc.), declination after demagnetisation, inclination after demagnetisation (all in degrees) and intensity (in $\mu\text{Am}^2\text{kg}^{-1}$) and susceptibility ($\times 10^{-8}\text{m}^3\text{kg}^{-1}$) from all the samples taken from Stanwick.

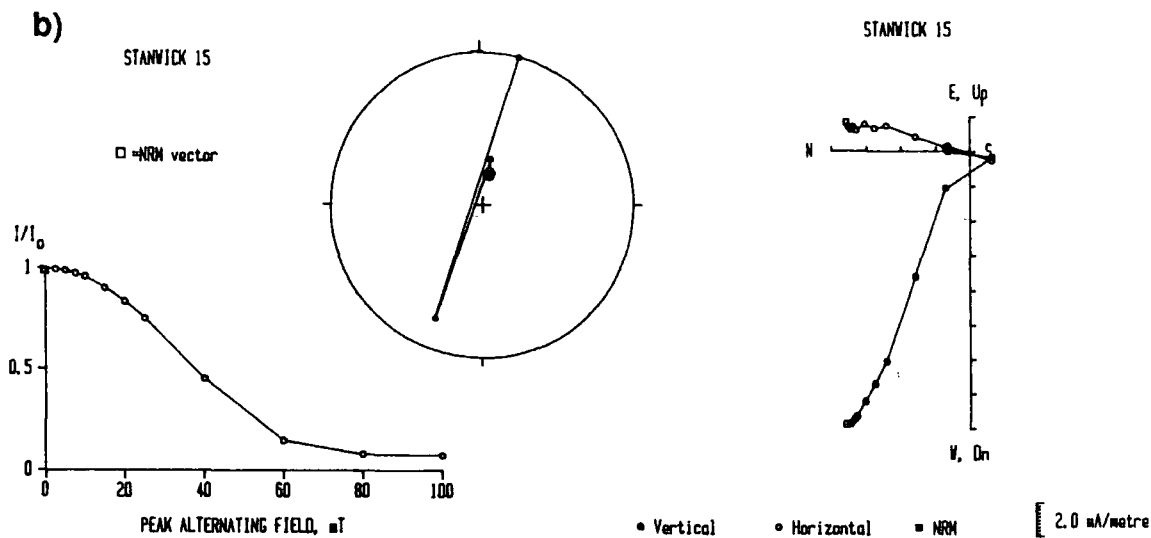
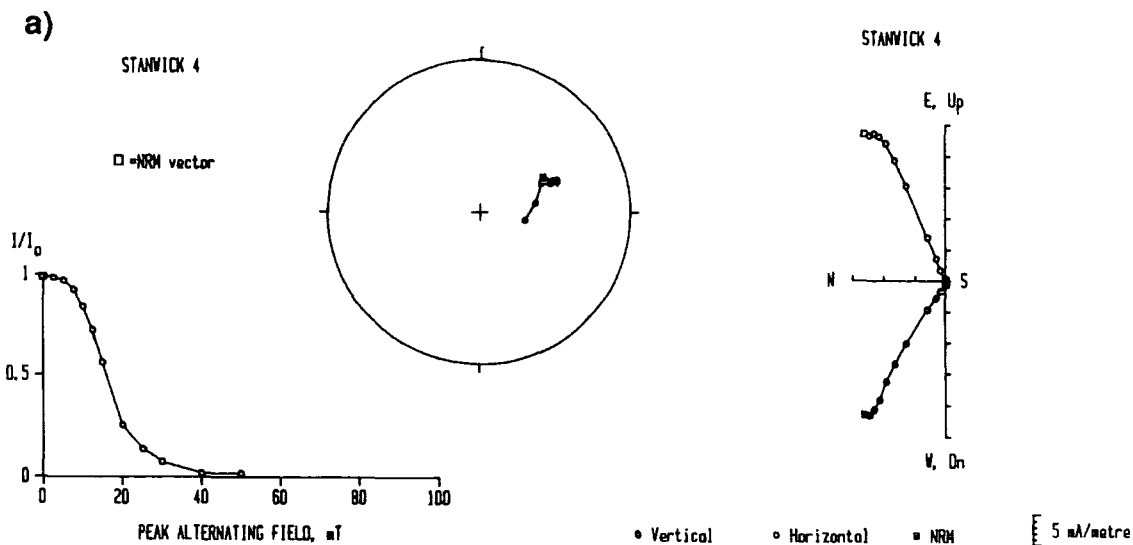


Figure 3.56: Stereographic, intensity and Zijderveld plots of the behaviour of *a)* typical sample (STAN 4) from the silt, context 1388, *b)* typical sample (STAN 15) from the clay lens, context 1387, on alternating field demagnetisation.

indicated that little directional change occurred in the magnetisation up to a demagnetising field of 30mT. The movement of the vector end-point shown on the Zijderveld plot showed a small change in direction followed by linear behaviour, suggesting that the remanence comprised of a stable component of magnetisation with a slight overprint. The stable component was statistically well defined with a stability index of 6.0 (very stable) over a range of 7.5-25mT. The intensity fell very sharply, reducing to less than 2% of the original value after demagnetisation in fields of 40mT, with a very low median destructive field of 15mT. These observations indicated that the magnetisation was very soft but had a stable component, measurable above the noise level of the magnetometer.

As the material was homogeneous and the pilot samples showed very similar behaviour on demagnetisation, the remaining samples were demagnetised in a field of 10mT to remove the softer component of magnetisation. After partial demagnetisation the dispersion had increased, giving an α_{95} of 22.4° (Fig. 3.55).

Magnetic fabric

Specific susceptibility was much higher than most other sediments in this study, falling in the range $22.2-73.0 \times 10^{-8} \text{m}^3 \text{kg}^{-1}$ and the magnetic fabric was also very strong, with $h\%$ in the range 4.1-11.3%. q values fell in the range 0.07-0.98, 86% of them in the range characteristic of an undisturbed depositional fabric. The minimum axes were very loosely grouped, indicating a weak magnetic foliation (Fig. 3.57a) and the maximum axes were scattered showing no obvious lineation. This fabric suggested that the sediment might have been deposited grain by grain in water and that elongated grains had not been strongly affected by orienting forces, such as current flow. However, it must be noted that the wide range of susceptibilities and the strong degree of overall anisotropy of susceptibility was very unusual.

Magnetic mineralogy

Application of pulse fields of increasing intensity to a pilot sample resulted in a sharp increase of induced IRM, followed by a small further increase at higher fields (e.g. Fig. 3.58a). The SIRM value was $4.12 \text{mAm}^2 \text{kg}^{-1}$ and 99% of this value was reached in an applied field of 1T. $(B_0)_{\text{cr}}$ had a very low value of 13mT (e.g. Fig. 3.58b) and the S ratio was 0.9, suggesting that the magnetic mineral carrying the remanence was almost entirely magnetite, with virtually no contribution from harder magnetic minerals. The low value of $(B_0)_{\text{cr}}$ implied that the magnetite was mainly in the form of larger, multidomain grains.

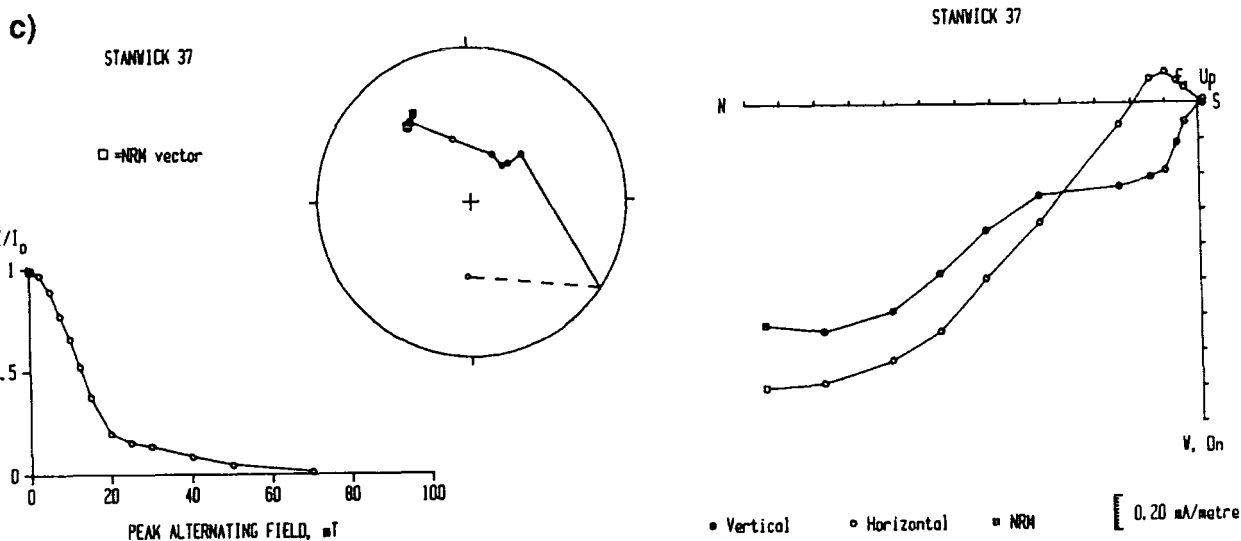


Figure 3.56c): Stereographic, intensity and Zijderveld plots of the behaviour of a typical sample (STAN 37) from the lower clay, context 1384, on alternating field demagnetisation.

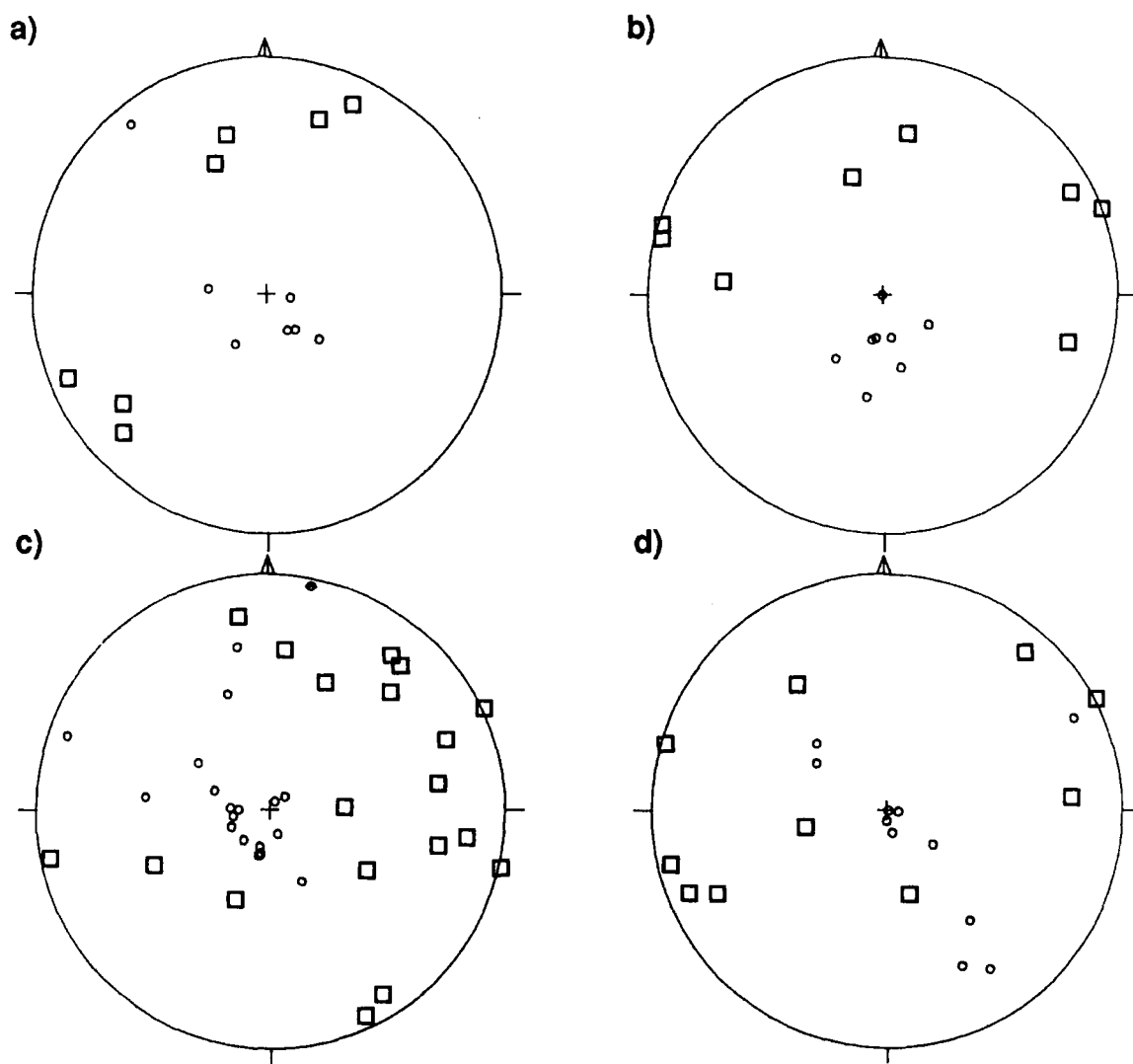


Figure 3.57: Magnetic fabric of samples a) STAN 1-9, b) STAN 10-17, c) STAN 18-36 and d) STAN 37-47.

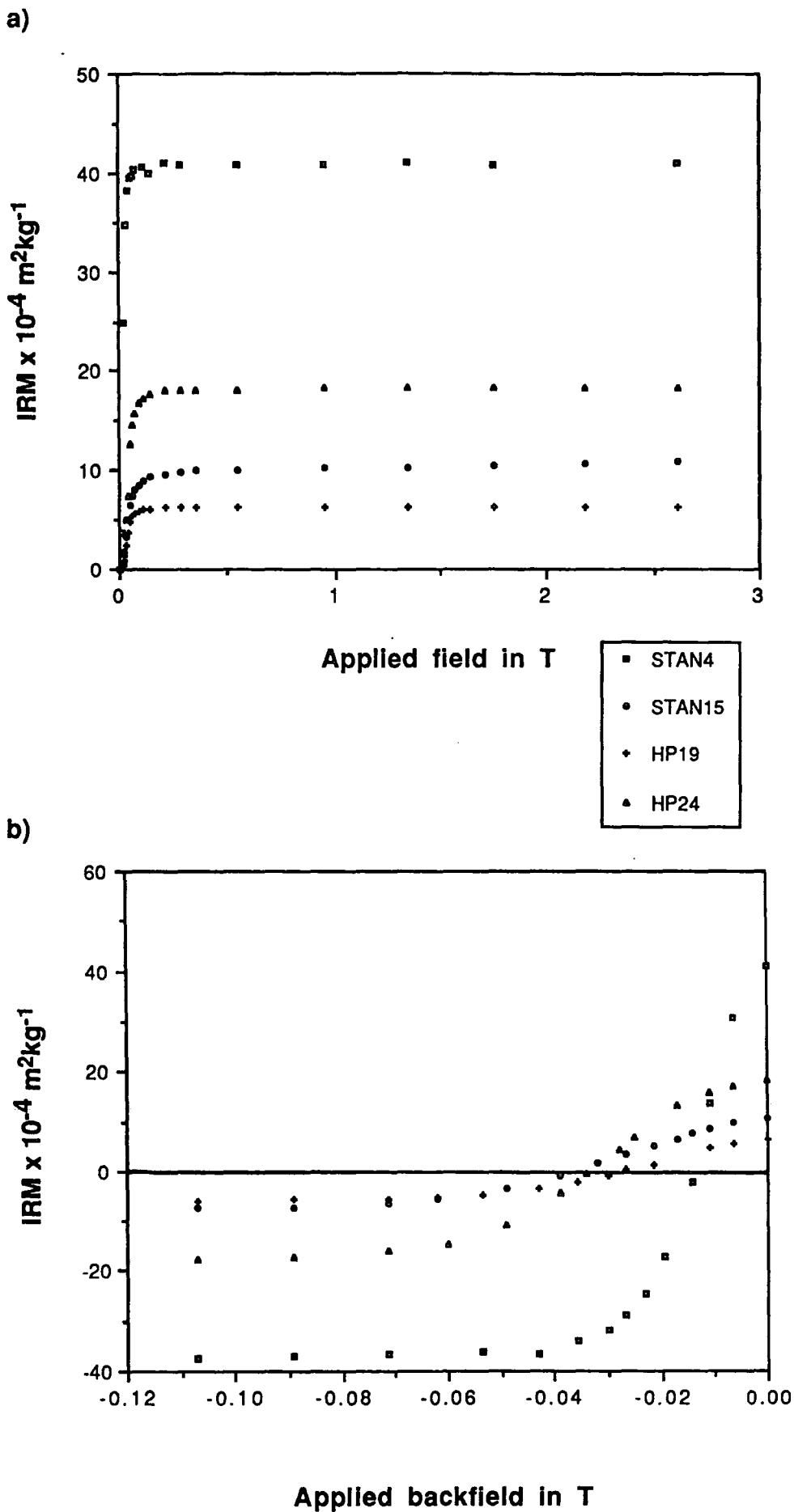


Figure 3.58 a: IRM build-up curve for samples STAN 4, STAN 15, HP 19 and HP 24.
 b: Plot of back coercivity for samples STAN 4, STAN 15, HP 19 and HP 24.

Results of magnetic measurements: the clay lens within Context 1387

Natural remanent magnetisation

The intensity of NRM of samples from the clay lens fell in the range 6.7-18.9 $\mu\text{Am}^2\text{kg}^{-1}$, slightly weaker than context 1388, but still above the noise level of the magnetometer. The directions were well grouped (Fig. 3.55), with an α_{95} value of 2.3° based on all 8 samples.

Demagnetisation

The behaviour on demagnetisation of one of the 4 pilot samples is shown in Fig. 3.56b. The stereographic projection showed no perceptible movement of the vector on demagnetisation up to fields of 60mT. The Zijderveld plot confirmed that the remanence mainly comprised of a single stable component, with a slight overprint removed at low fields. The plot of change in normalised intensity with applied field fell less sharply than that of samples from context 1388, with more than 45% of the original value remaining after demagnetisation at 40mT, and a higher median destructive field of 30-40mT. These observations indicated that there was a stable remanence, which had a stability index of 16.4 (extremely stable) over the range 7.5-40mT and was considerably harder than that of context 1388.

The remaining samples were demagnetised in a field of 10mT to remove the softer overprint. It was noted that the dispersion of magnetic directions increased after demagnetisation to an α_{95} of 11.4° (Fig. 3.55).

Magnetic fabric

Specific susceptibility was in the range 8.7-11.5 $\times 10^{-8}\text{m}^3\text{kg}^{-1}$, much lower than that of context 1388. The magnetic fabric was also found to be weaker than that of context 1388, with $h\%$ in the range 1.5-3.4%. The q values fell in the range 0.23-1.22, 63% of them in the range characteristic of an undisturbed primary depositional fabric. The minimum axes were loosely grouped (Fig. 3.57b) indicating a weak foliation plane and the maximum axes were rather scattered giving no clear indication of a lineation. The positions of both minimum and maximum axes were consistent with a shear force having acted on the sediment, perhaps due to compaction causing a systematic disturbance of the magnetic fabric. This suggestion was consistent with the sedimentary structures observed.

Magnetic mineralogy

A typical SIRM value was 1.08 $\text{mAm}^2\text{kg}^{-1}$ and 94% of this value was reached in an applied field of 1T (Fig. 3.58a). $(B_0)_{\text{cr}}$ was 37mT, much higher than context 1388 (Fig. 3.58b) and the S ratio was 0.7. These parameters suggested that a soft magnetic

mineral, such as magnetite, was the dominant remanence carrier. However, there was a significant contribution from harder magnetic minerals, possibly haematite or goethite, as shown by the comparatively low S ratio. The high value of $(B_o)_{cr}$ suggests that a mixture of magnetite and haematite/goethite grains were contributing to the remanence.

Results of magnetic measurements: Context 1387- the vertical section.

Natural remanent magnetisation

The NRM intensity of the remaining samples from context 1387 fell in the range $3.9\text{-}20.6\mu\text{Am}^2\text{kg}^{-1}$, showing a general increase and then decrease through the section. The magnetic directions were fairly well grouped down the section but no obvious trends were discernible (Fig. 3.55).

Demagnetisation

All 4 of the pilot samples demagnetised exhibited different behaviour (not shown) and none indicated that the magnetic vector was moving towards a stable endpoint. The intensity generally fell very sharply with increasing applied fields, reducing to less than 6% of the original value after demagnetisation in fields of 40mT and the median destructive field was very low, 12.5-15mT. These observations indicated that most of the magnetisation was very soft, with no obvious stable component measurable above the noise level of the magnetometer.

The remaining samples were demagnetised in a field of 10mT to remove the softest component of magnetisation in an attempt to improve the grouping. However, after partial demagnetisation the dispersion increased considerably (Fig. 3.55).

Magnetic fabric

Specific susceptibility was in the range $8.1\text{-}28.4\times 10^{-8}\text{m}^3\text{kg}^{-1}$, showing similar variations to the intensity trends down the section. The magnetic fabric was found to be fairly weak, with $h\%$ in the range 1.8-3.9%. q values fell in the range 0.12-1.24, 68% of them in the range characteristic of an undisturbed depositional fabric. The minimum axes were very loosely grouped, with a weak magnetic foliation (Fig. 3.57c), possibly suggesting grain by grain deposition, whereas the maximum axes were scattered showing no obvious lineation. This fabric indicated either that there had been no preferential alignment of elongated grains or that the axes were too weak to be resolved accurately.

Magnetic mineralogy

SIRM values were varied but a typical value was $1.63\text{mAm}^2\text{kg}^{-1}$, with around 96% of this value reached in an applied field of 1T. $(B_0)_{\text{cr}}$ was around 25mT and the S ratio was 0.8, suggesting that the magnetic mineral carrying the remanence was predominantly magnetite, with a contribution from harder magnetic minerals.

Results of magnetic measurements: Context 1384

Natural remanent magnetisation

The intensity of NRM of samples from context 1384 was in the range $2.2\text{--}16.8\mu\text{Am}^2\text{kg}^{-1}$, similar to the intensity of magnetisation of the higher clay lens (within context 1387). The directions of magnetisation were fairly well grouped (Fig. 3.55), with an α_{95} value of 6.6° based on all 11 samples.

Demagnetisation

The behaviour of one of the 3 samples subjected to stepwise demagnetisation is shown in Fig. 3.56c. The Zijderveld plot and stereographic projection showed that the remanence consisted of a soft magnetic overprint obscuring a stable component which in turn overprinted a further component, revealed at higher demagnetising fields. The intensity plot showed one very soft component of magnetisation and another of higher coercivity appearing in fields over 20mT. 20% of the original magnetisation remained after demagnetisation at 20mT which fell to 1% in fields of 70mT and the median destructive field was 12.5-15mT.

As the material was homogeneous and the pilot samples showed virtually identical behaviour on demagnetisation, the remaining samples were demagnetised in a field of 10mT and 30mT in an attempt to isolate the two components. After each demagnetisation the dispersion increased with an α_{95} of 18.6° after demagnetisation to 10mT (Fig. 3.55) and an α_{95} of 21.3° after demagnetisation to 30mT.

Magnetic fabric

Specific susceptibility was in the range $8.6\text{--}19.1 \times 10^{-8}\text{m}^3\text{kg}^{-1}$, similar to context 1387. The magnetic fabric was found to be generally weak, with $h\%$ in the range 1.3-4.1%. The q values ranged from 0.24-1.09, with only 55% falling in the range characteristic of an undisturbed depositional fabric. The maximum axes were scattered (Fig. 3.57d), possibly indicating the inability of the instrument to measure such a weak magnetic fabric or suggesting that there was no systematic alignment of elongated grains. However the minimum axes did appear to show a slightly girdled distribution, which is often associated with slumped material (e.g. Noel, 1986c).

Magnetic mineralogy

IRM acquisition showed a similar pattern to that of the material in context 1387, with 92% of the SIRM being attained in a field of 1T and an SIRM value of $1.01\text{mAm}^2\text{kg}^{-1}$. $(B_0)_{\text{cr}}$ was 20mT and the S ratio of 0.66 indicated that, while the predominant remanence carrying mineral was probably magnetite, there was a contribution from a harder, unsaturated magnetic mineral, possibly haematite or goethite, which may have been the carrier of the harder, stable component.

General conclusions

In all the contexts sampled, the magnetic fabric was consistent with the material being waterlain in origin, and in some cases suggested that slumping had occurred. There was no indication of preferential alignment of elongated grains. However, in general, the magnetisation was very soft and in all cases the dispersion of magnetic directions increased upon demagnetisation. This suggested that, if the geomagnetic field at the time of deposition had been recorded, this record had been completely obscured by later overprints, possibly of chemical or viscous origin, and so no dating information was available. Contexts 1387 and 1384 had very similar mineralogies, with both magnetite and haematite/goethite contributing to the remanence; the magnetite may have been detrital in origin and that the haematite/goethite may be the result of post-depositional chemical changes. Context 1388 had no significant haematite/goethite contribution and the magnetite grains were much larger than those of other sediments from this study. The difference in magnetic mineralogy and the appearance of the sand lens suggested that it came from a different source to the rest of the material. It might possibly be a dump deposit.

3.4.8 Hartlepool Bay, Hartlepool, Co. Durham

(O.S. Grid Ref. NZ 5140 3210)

Site description

The peat beds found in the intertidal zone of Hartlepool Bay (Fig. 3.59) are of archaeological interest as they contain artefactual evidence of human activity during the late Mesolithic and early Neolithic periods, and biological evidence of the changing environment exploited by humans (Tooley, 1978). The habitat available to early humans depended chiefly on the relationship between the sea and the land. For example, a rise in sea-level would cause a marine transgression into low lying areas, with movement landwards of coastal plant species and an acceleration of the erosion of cliffs. Conversely, a fall in sea-level would result in the shore advancing seawards and more land being colonised by herbaceous plant species. In Hartlepool Bay changes in sea-level have resulted in the formation of alternate layers of organic and inorganic deposits, which have been shown by coring to differ in composition, sequence and areal extent across the bay (Tooley, 1984). In general, the sequences commenced with boulder clay which had an undulating surface and the depressions were infilled with biogenic sediments. This was followed by a basal peat, overlain by a grey, clayey silt which contained woody detritus and valves indicative of marine estuarine conditions. This deposit was in turn overlain by limus and woody detritus (Tooley, 1984). Radiocarbon dating of organic material taken from under the clay gave a date of 4250calBC-3990calBC and material over the clay was dated at 4090calBC-3990calBC (radiocarbon ages 5285±120BP (Hv. 4712) and 5240±70BP (Hv. 3459) respectively, errors at 1σ, from Tooley (1978), calibrated using Pearson *et al.* (1986)).

The archaeological finds from the foreshore of Hartlepool Bay included flints, struck flakes, charcoal and worked wooden objects. In 1972 skeletal remains were found in peat just south of the sampling site. The skeleton was a male of short, stocky build, aged 25-30 (Powers, 1972 in Tooley, 1978). The dentition showed no caries, but the teeth were badly worn and there was evidence of gum recession. Examination of the cranium revealed two blows on the head had been sustained but recovered from, there was a well healed rib fracture and evidence of arthritis on the extant vertebrae. The skeleton was disarticulated, possibly by predators or peat erosion in the intertidal zone, and the posture indicated a bog burial. A radiocarbon date of 3530calBC-3370calBC (radiocarbon ages 4680±60BP (Hv. 5220), errors at 1σ, from Tooley (1978), calibrated using Pearson *et al.* (1986)) was obtained from cleaned bones. Pollen from a sample adjacent to the cranium included salt marsh taxa and a change in the ratios of oak and alder pollen suggested burial during a period of high ground water, possibly due to a sea

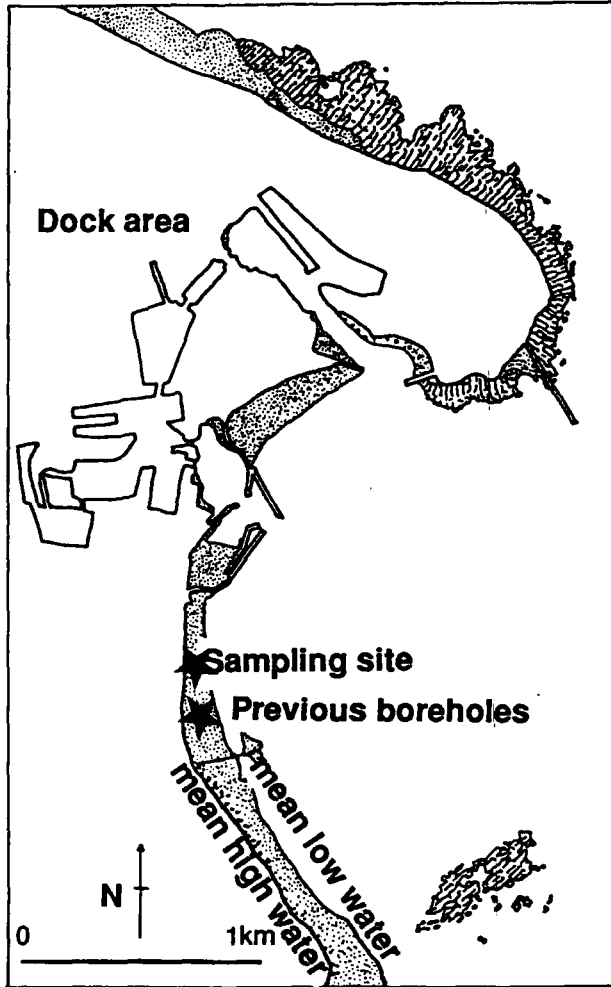


Figure 3.59: Plan of Hartlepool Bay (after Tooley, 1984).

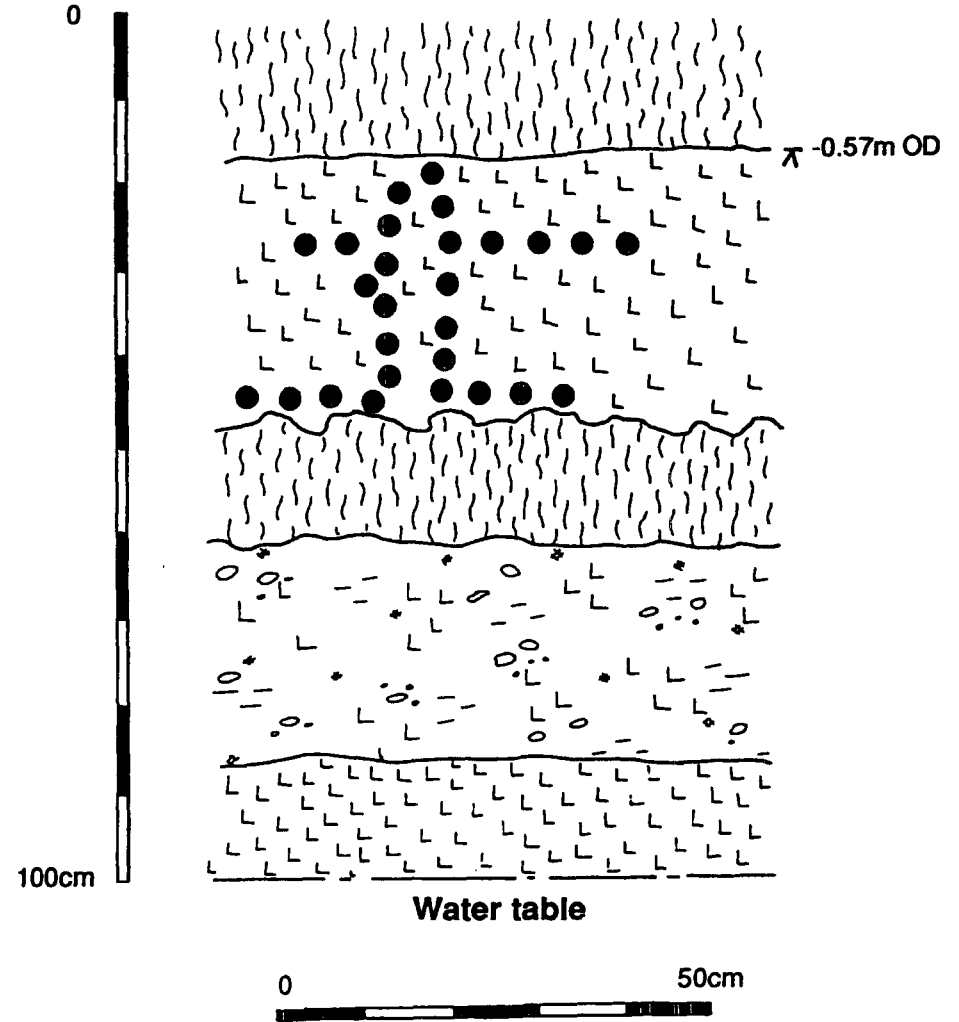


Figure 3.60: Vertical section of Hartlepool deposits, showing the location of samples.

level rise (Tooley, 1984). Pollen from core samples of the organic deposits in the inter-tidal zone were dominated by oak and alder pollen and recorded the elm decline, hence giving a date of almost 5000 years old. Herbaceous and aquatic taxa were also well represented, suggesting the existence of dry land, fresh and brackish water habitats. Low frequencies of pollen from domesticated and cereal plants and the presence of cow and pig remains suggested both pastoral and arable agriculture were in operation (Tooley, 1984).

Description of the deposits sampled

Archaeological excavations are currently being carried out on the foreshore (Innes *et al.*, 1991), but in order to examine the complete sequence of deposits, a section was cut through the inter-tidal peat beds using a mechanical digger. The east face of this section was cleaned, examined and sampled. The section (Fig. 3.60) consisted of an upper limnic peat with *Phragmites*, underlain by a grey, silty clay, which gave way to a brown limnic peat. Underlying this was a further silty clay, containing stones and charcoal. The sequence ended in the brown boulder clay which descended beneath the water table.

Samples for archaeomagnetic investigations were taken from the upper silty clay (-3.50.D.), which was about 30cm thick at this point (Fig 3.60). The material was a grey (Munsell No. 10YR 5/1), fine, silty clay; mottled with *Phragmites* flecks. It was moist and plastic and there were no visible sedimentary structures. In the upper 5cm there was evidence of fine rooting from the horizon above, which was a brown well-laminated limnic deposit containing *Phragmites*, birch twigs and some sandy lenses. Below the horizon sampled was a dark brown, slightly laminated, sandy, limnic peat containing considerable (about 10%) woody detritus. The lower boundary was a wavy interface and the transition occurred over about 5cm, consistent with erosion of the lower peat by wave action, followed by infilling with the silty clay. The horizon sampled appeared to be horizontal and there was no visible evidence of slumping.

The silty clay was soft and therefore easily sampled with tubes, creating little visible disturbance. 27 samples were taken in a vertical column and two horizontal groups (Fig. 3.60). One horizontal group was situated towards the top of the deposit and the other in the lower boundary. Orientation was carried out using a magnetic compass.

Archaeological interpretation of the deposits

Tooley (1978) interpreted the environmental evidence as being indicative of fluctuations in sea-level and associated changes in the freshwater table. A rise in sea-level led to the oak-alder fen vegetation being replaced by water lily and bulrush communities and biogenic sedimentation being replaced by minerogenic sedimentation, with pollen indicative of salt marsh estuarine conditions. Marine conditions ended and the salt marsh was replaced by fen communities of oak, willow and alder with localised freshwater reedswamps. The archaeological and environmental evidence suggested that early humans exploited these changes in ecology to establish mixed pastoral and arable farming. It appeared that the silty clay sampled was an estuarine deposit, laid down at a time of high sea level. Coring and augering indicated that the silty clay sampled underlay the peat containing the inhumation. Organic matter in the upper limnic deposit was recently dated to 4470calBC-4330calBC by radiocarbon and a date of 5010calBC-4750calBC was obtained for material within the peat below the unit sampled (radiocarbon ages $5530\pm 90\text{BP}$ (Q-2662) and $5975\pm 120\text{BP}$ (Q-2661) respectively from M. Tooley (pers. comm.) calibrated using Pearson *et al.* (1986) with errors at 1σ).

Results of magnetic measurements

Natural remanent magnetisation

The intensity of NRM of samples from the upper part of the section fell in the narrow range $2.9\text{-}9.7\mu\text{Am}^2\text{kg}^{-1}$ and the directions were fairly closely grouped (Fig. 3.61). The α_{95} value of all 19 upper samples together was 3.3° . The intensity of NRM of the eight lowest samples fell in the wider range $2.1\text{-}35.4\mu\text{Am}^2\text{kg}^{-1}$ and the directions were more dispersed with an α_{95} of 7.6° .

Demagnetisation

7 of the 27 samples were stepwise demagnetised. For a typical sample from the upper part of the horizon (Fig. 3.62) the stereographic projection indicated that little directional change occurred in the magnetisation up to a demagnetising field of 30mT. The linear behaviour of the vector end-point shown on the Zijderveld plot confirmed that the remanence comprised of a single stable component of magnetisation with a slight viscous overprint. The slight kinks on the Zijderveld plot were attributed to difficulties in measuring the magnetisation of the sample as it became weaker. The stable component was statistically well defined with a stability index of 5.4 (very stable) over a range of 2.5-25mT. The plot of change in normalised intensity with increasing applied field fell smoothly and sharply, the intensity reducing to less than 7% of the original value after demagnetisation in fields of 50mT, with a low median destructive field of 15-20mT.

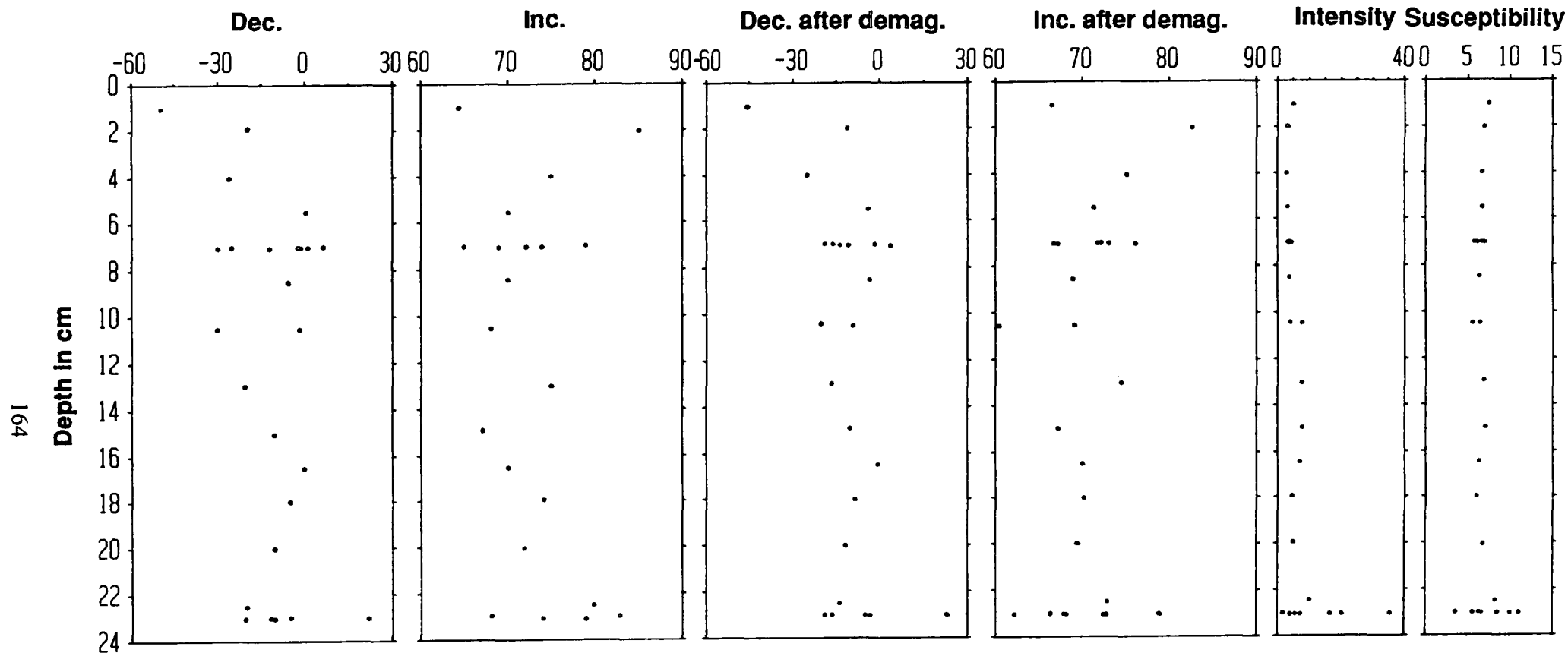


Figure 3.61: Plot of depth against NRM declination (Dec.), NRM inclination (Inc.), declination after demagnetisation, inclination after demagnetisation (all in degrees) and intensity (in $\mu\text{Am}^2\text{kg}^{-1}$) and susceptibility ($\times 10^{-8}\text{m}^3\text{kg}^{-1}$) from a vertical section through the Hartlepool deposit.

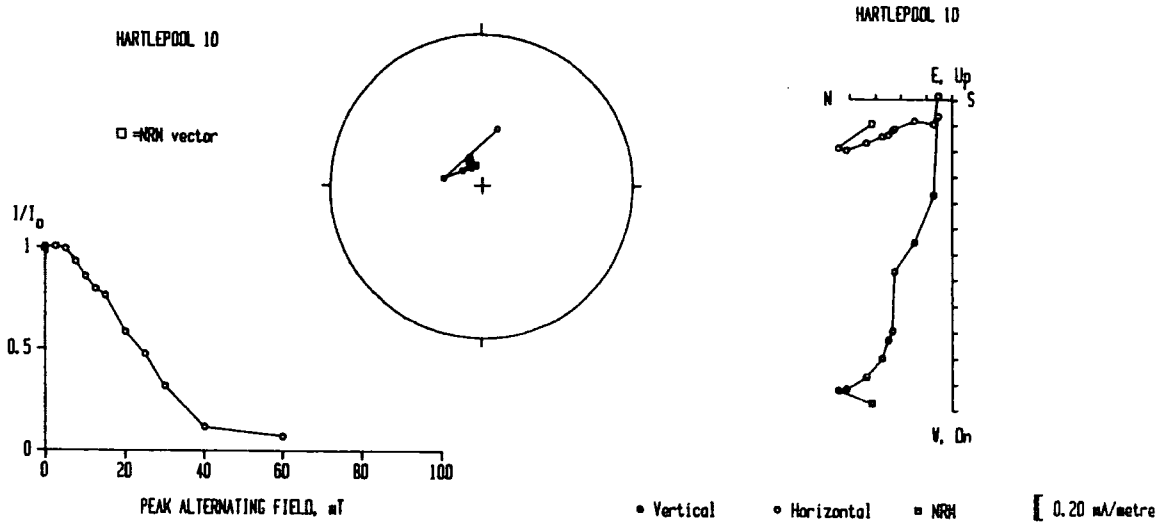


Figure 3.62: Stereographic, intensity and Zijdeveld plots of the behaviour of a typical sample from the upper horizon (HP 10) on alternating field demagnetisation.

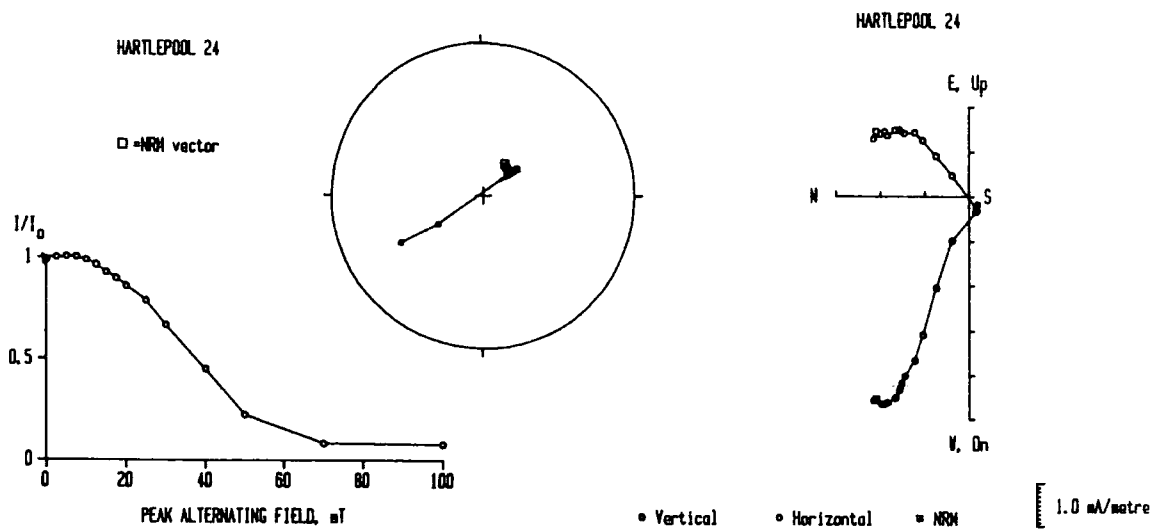


Figure 3.63: Stereographic, intensity and Zijdeveld plots of the behaviour of a sample from the lower horizon (HP 24) on alternating field demagnetisation.

These observations indicated that the magnetisation was soft but had a stable component. In contrast, demagnetisation of a sample from the lower part of the horizon (Fig. 3.63) showed that its magnetisation consisted of at least 2 components. The magnetisation was harder, with a median destructive field of 30-40mT and about 20% remaining after demagnetisation at 50mT, possibly indicating a different mineralogy from the upper samples.

As the upper material was homogeneous and the pilot samples showed very similar behaviour on demagnetisation, the remainder were demagnetised in a field of 10mT to remove the small viscous component. The samples from the upper 20cm showed no variations in direction distinguishable above the dispersion in magnetic directions indicated by the samples taken from a single horizon. Hence, it would appear that there is no record of a secular variation and so the samples had to be treated as representing a single field direction. Their directions of magnetisation were combined to give an α_{95} of 2.4° based on 19 samples (Fig. 3.61) with virtually no change in mean direction from the NRM values. After demagnetisation in a field of 10mT the dispersion in the magnetic directions of the lower samples had decreased to $\alpha_{95}=7.1^\circ$, but was still greater than the dispersion over the rest of the section (Fig 3.61).

Magnetic fabric

Specific susceptibility of samples from the top 20cm was in the range $5.6-7.6 \times 10^{-8} \text{m}^3 \text{kg}^{-1}$, whereas the specific susceptibility of the lower samples was widely scattered between 3.7 and $11.1 \times 10^{-8} \text{m}^3 \text{kg}^{-1}$. The magnetic fabric was found to be fairly weak, with $h\%$ in the range 1.4-4.1% for the upper samples and 1.2-8.5% for the lower samples. q values were very scattered falling in the range 0.24-1.33 and 0.22-1.63 respectively, with only 32% of the q values for the upper samples and 50% of the q values for the lower samples falling in the range characteristic of an undisturbed depositional fabric. The maximum axes of susceptibility of the upper samples were well grouped (Fig. 3.64a), indicating that a magnetic fabric had been acquired by the systematic orientation of elongated grains. The minimum axes showed a girdled distribution which can be considered to be indicative of slumping (see also Section 3.4.7). Both the maximum and minimum axes of susceptibility of the lower horizon samples were very scattered (not shown), suggesting that these magnetic grains had not been aligned on deposition or that they had been disturbed subsequently.

An attempt was made to determine the direction of palaeoflow using the method of Noel and Rudnicki (1988) as described in section 2.3.2. Although flow in the direction 145° from North was indicated (Fig. 3.64b), this was based on only 50% of the crossings occurring after the remanence. Given this information, it would seem more likely that the

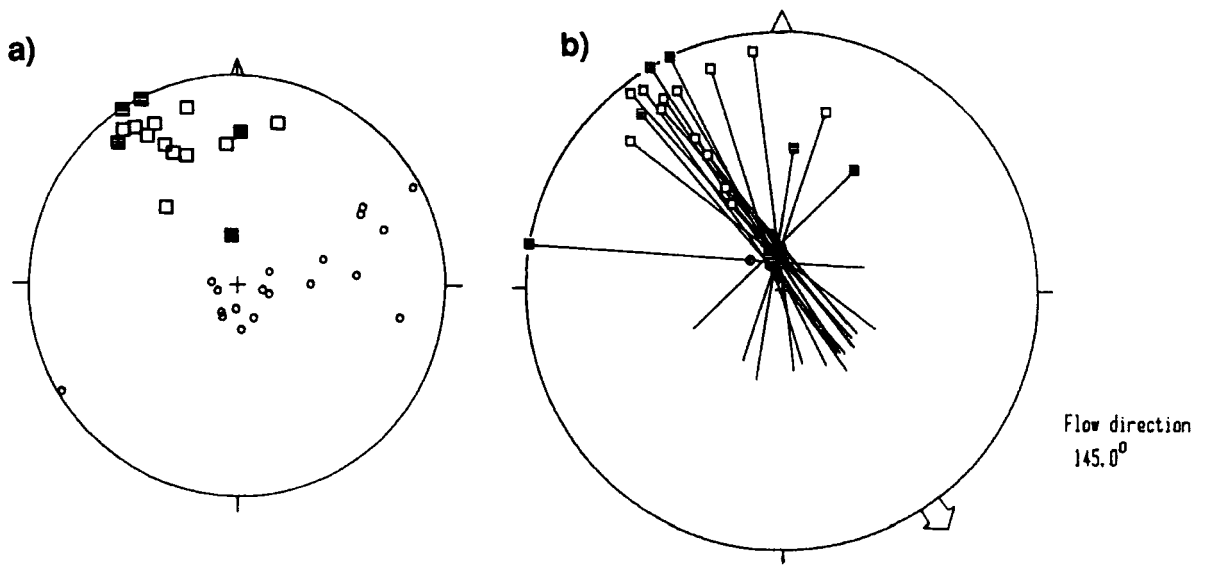


Figure 3.64 a: Magnetic fabric of samples HP 1-27.
 b: Determination of flow direction from magnetic fabric and NRM of samples HP1-21. Arrow indicates the mean flow direction.

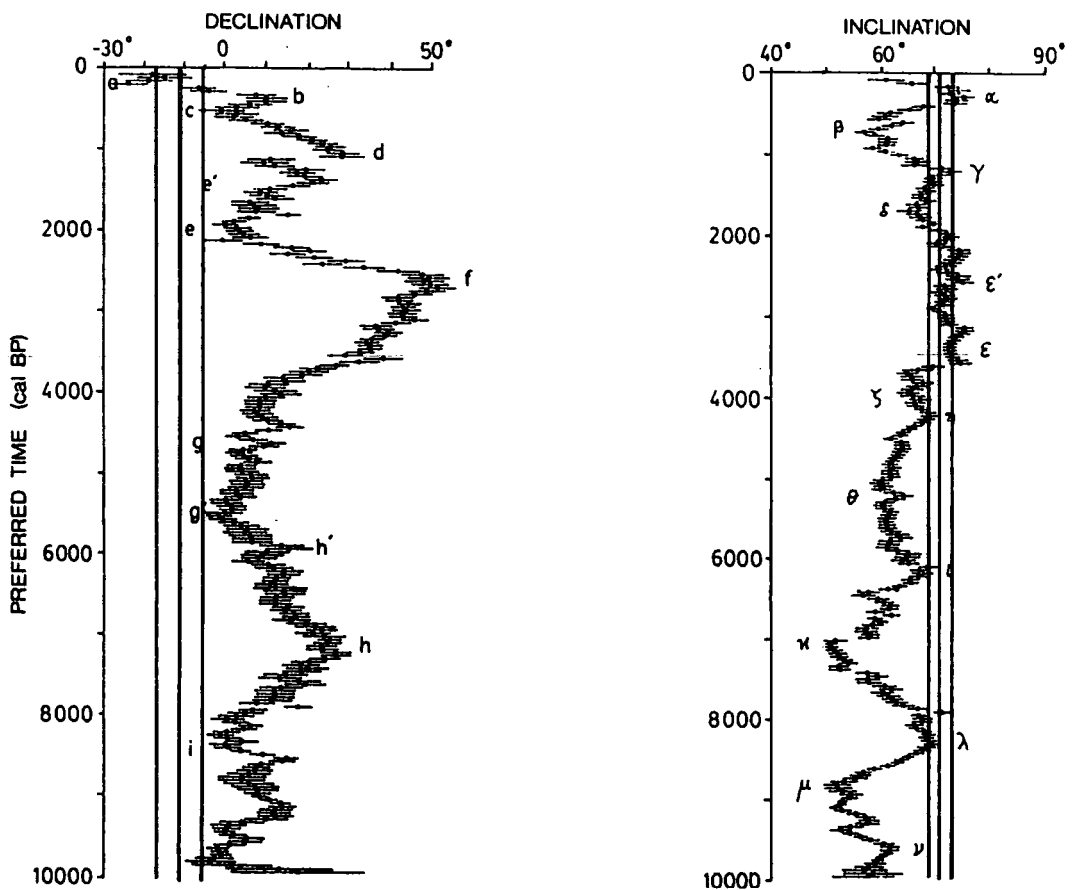


Figure 3.65: Mean Hartlepool magnetic direction after demagnetisation with errors at 95% confidence, compared to lake sediment secular variation curve of Turner and Thompson (1982).

lineation arose from orientation in the geomagnetic field rather than as a result of fluid stress.

Magnetic mineralogy

Application of pulse fields of increasing intensity to a sample resulted in a sharp increase of induced IRM, followed by a very small further increase at higher fields (Fig. 3.58a). The SIRM value for a sample from the top of the section was lower than that of most other sediments, $0.63\text{mAm}^2\text{kg}^{-1}$ and 99% of this value was reached in an applied field of 1T. The SIRM of a sample from the lower part of the section was considerably higher, $1.8\text{mAm}^2\text{kg}^{-1}$, 99% of this being reached in applied fields of 1T. $(B_0)_{\text{cr}}$ was 27mT for the upper sample and 32mT for the lower (Fig. 3.58b). The *S* ratio was 0.96 in both cases. These parameters suggested that the magnetic mineral carrying the remanence in all the samples was predominantly magnetite with virtually no contribution from harder magnetic minerals. The change in value of $(B_0)_{\text{cr}}$ might suggest that the magnetite grain size was smaller in the lower horizon, which might contribute to the slightly harder magnetic properties revealed on demagnetisation.

General conclusions

The study of remanent magnetisation shows that a stable magnetic remanence was preserved in the material of the upper 20cm of the deposit. If the magnetisation was depositional or post-depositional in origin, the lack of discernible variation in declination or inclination would suggest that the deposit had been laid down over a period that was short with respect to secular variation. Magnetic fabric appeared to result from orientation in the geomagnetic field and the deposit had possibly slumped subsequently, although there were no visual signs of such a disturbance. The remanence appeared to be carried predominantly in magnetite grains. In contrast, the lower 10cm of silty clay generally had stable magnetisations but these were more scattered and the magnetic mineralogy appeared to be slightly different. This may have arisen from chemical changes or physical mixing at the boundary with the peat.

On the assumption that the samples in the top 20cm of the horizon represented a single magnetic field, their vector mean magnetic direction and its associated α_{95} value were calculated. While the mean magnetic direction was consistent with the geomagnetic field between the present and AD1900 or the 1st century BC, the archaeological evidence indicates that the deposit dates to before the period covered by the archaeomagnetic calibration curve. Hence dating was carried out by comparison with the lake sediment curve (Fig. 3.65). As mentioned previously (Section 2.5.4 and with reference to the Farnley samples in Section 3.4.6), comparison of a single magnetic direction with the

lake sediment curve is ill-advised. In this case the declination was unusually easterly and, if the more recent dates suggested above were eliminated on archaeological grounds, the only similar geomagnetic field direction was found between 6000-6500calBC (at a 95% level of confidence). No comparison could be made with the revised calibration curve in Chapter 5 as the deposit was too early.

The result of using this similar geomagnetic direction as an indication of the date of deposition would lead to the conclusion that deposition occurred much earlier than was indicated by radiocarbon dates. While it is possible that the radiocarbon dates are in error, the date ranges obtained from the lake sediment curve must be treated with caution, as the use of the curve in this manner has some intrinsic shortcomings. As no secular variation could be extracted from the magnetic directions (possibly as the section was too short or deposition was too fast), the dating was based on a single mean direction. However, the absolute values of declination of the lake sediment curve are open to question (Section 3.3), particularly in the lower region (below 5000 years calBC). The absolute dating of a deposit which is too old to be dated with the conventional archaeomagnetic calibration curve and which records no secular variation would appear to be beyond the scope of conventional archaeomagnetic techniques. A new approach to obtaining such dates is required (Section 5.6.4).

3.4.9 West Heslerton Anglo-Saxon Settlement, West Heslerton, North Yorkshire.

(O.S. Grid Ref. SE 917 736)

Site description

West Heslerton is situated in North Yorkshire, on the southern edge of the Vale of Pickering (Fig. 3.1). Interest in the area was prompted by the chance discovery of Anglian metalwork in 1977 and a series of small-scale rescue excavations were carried out in subsequent years, in advance of quarrying (Powlesland, 1986). These revealed the site to be multi-period, giving an insight into human activity over the last 8000 years. Evidence of occupation commenced with a late Mesolithic flint knapping area and there appeared to be domestic activity and attempts to establish a field system from the Late Neolithic. During the Early Bronze Age, two barrow cemeteries were constructed and the finds of that period included an important series of beakers and food vessels. The central part of the site was intensively occupied from the Late Bronze Age and Early Iron Age until the Roman period, when much of it was used for agriculture. In the early Anglo-Saxon period a cemetery was established which contained over 200 individuals. During the later Medieval and post-Medieval periods the site continued in agricultural use and was gradually covered by blown sands, which protected the archaeological remains from plough damage.

Since 1987 investigations have concentrated on the Anglian settlement contemporaneous with the cemetery, first discovered in 1982 (Powlesland, 1987). This settlement was of great interest as it was the first opportunity Northern England, and only the third time nationwide, to examine both an early Anglo-Saxon settlement and its associated cemetery. It was hoped that current detailed excavations would add to the very limited existing knowledge of the period (D. Powlesland, pers. comm.).

The historical setting

From the late 4th century AD, the Roman economy and the cities it supported were in decline, accompanied by instability in the government and a deterioration in the climate (Powlesland, 1987). Traditionally, the Roman period ended in AD410, when the Britons unsuccessfully sought aid from Rome in protecting themselves from invaders. The subsequent period is known as the Dark Ages. No written records exist, so the archaeological evidence is of vital importance. However, the archaeological remains are often hard to interpret as buildings, ceramics and coins from the Roman period were extensively reused. Excavations in major cities have shown that the urban centres of the

Roman period ceased to function in the 5th century AD and a distinctive early Anglo-Saxon culture was adopted. These changes may have resulted from mass migration into Britain from Europe and leave little indication of what happened to the native Romano-British population, as the new culture affected settlement patterns, economy and society in general. Arnold (1984) provides a comprehensive account of the archaeological evidence for the changes of this period.

In Heselton Parish there is a major Iron Age and Romano-British settlement just over 1km from the Anglian site. This early settlement appeared to have been deserted by AD450, as the water-table rose, making the site less attractive for occupation. At around this time, the Anglo-Saxon settlement sprang up on higher, well-drained ground. Archaeological evidence suggests that the Anglian site at West Heselton was occupied for around 400 years before being abandoned in favour of a settlement established around the existing church (Powesland, 1987).

The current excavation

Excavation has shown that the Anglian village extended over about 40 acres and was well-organised, with different areas for housing, industry and agriculture. A small stream ran through the middle of the village, fed by a spring which is still active (Fig. 3.66). The houses were situated to the east of the stream on two raised knolls of chalk; to the north-west of the stream was an area of industrial and craft activity. Over 150 buildings have been excavated so far, including large houses which probably had two storeys, and a number of Grubenhäuser (literally meaning 'hole-in-the-ground houses'), which may have been used for grain storage. A high meat content in the Anglo-Saxon diet was indicated by the 300,000 animal bones discovered. In addition to these, there have been over 80,000 finds, including evidence of textile manufacture, metal and bone working and brewing (D. Powesland, pers. comm.).

Excavations in 1990 covered an 11 acre site in the south-west part of the village (Fig. 3.66), concentrating on the area to the west of the present day spring. A large stock enclosure and a post-hole building were discovered. The latter was dated to about AD800, using its associated pottery. Middle Saxon pottery and other material in the vicinity indicated that occupation had continued until AD850. Near to the spring the archaeology was very complex, with hundreds of intersecting features. These ranged from Roman pits and ditches, to features that contained large quantities of slag and were apparently associated with Anglo-Saxon industry. The most exciting discovery was an oak-lined well and it was hoped to date the sediments within this by archaeomagnetism.

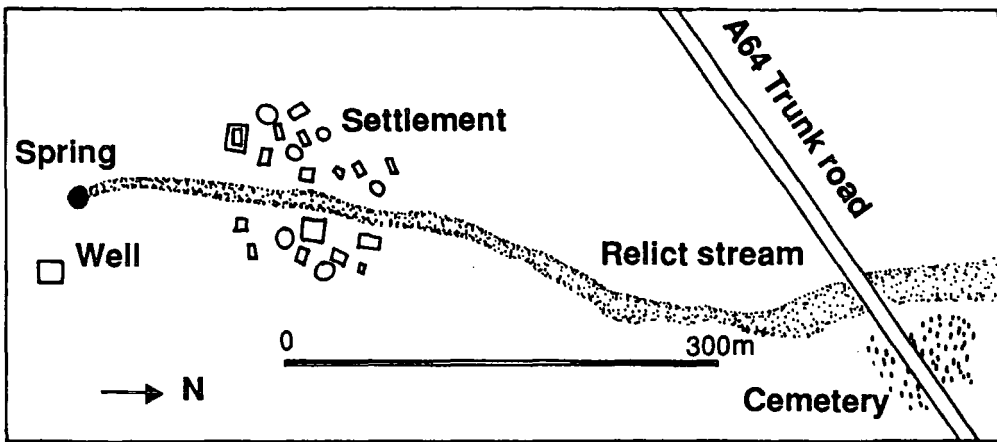


Figure 3.66: Site plan of excavations at West Heslerton (after Powesland, 1987).

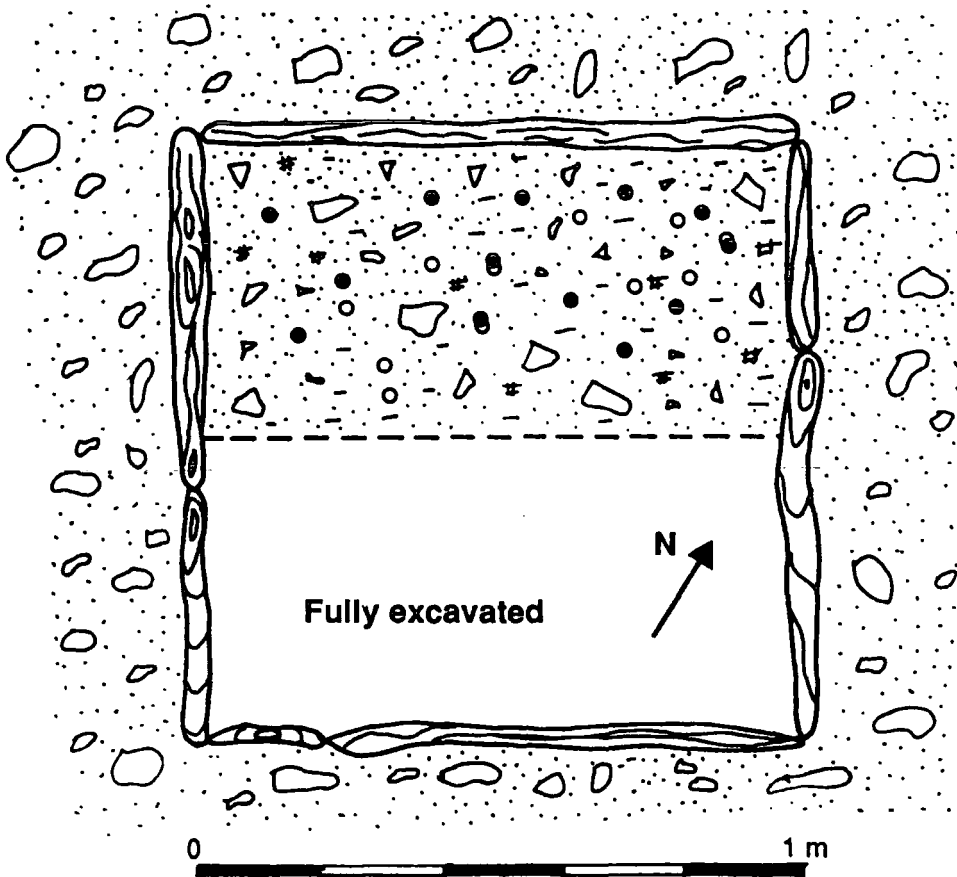


Figure 3.67: Plan drawing of well, showing location of samples. Open circles represent upper samples and solid circle represent lower samples.

Description of the well and its sampling

The well was situated near to the spring in the south-eastern area of the site (Fig. 3.66). It measured about 1m² in plan and was only 50cm deep, having been truncated by ploughing (Fig. 3.67). It was cut into the natural ground surface, which consisted of sands and gravels, derived as post-glacial outwash from Forge Valley in the north-west corner of the vale. The well was lined with large oak planks. The wood lining and fill were waterlogged and hence the fill contained preserved organic material. Samples were taken from the bottom 20cm of deposit, with the disturbed material above this being removed by trowelling. The fill was an unmottled, black (Munsell No. 5YR 2.5/1), sandy silt, containing organic matter. About 20% of the matrix (by volume) was angular chalk inclusions which varied in size from very small to approximately 10cm³. The chalk pieces showed no lateral pattern of distribution or orientation, but the frequency decreased with depth. The sandy silt was neither plastic nor sticky, but very soft and crumbled easily under pressure. There were also a small number of twigs and bone inclusions, but no rootlets or evidence of animal activity. No laminations or evidence of slumping were visible, but the water-logging made such observations difficult. Half of the well had been excavated to its wooden base (+59.15m OD), but the other half remained for sampling (Fig. 3.67).

Samples were taken from a cleaned horizontal surface, avoiding the chalk pieces as far as possible. The underlying surface was then cleaned and a further set of samples taken from the lower part of the sediment. The lower material was easier to sample because of the reduction in chalk content. 25 samples were taken in this manner. Orientation was carried out with a magnetic compass since there was no shoring and it was not possible to use a sun compass.

Archaeological interpretation of the deposits

The context sampled was clearly deliberately constructed as a well, the only one found on the site, which was otherwise fed by stream channels draining from the spring line at the foot of the Wolds. The sandy silt at the bottom might represent the first deposit after the well was constructed, although the well may have been cleaned subsequently. The fill contained small quantities of bone and organic matter, probably leaves, but no archaeological artefacts.

Results of magnetic measurements

Natural remanent magnetisation

The mean intensity of the NRM of the samples was in the range 2.2-16.4 $\mu\text{Am}^2\text{kg}^{-1}$. The NRM directions were generally dispersed, with the lower samples appearing to be more closely grouped (Fig. 3.68a). One sample (WHES12) showed a negative inclination. Even excluding the sample with the negative inclination, the α_{95} value calculated using all the other samples was fairly high, 8.8°.

Demagnetisation

Stepwise alternating field demagnetisation of 5 pilot samples was carried out and a typical example is shown in Fig. 3.69. The stereographic projection indicated little directional change up to a demagnetising field of 40mT when less than 14% of the remanence remained. After 40mT the directions of the vectors became more dispersed, partly due to their weakness and possibly also due to laboratory induced remanences (Section 2.2.2). The linear behaviour of a plot of successive vector end points confirmed that the sediment's remanence comprised of a single component of stability index 14.0 (very stable) over the range 2.5-30mT. The plot of change in normalised intensity with increasing peak field fell smoothly and sharply, demonstrating that the magnetisation was soft and almost entirely destroyed by fields of 50mT or above. The median destructive field was 17.5-25mT. This behaviour suggested that the predominant magnetic mineral was magnetite.

Two samples with outlying directions of magnetisation were demagnetised. WHES11 showed the presence of at least two magnetic vectors with no stable endpoint being reached on demagnetisation. WHES12 (the sample with a negative inclination) showed a slight rise in intensity, which might have represented the removal of a small normal viscous overprint but there was no significant change in direction. The magnetisation of WHES12 was harder than that of the other samples, with a median destructive field of 30-40mT and 30% of the magnetisation remaining at 40mT. These properties suggested a different mineralogy, which was confirmed by the discovery of a pebble in the sample when it was dissected.

A demagnetisation field of 15mT was chosen for the remaining samples in order to isolate the primary component (Fig.3.68b). There was noticeably greater dispersion in the magnetic directions of the upper samples, despite their fairly stable magnetic directions, possibly due to the inclusion of more small chalk pieces in these samples. It was decided to consider only samples from the lower, less stony layer in the calculation of mean direction and to exclude obvious outliers. Thus an α_{95} value of 5.8° was obtained, based on the thirteen samples from the lower horizon. This large dispersion

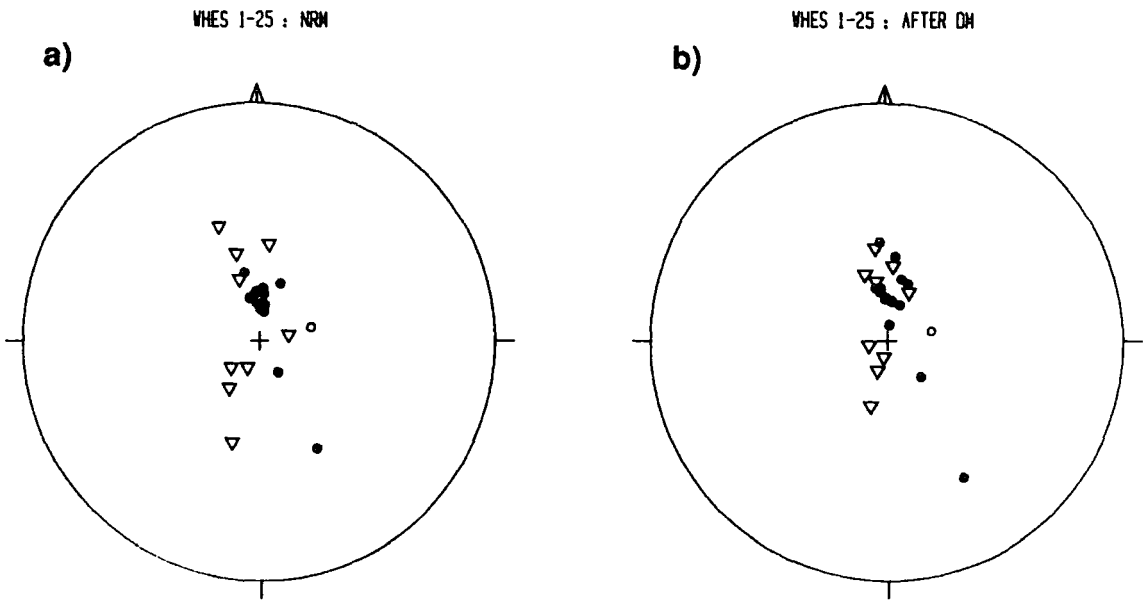


Figure 3.68: Stereographic plot of the directions of magnetisation of samples WHES 1-25 a) NRM values and b) after partial demagnetisation. Triangles represent upper samples, circles represent lower samples.

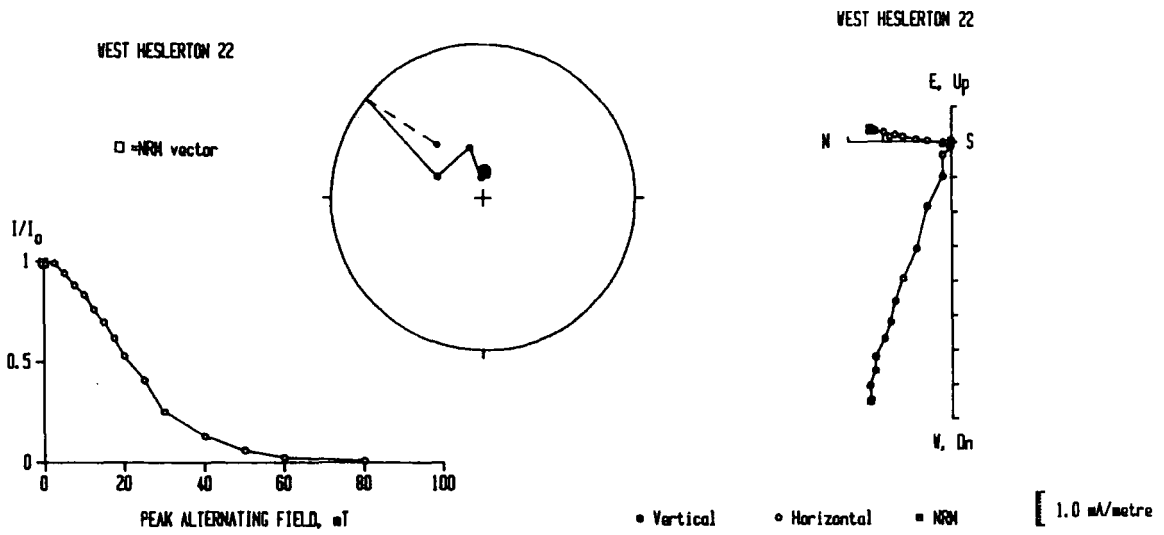


Figure 3.69: Stereographic, intensity and Zijderveld plots of the behaviour of a typical sample (WHES 22) on alternating field demagnetisation.

might be caused by the inclusion of small stones in samples (a number of which were found on dissection), which would distort the overall remanence, or by disturbance of the material on deposition or sampling.

Magnetic fabric

The specific susceptibility of the samples was in the range $3.5\text{-}29.7 \times 10^{-8} \text{m}^3 \text{kg}^{-1}$. The mean susceptibility anisotropy of the samples, $h\%$, was high, between 5.0-7.1%. The q values fell in the range 0.08-0.96, with 83% falling in the range deemed diagnostic of undisturbed depositional magnetic fabric. The axes of minimum susceptibility clustered to define a near horizontal magnetic foliation plane and the maximum axes were widely scattered at shallow inclinations (Fig. 3.70). These observations would suggest that deposition of the sediment had occurred grain by grain and that it had been unaffected by fluid flow, as would be expected in this particular depositional environment.

Magnetic mineralogy

The behaviour of two representative samples in an isothermal magnetic field was investigated (Fig. 3.71). The SIRM values fell in the range $1.8\text{-}2.3 \text{mAm}^2 \text{kg}^{-1}$ and at least 96% of this was acquired in fields of less than 1T. The back coercivity, $(B_0)_{\text{cr}}$ had values of 20-23mT, while S was 0.88 in both cases. These parameters indicated that the magnetic remanence was probably carried predominantly by magnetite.

General conclusions

The magnetic properties of this material indicated that, while the samples from the upper fill of the well had dispersed magnetic directions, the lower samples appeared to retain a record of the geomagnetic field on or after deposition in magnetite grains within the sediment. The magnetic fabric indicated that deposition had occurred from static water, as would be expected in a well. When the mean magnetic direction after demagnetisation of the lower samples was corrected to Meriden (Table 1C) and compared to the calibration curve (Fig. 3.72), it fell on the curve between AD300 and AD400. However, the large error bars at 95% confidence meant that the only conclusion justifiable was that the remanence dated from between AD50 and AD500. The large uncertainty in date arose from the lack of precision with which the magnetic vector was defined, possibly owing to disturbance of the sediment on or after deposition, or to the presence of small inclusions in the samples. The behaviour of the calibration curve between AD300 and AD800 is not well known, because of a lack of archaeomagnetic measurements on dated material from that period. While the date range obtained did not add a great deal of new information for the archaeologist, it was consistent with the

WHES 1-25 : FABRIC

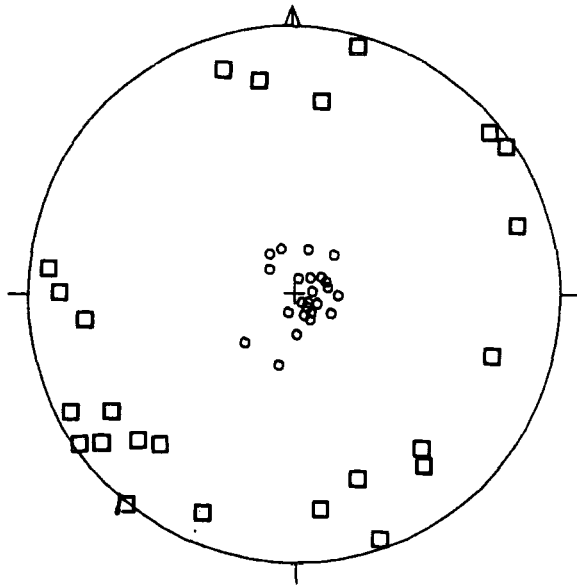


Figure 3.70: Magnetic fabric of samples WHES 1-25.

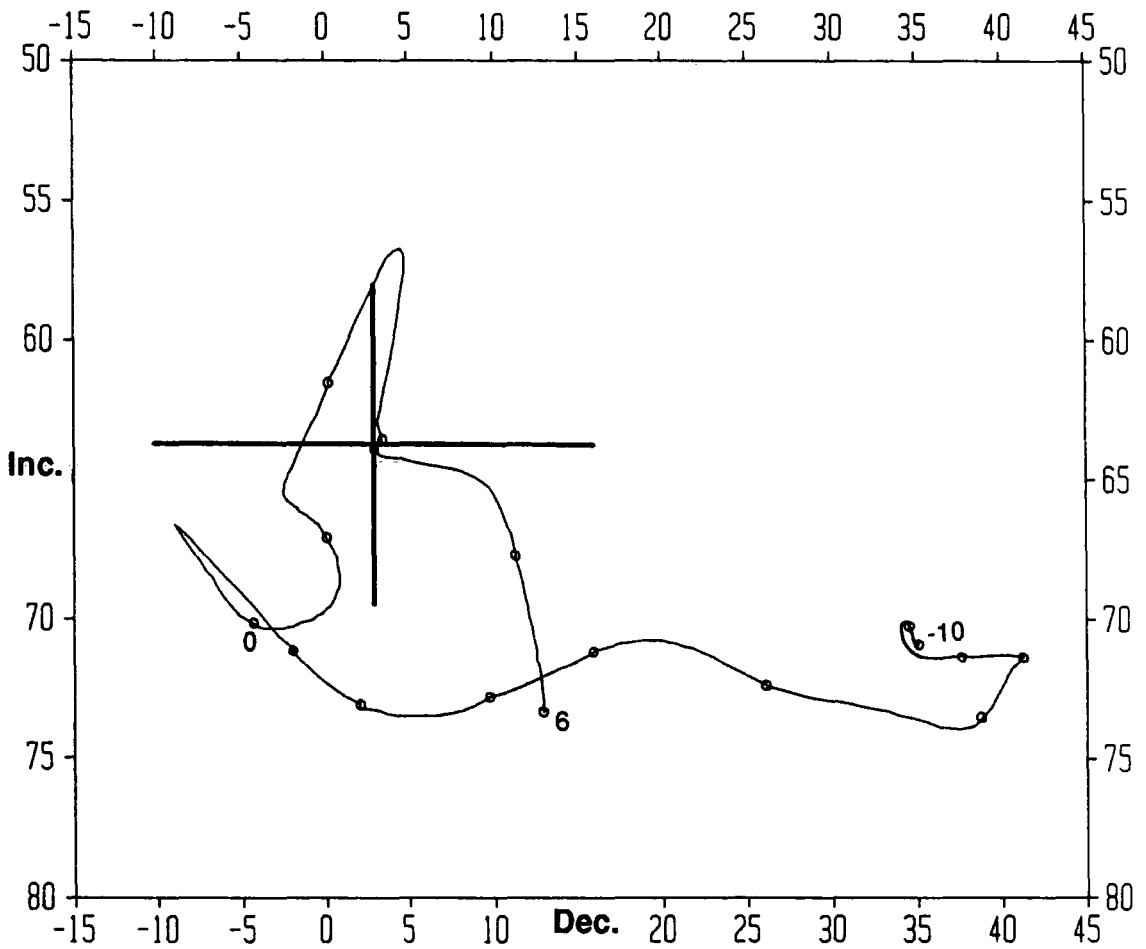


Figure 3.72: Mean magnetic directions after demagnetisation of lower samples from well with errors at 95% confidence, corrected to Meriden and fitted to the British calibration curve covering 1000BC-AD600. The calibration curve was digitised from that of Clark *et al.* (1988); circles indicate centuries and the figures are 100's of years.

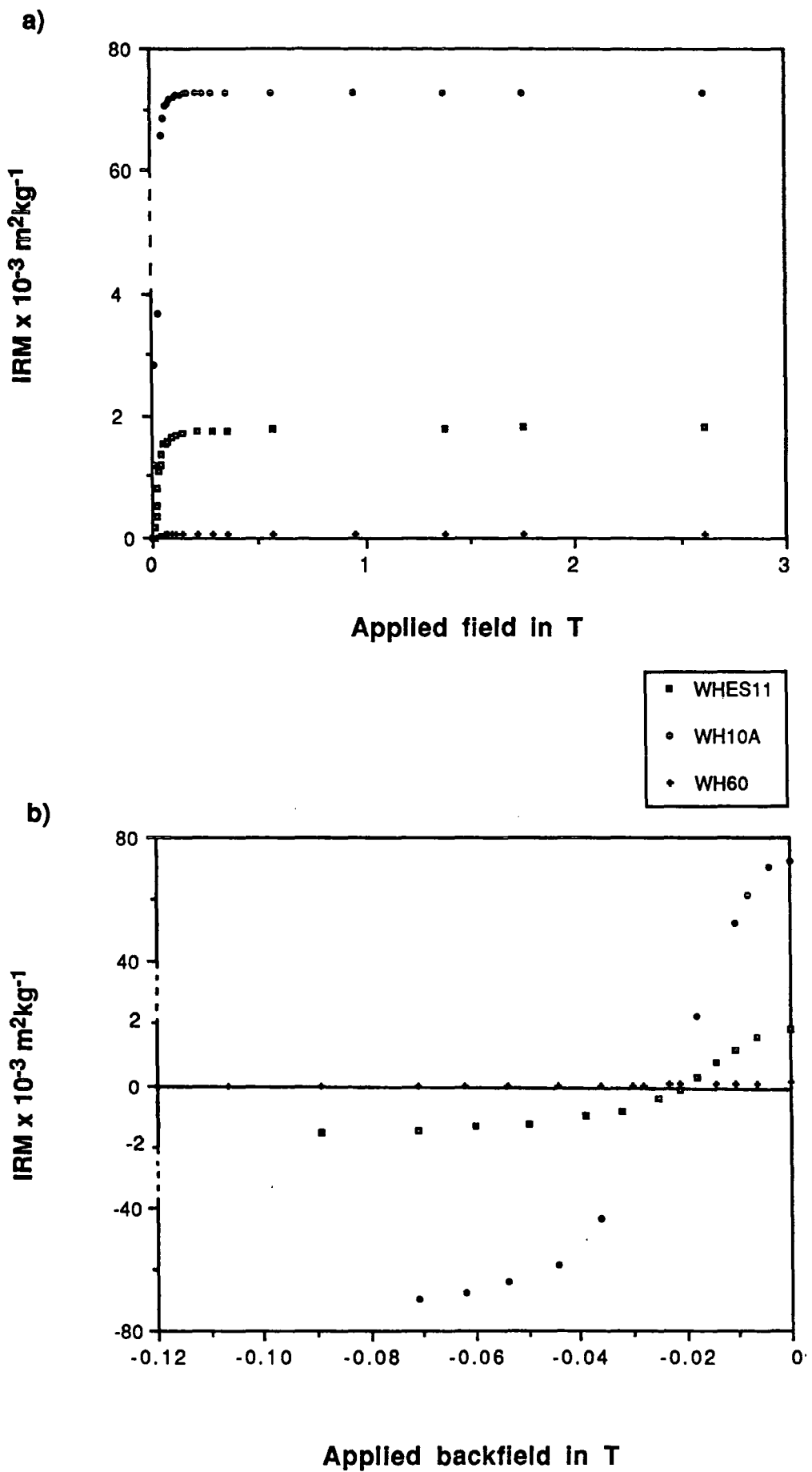


Figure 3.71 a: IRM build-up curve for samples WHES 11, WH 10A and WH 60.
 b: Plot of back coercivity for samples WHES 11, WH 10A and WH 60.

archaeological evidence. A comparison with the date obtained by dendrochronology using the oak lining is intended, when such information is available. This archaeomagnetic study accentuated the problems of using archaeomagnetic dating in the Dark Ages, when the calibration curve is so poorly defined, and the problems of dating an imprecise magnetic vector. Section 5.6.4 contains an attempt to date the magnetic direction using the revised curve constructed in Chapter 5.

3.4.10 Wood Hall Moated Farm, Nr. Womersley, North Yorkshire.

(O.S. Grid Ref. SE 536 206)

Moated enclosures in Britain

Over 5000 moated sites have been recorded in Britain (Aberg, 1978) spanning from 12th century AD to the 18th century AD. From excavated sites (Clarke, 1984 p49) and documentary sources (Taylor, 1974 pp87-146), most appear to be Medieval, making them one of the most common types of site of this period in lowland Britain. They exist in various states; some still intact and others appearing as no more than a pond or ponds with associated buildings. There is also great variety in their apparent purpose, ranging from royal or aristocratic rural retreats, monastic granges and manor houses to farmers' homesteads. They are widely distributed across the country, but seem to be more dense in regions with a clay sub-soil, which may be an important prerequisite for digging a moat (Clarke, 1984 p53). Their distribution may also reflect settlement patterns and land tenure in the Middle Ages (Clarke, 1984 pp53-54), as many lie on the outskirts of villages and were associated with the manorial system.

Moated sites reflected changes in climate, economy and social trends at a time when the majority of the population was living in the countryside. Four main chronological phases of development have been suggested by Le Patourel and Roberts (1978) and are of interest when considering the dating of such sites:

- 1) A phase of unknown duration during which the moat evolved.
- 2) An innovatory phase (AD1150-1200) when small numbers of moats were established throughout the country. These may have had a more defensive function than later examples, particularly in the unsettled political atmosphere of the reign of Henry II (AD1135-89). The period corresponds to the destruction of woodland in 12th and 13th century AD, when population expansion led to clearance of previously uncultivated land.
- 3) A phase of expansion from AD1200-1325, during which there was a considerable increase in the number of moated sites constructed. It is suggested (Le Patourel & Roberts, 1978) that 70% of known sites came into being at this time, which also heralded a period of agricultural expansion and further population growth.

- 4) A decline in new moat construction and the abandonment or conversion of existing sites may have been related to the economic recession and agricultural slump of the 14th and 15th centuries, with the associated over-population, climatic deterioration, soil exhaustion and taxation (Baker, 1976). The plagues of the mid-14th century AD, including the Black Death in 1348, would have accelerated the decline. By the end of the Middle Ages the new wealth created by sheep farming and commercial activities enabled the gentry to build new houses on a large scale and forsake 'the damp insanitary sites of former ages' (Roberts, 1961-63).

Despite the abundance of moated sites, at least 320 in Yorkshire alone (Le Patourel, 1973 p109), only around 150 have been excavated in Britain. Even these excavations have usually been under rescue conditions, in response to a threat of imminent destruction. Hence they have been small scale and involved sites that would not necessarily have been objectively selected for excavation (Aberg, 1983). For these reasons, it is difficult to infer the purpose of the moat from the small number excavated. Many factors may have influenced their construction but the most likely are defence, drainage and status. A moat might act in a defensive capacity, but many were little more than ditches surrounding a small area with neither the need nor potential for defence (Clarke, 1984 p56). A defensive role might be more relevant in Northern areas subjected to frequent Scottish raids or as protection from discontented peasantry, robbers or predators. Many moated sites are located on marginal land with heavy soils and poor drainage and when the climate in Britain declined dramatically, in AD1310-1320, the role of the moat as a drain would have become more important. Although Wood Hall is 65km from the sea, it is only 10m above sea-level and has heavy soils which are easily waterlogged, so drainage is likely to have been an important factor. Moated dwellings often belonged to lesser aristocracy or successful freemen, and moats may have arisen from a desire to emulate the moated castles of the nobility. This theory is difficult to substantiate from the archaeological record. In addition, moats may have served a purpose as firebreaks in wooded country, cisterns or fish-ponds (Clarke, 1984 p56).

Site description

Wood Hall was a typical example of a moated enclosure, situated near the village of Womersley in North Yorkshire (Fig. 3.1). The site (Fig. 3.73) consisted of a main platform of approximately 3 acres, surrounded by a waterlogged moat which was crossed by a causeway or a bridge on the southern side and had been back-filled in places. The south-western quadrant of this enclosure was occupied by the remains of post-Medieval buildings, including a substantial Georgian house. The central platform

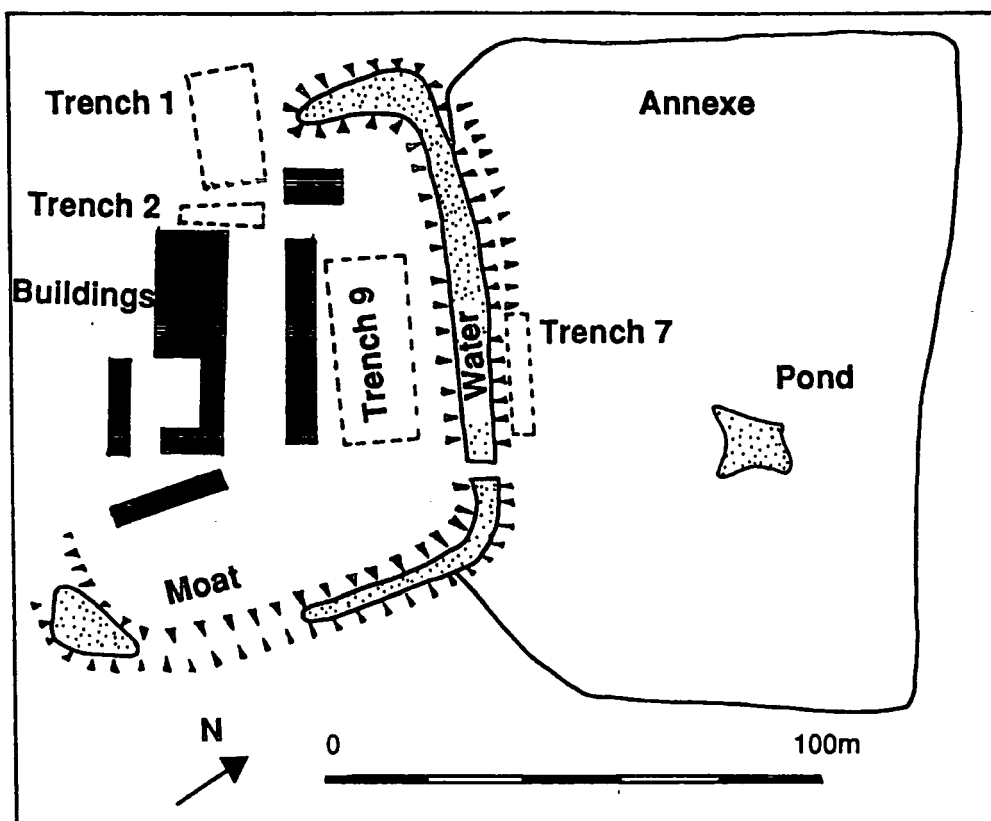


Figure 3.73: Plan of excavations at Wood Hall. Dotted lines indicate excavated areas.

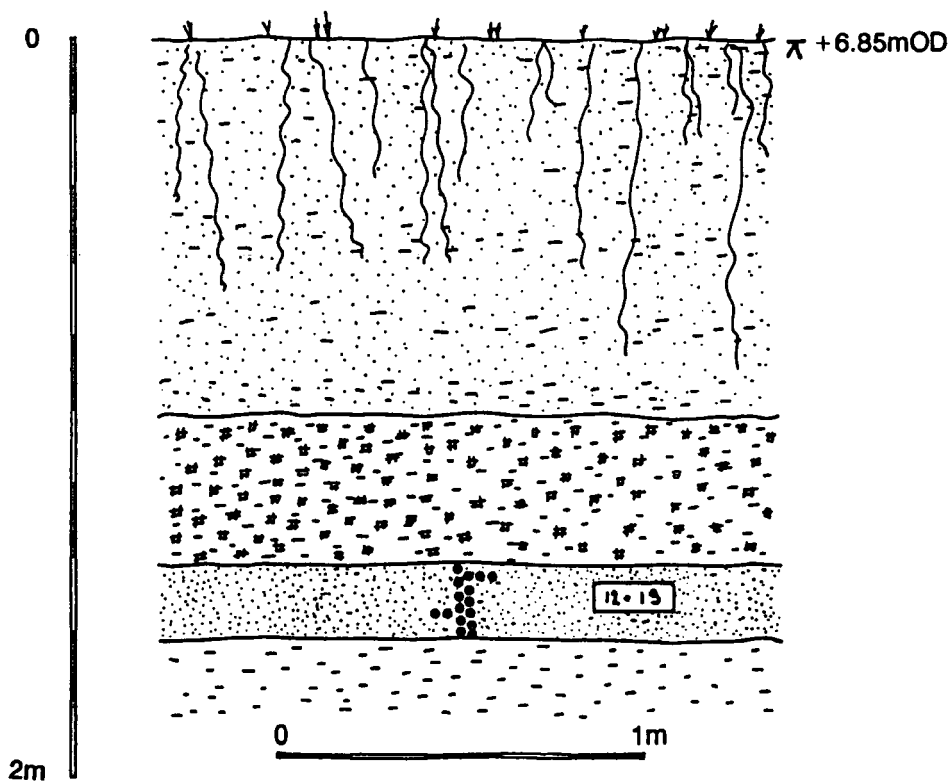


Figure 3.74: Vertical section drawing of moat fill, showing the location of samples.

was slightly higher than surrounding country, possibly as a result of upcast from the moat being spread on the platform (V. Metcalf, pers. comm.). A second field or annexe of nearly 5 acres, also enclosed by a bank and ditch, was situated on the north side of the main moated area and linked to it by a bridge. This contained traces of ponds and buildings. There was a low bank between the main enclosure and the annexe, possibly residue from cleaning of the moat or deliberately constructed to prevent children or animals falling in (D. Heslop, pers. comm.). The area of enclosed water meadow in the annexe may have been a secure paddock for grazing animals and was later known as Calf Close. The suggestion that grass was maintained in the enclosure for the production of hay was supported by the presence of sand banks. These were formed by the melt-water from retreating glaciers at the end of the Devensian period (about 18000 years ago), when this region was covered by a vast tidal estuary known as Lake Humber (Gaunt & Barclay, 1990). Such sand banks would have been destroyed by ploughing. A complex drainage system surrounded the moated enclosure and annexe. It has been suggested that the large drains, constructed to drain the land when woodland was cleared for agriculture, may demarcate ancient land subdivisions (D. Heslop, pers. comm.).

The village of Womersley, 1.5km to the south of the site, was the centre of ancient settlement in the area. Roman remains have been uncovered during quarrying and a Saxon brooch was found nearby. The Domesday survey in AD1086 recorded a manor house, church and 14 families in the village, working two large fields divided into strips. Wood Hall itself was not mentioned in the survey, probably because the associated land was unoccupied, being wooded and poorly drained. The first documentary mention of Wood Hall was as a manor 'in the park of Womersley' in around AD1327, when it was owned by Queen Isabella, wife of Edward II (V. Metcalf, pers. comm.).

Wood Hall moated farm is under long term threat from the expansion of the nearby coal ash dump. An extensive excavation has been planned by the Central Electricity Generating Board and North Yorkshire County Council, incorporating a landscape survey of the vicinity. In the seasons 1988-1990 a number of trial trenches were dug in the moated enclosure and adjoining pasture (Fig. 3.73). In 1988-89 trench 1 was dug across the moat at a point in the south-west quadrant, where it had been backfilled. This trench revealed a number of deposits that might have been waterlain and these were sampled for archaeomagnetic studies, as described below. A second trench (trench 2) examined the area immediately adjacent to the moat section. A limestone building and a farm yard were located, probably dating to the 17th or 18th century AD and depicted on the tithe map of 1805 (D. Heslop, pers. comm.). Below the farmyard was a group of post holes of timber uprights which may have originated in the Medieval period. Nothing of interest to the archaeomagnetic study was found in trench 2. The following season, the later farm remains in the south-eastern corner were excavated

(trench 9) and trench 7 was dug in the annexe, parallel to the moat. The latter trench uncovered a channel leading into the moat (D. Heslop, pers. comm.) and archaeomagnetic samples were taken from the fill, as described below.

Description of the sampling of the moat deposits

Trench 1 (Fig. 3.73) cut through the backfilled part of the moat, revealing a series of deposits in the fill (Fig. 3.74). The moat was extremely substantial, 17m wide in parts but only 1.6m deep, and was cut into boulder clay. Above the clay was a horizon of sandy material sealed by a thick silt layer, containing a high proportion (about 50% by volume) of organic material, including wood and leaves. The silt layer was sealed by a series of sands and silts, which were extensively bioturbated and rootleted and showed the rusty mottling characteristic of iron redeposition and panning.

Context Nos. 12 and 13: Most of the deposits contained a very high proportion of organic material and were extremely bioturbated, a process which was clearly still continuing (as shown by the presence of worms) making them unsuitable for investigation and so only the lowest sand was sampled. This horizon was approximately 20cm thick and overlay the boulder clay into which the moat was cut. It underlay the silts with high organic content. The sand was coarse-grained, very wet and contained no organic material or archaeological artefacts. Context 12, the upper 10cm of the sand was black (Munsell No. 7.5YR 3/0), possibly indicating reduction by contact with the organic material. The lower 10cm of the same material was given the context number 13 and was red (Munsell No. 7.5YR 4/3). 15 samples were taken from a cleaned vertical section through this deposit by the tube method (Fig. 3.74) and oriented using a magnetic compass.

Archaeological interpretation of the moat deposits.

The moat appeared far too wide for purely drainage purposes and was very shallow. It has been suggested (D. Heslop, pers. comm.) that the intention had been to dig deeper but that these attempts had been frustrated by the intractable boulder clay and groundwater immediately below the surface. The horizon sampled appeared to comprise of material derived from the upper sides of the ditch and was possibly washed in when the moat was first cut or last cleaned. Extensive sampling and wet sieving for environmental studies revealed that organic material was well preserved in the overlying silt. However, tree roots and the slow speed of deposition meant that any Medieval remains had been contaminated by later material, except at the lowest levels. Organic

material accounted for over 50% of the matrix and appeared to derive mainly from vegetation growing around the edge of the moat. Artefactual finds were few, suggesting that the moat had been deliberately kept clean, but a small number of 14th and 15th century AD potsherds were recovered. The upper horizons appeared to be material dumped in the moat to backfill it, presumably after it had fallen into disuse.

Results of magnetic measurements: Contexts 12 and 13

Natural remanent magnetisation

The intensity of NRM was in the range $0.32\text{-}6.48\mu\text{Am}^2\text{kg}^{-1}$, higher in the upper part of the deposit and lower, but still generally measurable, towards the bottom of the deposit. The NRM directions seemed to show a general trend from easterly to westerly declinations and an increase in inclination down the section (Fig. 3.75), although no attempt was made to establish such a trend statistically (Section 2.5.3).

Demagnetisation

Stepwise alternating field demagnetisation of 4 pilot samples was carried out and the results for a typical sample are presented in Fig. 3.76. The demagnetisation plots revealed a very scattered pattern of magnetic vectors with no stable end point. It was also found that the direction of magnetisation changed significantly and the intensity reduced by up to 50% after storage in random orientations in field-free space in the laboratory (Fig. 3.75) for only two weeks.

Magnetic fabric

The specific susceptibility was extremely low, $0.09\text{-}0.13\times 10^{-8}\text{m}^3\text{kg}^{-1}$. The magnetic fabric appeared to be unusual. The maximum axes grouped at shallow inclinations, indicating a lineation (Fig. 3.77), but the axes of minimum susceptibility clustered at very shallow inclinations. The susceptibility anisotropy of the samples, $h\%$, was very high, in the range 9.8-22.3% and the q values fell in the range 0.18-1.21, 93% of them in the range normally associated with an undisturbed depositional magnetic fabric. It is possible that this unusual magnetic fabric arose from the disturbance of magnetic grains on sampling. As the grains were so anisotropic, only a small proportion would need to be reoriented in order to give a scattered magnetic fabric. For further conclusions to be drawn it would be necessary to conduct experiments into the effect of sampling disturbance on similar, very anisotropic, sandy sediments.

Magnetic mineralogy

As the remanence direction was unstable it was impossible to carry out IRM acquisition tests.

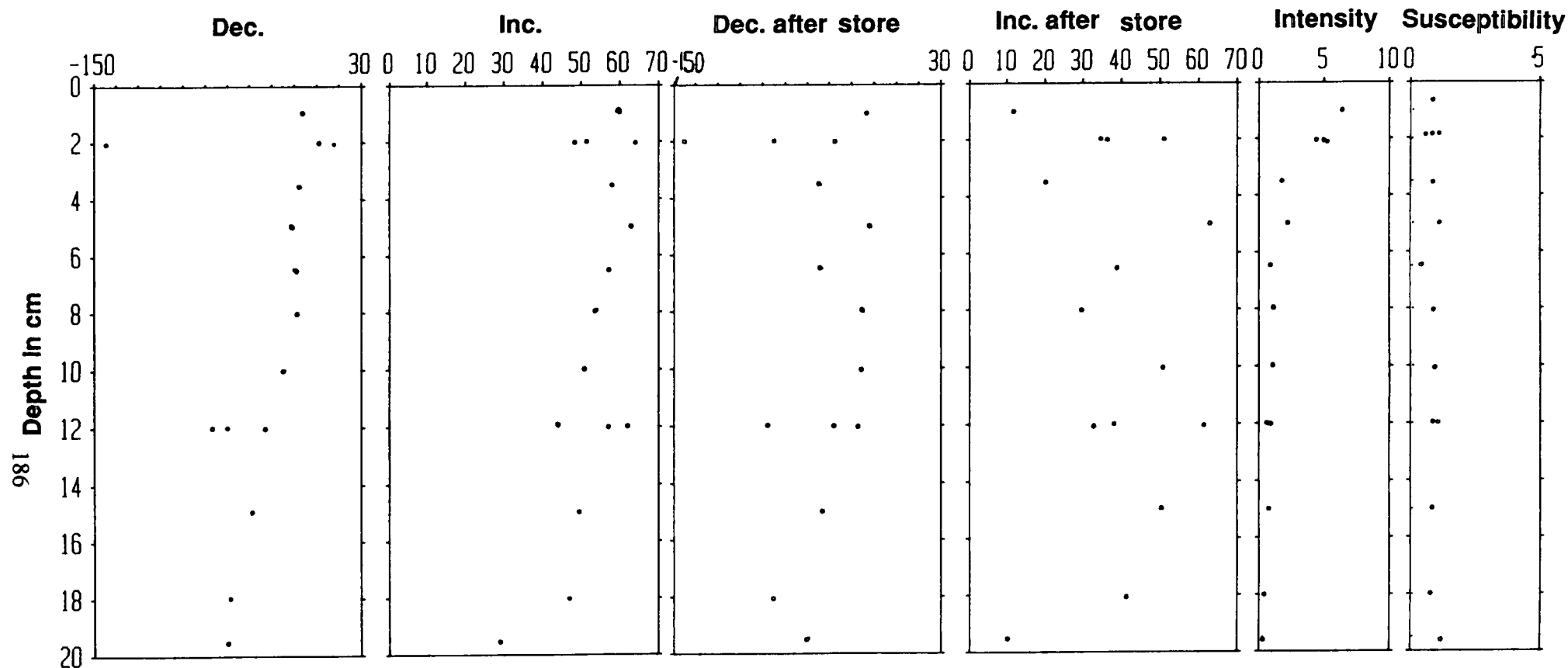


Figure 3.75: Plot of depth against NRM declination (Dec.), NRM inclination (Inc.), declination after storage, inclination after storage (all in degrees) and intensity (in $\mu\text{Am}^2\text{kg}^{-1}$) and susceptibility ($\times 10^{-8}\text{m}^3\text{kg}^{-1}$) from a vertical section through contexts 12 and 13.

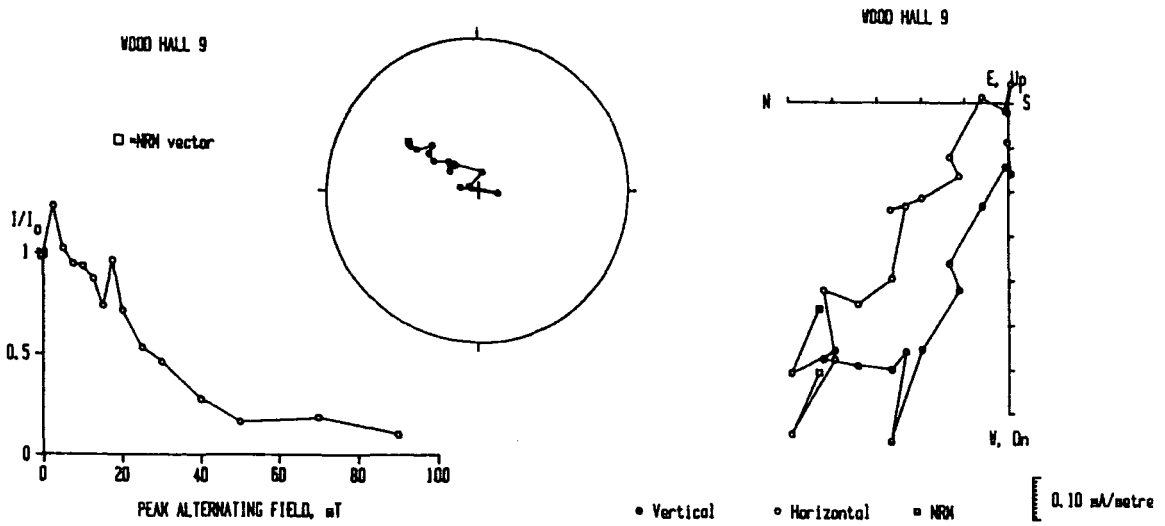


Figure 3.76: Stereographic, intensity and Zijdeveld plots of the behaviour of a typical sample (WH 9) from contexts 12 and 13 on alternating field demagnetisation.

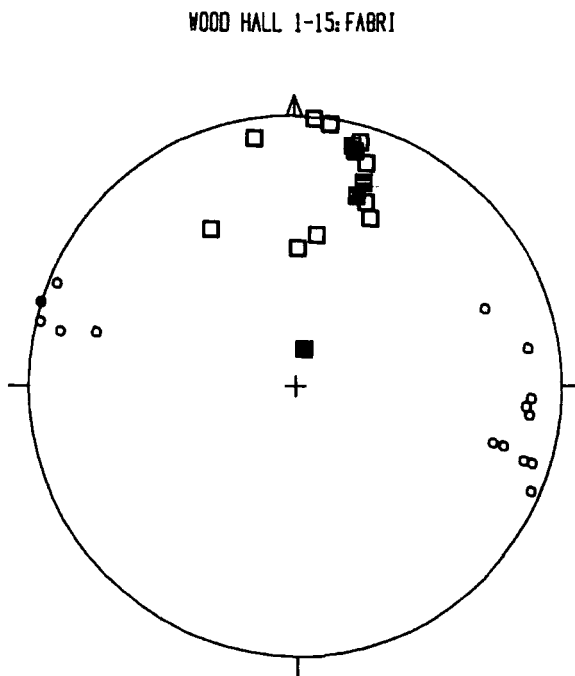


Figure 3.77: Magnetic fabric of samples WH 1-15 from contexts 12 and 13.

General conclusions

The loss of intensity of remanence and change in magnetic direction observed were similar to those found by Stober and Thompson (1979), which they attributed to the realignment of small magnetic particles as a sample dried (Section 1.4.2). The observations on this material were consistent with the physical reorientation of remanence-carrying grains as the sample dried out, which it did very quickly being a coarse-grained sand. This would cause changes in the remanence direction and intensity. However, the magnetic fabric remained unchanged as the sample dried, suggesting that the majority of magnetic minerals remained fixed in position, with only the remanence carrying grains free to move. This implied that the remanence-carrying grains were much smaller and possibly located in the pore spaces associated with larger grains. It was possible that the NRM did record geomagnetic secular variation as it was measured soon after the samples were taken, but no conclusions concerning date could be drawn, as the measurements were unrepeatable and the magnetic vector was unstable.

Description of the sampling of the drainage ditch

Excavation of trench 7 revealed a channel whose base was graded from the interior of the meadow towards the moat, intersecting it at right angles. A section through this channel (Fig. 3.78) showed that it had been cut into the natural boulder clay underlying the site. At the base of the channel was a horizontal layer of very dark grey (Munsell No. 7.5YR 3/0), silty clay (context 805), only 1cm thick and covering the entire base of the channel, about 2m wide at this point, thinning out towards the edge as the sides of the channel began to rise. This material was fine-grained with no mottling or evidence of sedimentary structures or slumping and was extremely moist and plastic. It contained a small number (less than 1% of the matrix) of stones, not more than 5mm in diameter and incorporated some organic remains, namely a few twigs. Overlying this was 1.5m of dark greyish brown (Munsell No. 10YR 3/2) silt (context 803), culminating in the present day vegetated ground surface. This deposit contained large quantities of organic material, including twigs and leaves. It had been subjected to intense bioturbation, with roots and animal burrows being easily visible throughout the cleaned section, destroying any sedimentary structures that might have been present. The contact between the silt and the silty clay was gradual over 3cm, whereas the contact onto the boulder clay was sharp. It was decided to sample the apparently undisturbed, thin, silty clay layer and, for comparison, the upper silt, despite its bioturbated appearance.

As the lower silty clay (context 805) was so thin, it was necessary to adapt the conventional sampling technique. The sample tubes used were open at both ends and

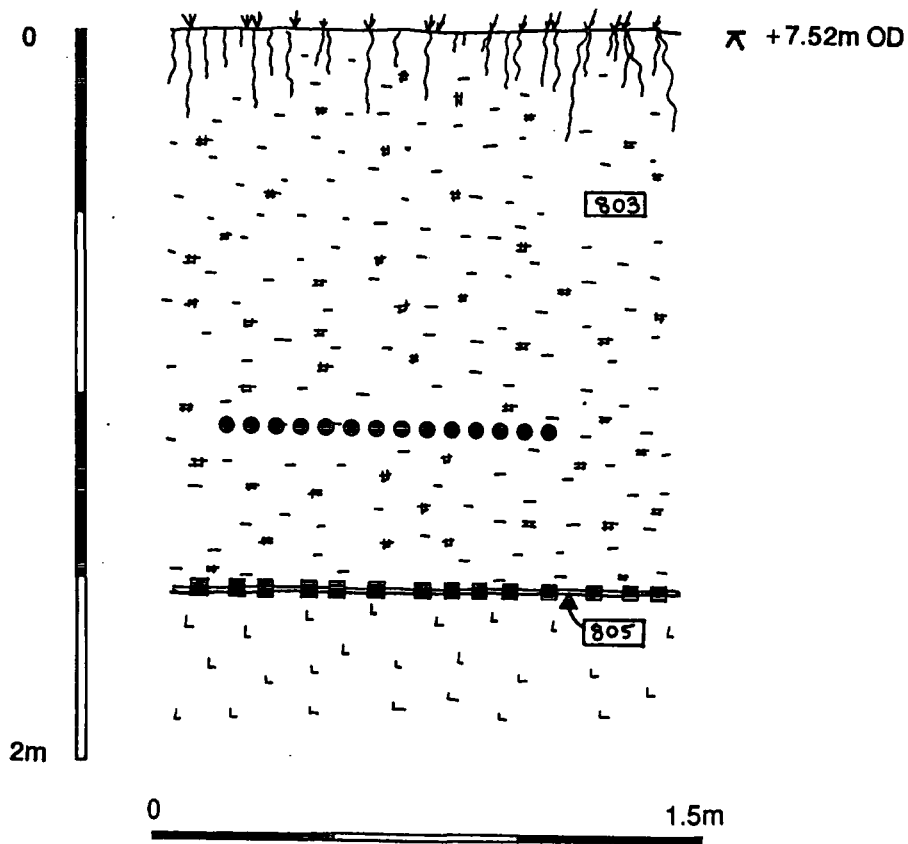


Figure 3.78: Vertical section drawing of drainage channel, showing location of samples.

were pushed vertically into the cleaned upper surface of the silty clay, right through into the underlying boulder clay. In the laboratory, the gap at the top of the sample was filled with plaster of Paris. When that was set the sample was inverted and the boulder clay was removed until the silty clay layer was reached and the gap filled with plaster. 14 samples were taken in this manner. Orientation was carried out with a magnetic compass as there was no shoring and it was not possible to use a sun compass. Samples were taken from the upper silt by pushing sample holders into a cleaned, vertical section (Fig. 3.78).

Archaeological interpretation of the deposits sampled

The position and orientation of the channel led the excavator to suggest that its purpose was to drain the paddock area which tended to get very waterlogged (D. Heslop, pers. comm.). The material covering the base of the channel described above (context 805) was interpreted as the first inwash into the channel after it was cut or last cleaned, thus implying that deposition took place over a short period of time and may have been affected by water flow into the moat. The overlying silt layer (context 803), with a higher organic content, might have represented material deposited in the channel over a longer period as it remained open, disturbed by biological activity and with organic material incorporated from over-hanging trees. There were no archaeological finds from either of these contexts.

Results of magnetic measurements: Context 805

Natural remanent magnetisation

The mean intensity of NRM was in the range 15.5-446.3 $\mu\text{Am}^2\text{kg}^{-1}$, very high in comparison with other sediments in this study. The NRM directions were closely grouped with one apparent outlier (Fig. 3.79a), but even including this outlier the α_{95} value was low, 3.0°.

Demagnetisation

Stepwise alternating field demagnetisation of 2 pilot samples (WH3A and WH10A) was carried out and the results for a typical sample are presented in Fig. 3.80. The stereographic projection indicated little directional change up to 40mT and the Zijderveld plots showed straight line behaviour, indicating the presence of a single component of magnetic direction. The single component was statistically well defined, with a stability index of 6.0 (very stable) and 6.7 (very stable) for pilot samples WH3A and WH9A respectively over the range 5-40mT. The intensity fell smoothly and sharply,

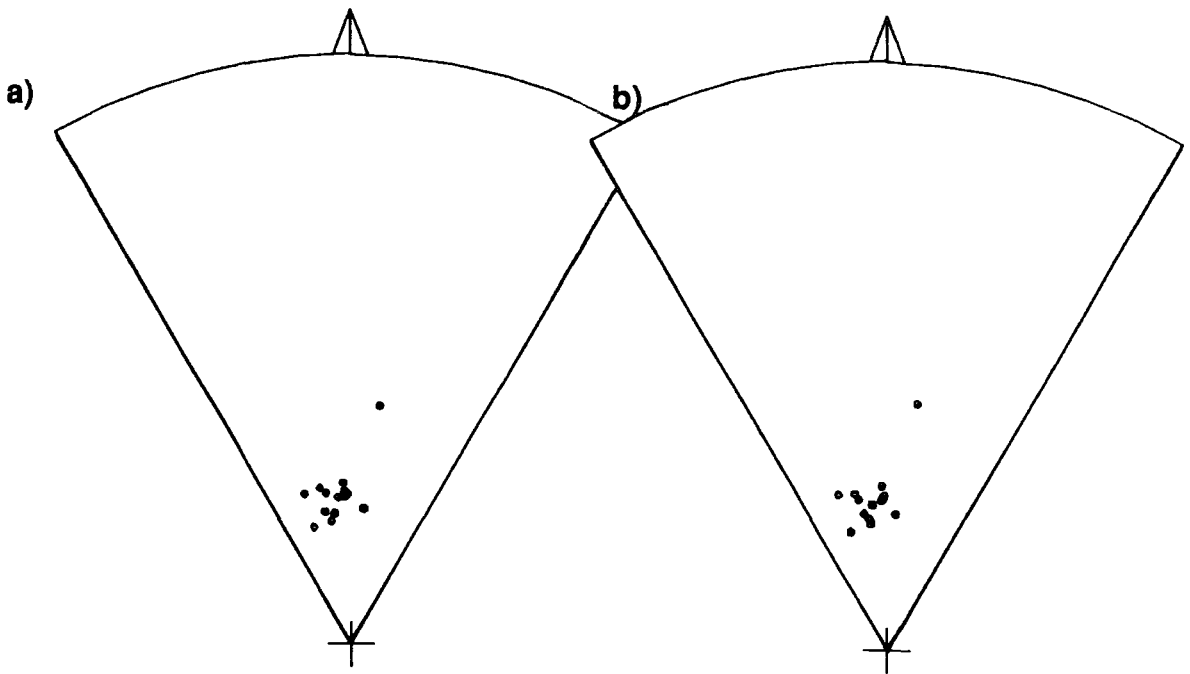


Figure 3.79: Stereographic plot of the directions of magnetisation of samples WH 1A-14A from context 805 a) NRM values and b) after partial demagnetisation.

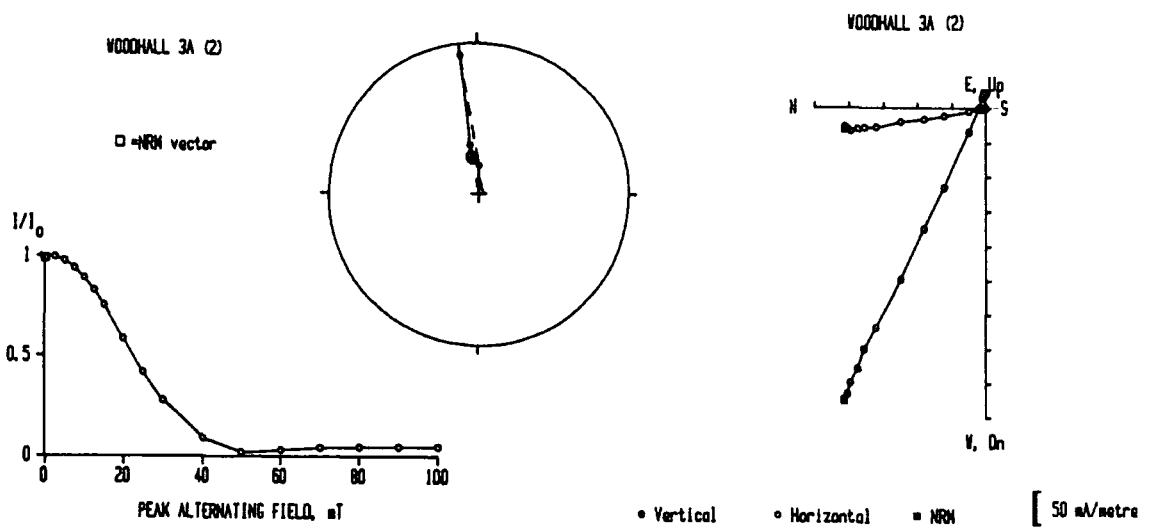


Figure 3.80: Stereographic, intensity and Zijderveld plots of the behaviour of a typical sample (WH3A) from context 805 on alternating field demagnetisation.

demonstrating that the magnetisation was fairly soft, with less than 5% of the original magnetisation remaining in fields of 50mT. This suggested that the magnetic mineral was likely to be magnetite. The median destructive field was 20-25mT. On demagnetisation the outlier (WH10A) showed similar behaviour to the two pilot samples and gave no indication of a reason for its anomalous direction, which was separated by 19.8° from the mean of the remaining samples. The displacement appeared to be entirely in inclination and so it was suggested that, while the sample holder had been oriented correctly, it may not have been pushed vertically into the sediment. Because of this uncertainty, the outlier was omitted from subsequent calculations.

The similarity of behaviour of pilot samples and the homogeneity of the material led to the selection of a demagnetising field of 10mT for the remaining samples to isolate the primary component, while removing spurious soft components of viscous remanent magnetisation. Bulk demagnetisation did not result in any significant change to the directions of magnetisation (Fig. 3.79b) or any change in α_{95} , confirming the stability of the magnetic direction. The α_{95} of 1.9° , based on 13 samples was comparable to the errors expected to arise from sample orientation and measurement (Section 2.6), indicating that there had been minimal post-depositional disturbance.

Magnetic fabric

The sediment showed features typical of a primary depositional style fabric, with axes of minimum susceptibility clustering to define a near-horizontal magnetic foliation plane and the maximum axes grouping to indicate a lineation (Fig. 3.81a). The specific susceptibility was generally high, in the range $1.6\text{--}43.4 \times 10^{-8} \text{m}^3 \text{kg}^{-1}$. $h\%$ fell in the range 3.2-11.3 and q values were between 0.05-0.71, with 86% in the range normally associated with an undisturbed depositional magnetic fabric. The lineation shown by the axes of maximum susceptibility suggested that water currents acted on the magnetic grains during deposition.

An attempt was made to determine the palaeoflow direction by the method of Noel and Rudnicki (1988) described in Section 2.3.2. This indicated that mean flow was roughly at 109° clockwise from north (Fig. 3.81b). While the exact course of the channel was undefined, this observation suggested that it appeared to run roughly north to south, into the moat.

Magnetic mineralogy

IRM acquisition tests on two pilot samples (e.g. Fig. 3.71) showed that 96-98% of the SIRM was acquired in fields of less than 1T and that the SIRM values were extremely high, 6.0 and $7.3 \times 10^{-2} \text{Am}^2 \text{kg}^{-1}$. $(B_0)_{\text{cr}}$ for the samples was in the range 23-30mT, with S being 0.98 in both cases, suggesting that the magnetic carrier was likely to

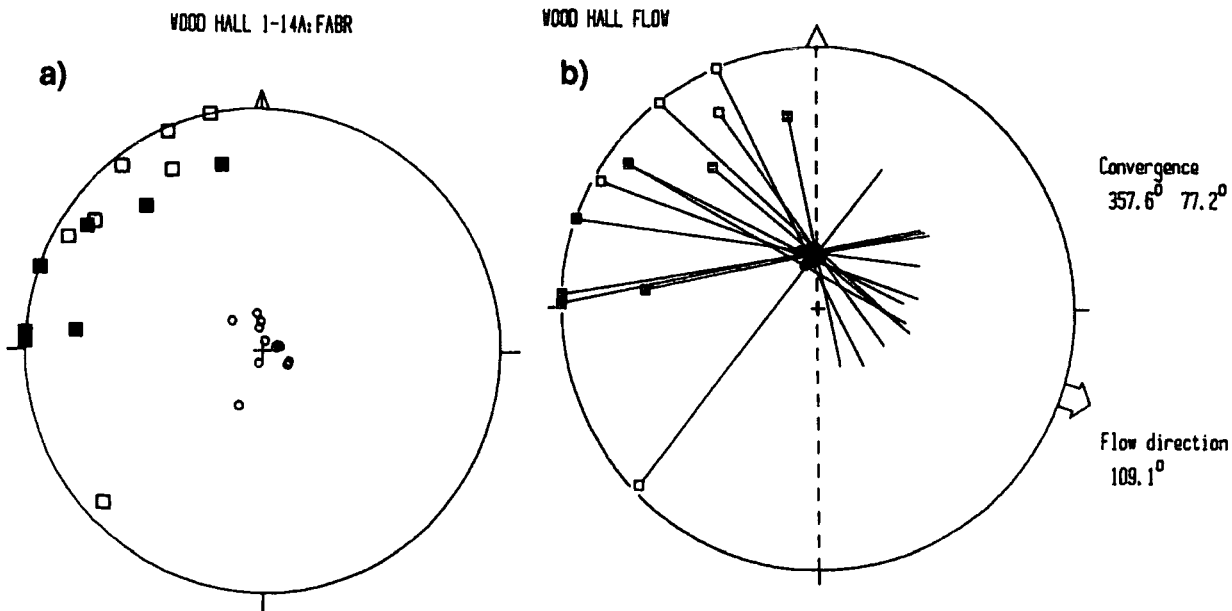


Figure 3.81 a: Magnetic fabric of samples WH 1A-14A from context 805.
 b: Determination of flow direction from magnetic fabric and NRM of samples WH 1A-14A from context 805. Arrow indicates mean direction of flow and dotted line indicates channel axis.

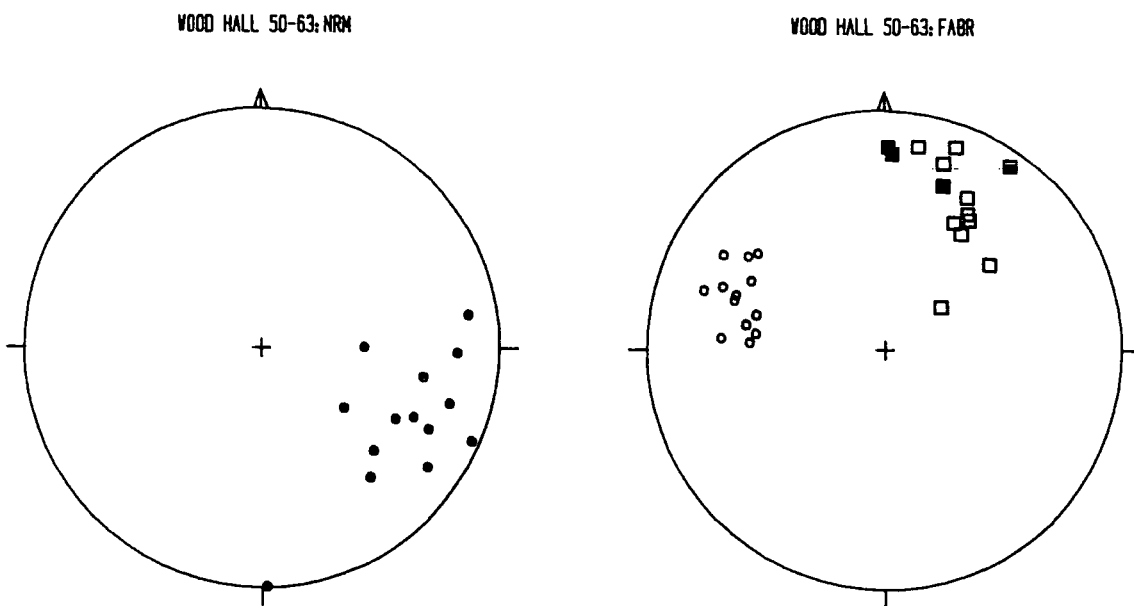


Figure 3.82 (left): Stereographic plot of the NRM directions of magnetisation of samples WH 50-63 from context 803

Figure 3.83 (right): Magnetic fabric of samples WH 50-63 from context 803.

be magnetite with very little contribution from any harder magnetic minerals. The high SIRM values corresponded with the high intensity of magnetisation and suggested that the concentration of remanence carrying grains was high.

Results of magnetic measurements: Context 803

Natural remanent magnetisation

The intensity of NRM of the group of samples taken from the bioturbated channel fill fell in the range $0.18\text{-}0.73\mu\text{Am}^2\text{kg}^{-1}$, all extremely low values. The NRM directions were dispersed at easterly declinations and shallow inclinations (Fig. 3.82), with an α_{95} value of 13.6° .

Demagnetisation

The intensity of magnetisation of the samples was considered too weak to carry out demagnetisation experiments, but the direction and intensity of the NRM appeared to remain unchanged after storage for several weeks in random orientations in the field-free space provided by a mu-metal shield.

Magnetic fabric

The specific susceptibilities were all low, $0.2\text{-}0.3\times 10^{-8}\text{m}^3\text{kg}^{-1}$, but the axes of minimum susceptibility clustered at shallow inclinations, as did the maximum axes, indicating a lineation (Fig. 3.83), giving a rather similar fabric to that of the Stakis Hotel samples (Section 3.4.2) and the moat samples described above. The susceptibility anisotropy of the samples, $h\%$, included some high values and was in the range $3.9\text{-}11.4\%$, similar to context 805. The q values were between $0.19\text{-}0.52$, all in the range associated with an undisturbed depositional magnetic fabric.

Magnetic mineralogy

IRM acquisition tests on a pilot sample (Fig. 3.71) showed that the SIRM value was very low, $6.9\times 10^{-5}\text{Am}^2\text{kg}^{-1}$ and that 89% of this was acquired in fields of 1T. $(B_o)_{cr}$ was 25mT and S was 0.8. These results suggested that the magnetic carrier was likely to be magnetite with a contribution from harder magnetic minerals, but the most significant factor was the low SIRM value which indicated that there was a very low concentration of remanence carrying minerals in the sediment matrix.

General conclusions

The magnetic properties of the material from context 805 indicated that a record of the geomagnetic field on or shortly after deposition was retained by magnetite grains within the sediment. The magnetic fabric did suggest that deposition had been affected by flow in a direction consistent with water flow from the enclosure into the moat. This would be expected if, as suggested, the channel's function was to drain the enclosure. In contrast, the intensity of the magnetisation of samples from context 803 was extremely weak. IRM tests showed that they contained insufficient stable, remanence-carrying magnetic grains to give a measurable record of the geomagnetic field at the time of deposition. The unusual magnetic fabric was difficult to account for, but was similar to the magnetic fabric obtained for other sediments with a very weak specific susceptibility and fairly high anisotropy of susceptibility (Section 3.4.2). More examples of similar sediments are required before specific conclusions can be drawn.

The mean magnetic direction of the silt samples from context 805 after demagnetisation was corrected to Meriden (Table 1C) and compared with the calibration curve (Fig. 3.84). It had a steeper inclination than curve in the period pertaining to AD1300-1350 and the error bars at 95% confidence did not actually intersect the curve. If the direction was corrected for flow as suggested by the flow determination of Noel and Rudnicki (1988) performed above, the mean direction then fell on the curve at around AD1310, with an uncertainty of ± 25 years, at the 95% level of confidence. This revised magnetic direction was also compared with the revised calibration curve of Chapter 5 (Section 5.6.4).

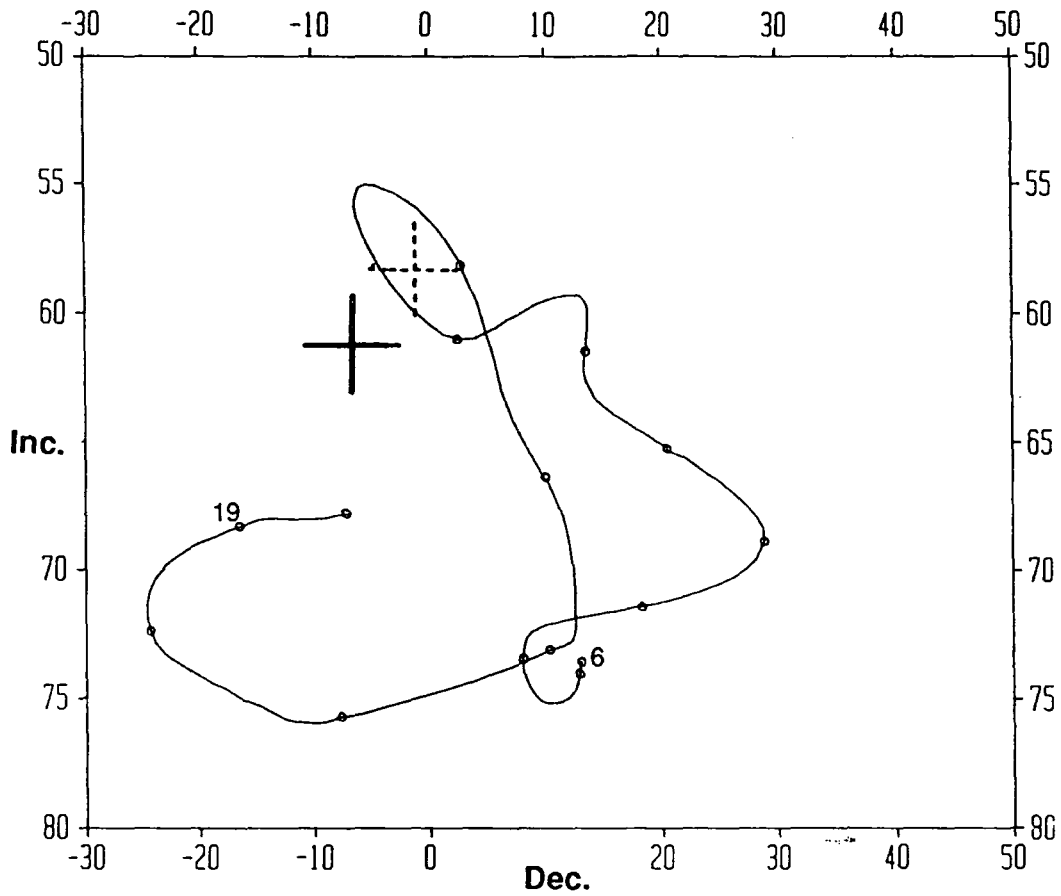


Figure 3.84: Mean magnetic directions after demagnetisation from context 805 with errors at 95% confidence, corrected to Meriden and fitted to the British calibration curve covering AD600-present. The calibration curve was digitised from that of Clark *et al.* (1988); circles indicate centuries and the figures are 100's of years. The dotted cross indicates the magnetic direction after correction for flow effects.

3.5 DISCUSSION OF THE RESULTS

3.5.1 *Introduction*

This study has investigated the magnetic properties of 31 deposits of water-lain sediments from a range of archaeological contexts; including fluvial, marine and static water depositional conditions. The wide variety of contexts included most of the types of water-lain sediments commonly encountered in British archaeological excavations. The study aimed to reveal the potential and the pitfalls of archaeomagnetic studies of such deposits and to indicate which environments might be most suitable for routine archaeomagnetic study. In most cases, archaeological evidence was available to indicate the date of the deposit and its mode of deposition, enabling comparison to be made with the archaeomagnetic results. This evidence arose either from the archaeological interpretation of the deposit in relation to the whole excavation, or from artefactual or biological remains preserved within the sediment matrix. In addition to successfully dating a number of sediments, archaeomagnetic investigations also provided information concerning the environment of deposition and the magnetic mineralogy of the sediment.

3.5.2 *Sampling, orientation and storage methods*

The sampling method employed utilised 2.5cm diameter plastic tubes (Section 2.1.3), which were pushed horizontally or vertically into a cleaned sediment surface. The advantage of the small holders, over the more commonly used 5.3cm diameter samples (Clark *et al*, 1988), was that they enabled very thin deposits to be sampled, as in the case of the primary ditch silt from Wood Hall (Context 805; Section 3.4.10). They were also quicker to insert; stones, roots and other obstructions could be more easily avoided; more samples could be taken and the geomagnetic record obtained was more detailed. In most cases the intensity of magnetisation was greater than $1 \times 10^{-8} \text{Am}^2$, sufficiently high to be easily measurable with a spinner magnetometer (Section 2.2.1). In a small number of cases (e.g. Prudhoe, Section 3.4.5) measurement with a cryogenic magnetometer would have been desirable as the magnetisation of samples was so weak. The main disadvantage of the small sample holders was the fact that large-grained, unconsolidated sediments were difficult to sample as they tended to crumble, as with the silty sands from Farnley (Section 3.4.6). It would have been desirable to consolidate material of this type before sampling, although a suitable method has yet to be found. Increased sampling disturbance might be expected with the smaller holders, but this did not appear to be the case; the dispersion of the magnetic vectors from a single context was sometimes as low as 1.5° (95% confidence e.g. Stakis Hotel, context 4159; Section 3.4.2), comparable with the least dispersed directions obtained using the large samples (Section 3.3).

The positioning of samples enabled further information to be extracted. Overlapping sample holders down a vertical section (Section 2.1.3) enabled a detailed record of variations in magnetic direction to be obtained, for example from the fill of the minor palaeochannel at Caldicot (Context 174; Section 3.4.4). Repeated sampling along a single sediment horizon enabled an assessment to be made of the dispersion of magnetic measurements within material expected to preserve a single magnetic direction (Section 2.1.3). The dispersion was sometimes as low as 1.5° (e.g. Stakis Hotel, context 4159; Section 3.4.2), smaller than that often obtained for fired structures. (See further discussion in Section 6.5). Samples taken by pushing holders both horizontally and vertically into the same sediment appeared to have very similar magnetisations, suggesting that errors arising from sample 'push' were small in comparison with errors from other sources (Section 2.6). For example, the 12 samples obtained by pushing sample holders vertically into context 2311 on the A.B.C. Cinema site had a mean declination of $2\pm 8^{\circ}$ and a mean inclination of $66\pm 3^{\circ}$, both at 95% confidence, whereas the magnetic directions of 12 samples taken with holders pushed horizontally into the same context had a mean declination of $8\pm 13^{\circ}$ and a mean inclination of $70\pm 4^{\circ}$, both at 95% confidence (Section 3.4.1). The clear overlap between these two sets of magnetic directions suggests that the errors arising from 'sample push direction' are small compared with the other errors arising in sampling and magnetisation acquisition.

Recording the orientation of samples proved to be rather difficult in some circumstances. While a magnetic compass is affected by local magnetic anomalies, it was generally found to be the most convenient method; fast, easy to use, robust and portable. Where comparison was made with other orientation methods, in the absence of strong local anomalies, as at Caldicot (Section 3.4.4), agreement between orientation by magnetic compass and gyro-theodolite was found to be within 2° . However, on sites such as A.B.C. Cinema and Stakis Hotel (Sections 3.4.1 and 3.4.2), steel shoring made the use of a magnetic compass impossible. In such cases, orientation was carried out using a gyro-theodolite or by reference to an established site grid. While a gyro-theodolite is widely applicable on archaeological sites, it is too expensive, delicate, cumbersome and difficult to use to be an ideal solution. The use of a sun compass was rarely feasible owing to a lack of sun! Despite the difficulties of sample orientation, the close grouping of some of the sediment magnetic directions suggested that the errors introduced by sample orientation were small, generally less than 2° .

Sample storage is an important aspect of sediment archaeomagnetism. In the laboratory, samples were sealed and stored in a cool, damp environment to prevent water-loss and associated grain reorientations (Section 2.1.5). In almost all cases the magnetisation was found to be stable over the weeks during which measurements were carried out. However, larger grained deposits, which would be expected to lose water

more quickly, occasionally showed changes in remanence direction and intensity on storage (detailed in Wood Hall, context 12 & 13; Section 3.4.10). It would therefore be recommended that samples should be sealed and stored in damp conditions and measurements should be carried out as soon as possible after sampling.

3.5.3 *Remanent magnetisation*

In the majority of cases the NRM of the sediment samples was easily measurable in a spinner fluxgate magnetometer, with some intensities as high as $4 \times 10^{-4} \text{Am}^2 \text{kg}^{-1}$. On this evidence, use of a cryogenic magnetometer (Section 2.2.1) would be unnecessary for most sediments, even given the small sample size, although it would have the advantage of increasing the speed with which samples could be measured. The NRM intensities were generally in a narrow range (e.g. ABC Cinema Context 2307: Section 3.4.1); samples with intensities an order of magnitude different from the main group usually also had anomalous remanence directions or showed atypical demagnetisation behaviour, often due to an inclusion in the sample revealed by dissection (e.g. West Heslerton: Section 3.4.9). Such anomalous remanences were rare, possibly because the sediments were chosen for their homogeneity and visible inclusions were more easily avoided with the small sample holders. The problems of sample inhomogeneity encountered in earlier archaeomagnetic studies (Section 3.3) were largely avoided by carefully selecting undisturbed, homogeneous sediments with no visible evidence of iron redeposition or panning.

Fig. 3.85a shows the relationship between the range of intensities of magnetisation and sediment type, in order of increasing grain size, including the sediments with high organic content for comparison. Quantitative measurements of grain size were not attempted. The broad groupings given were obtained by the qualitative tests commonly used in field archaeology (Keeley & Macphail, 1981); with sands having grain sizes of 2.0-0.06mm, silts with grain sizes of 0.06-0.002mm and clays with grain sizes less than 0.002mm. Excluded from this graph are samples shown by dissection to be anomalous (see above) and the modern analogue samples which appeared to be unrepresentative, as discussed in Section 3.4.3. Intensity tended to be higher in the smaller grained deposits of clay, silty clay or silt (e.g. Stakis Hotel; Section 3.4.2) than in the sandier material, such as the sand horizons in the Prudhoe deposits (Section 3.4.5). This might be expected as in the finer grained deposits the magnetised grains are likely to have had more time with which to align in the geomagnetic field and less disturbance by strong water currents. However, it must be remembered that the magnetic mineralogy and the concentration of these minerals are also significant factors. It seems likely that the wide range of intensities of magnetisation in the silty clay grain size is at least partially due to the large number of different deposits which fell in this category. The plot

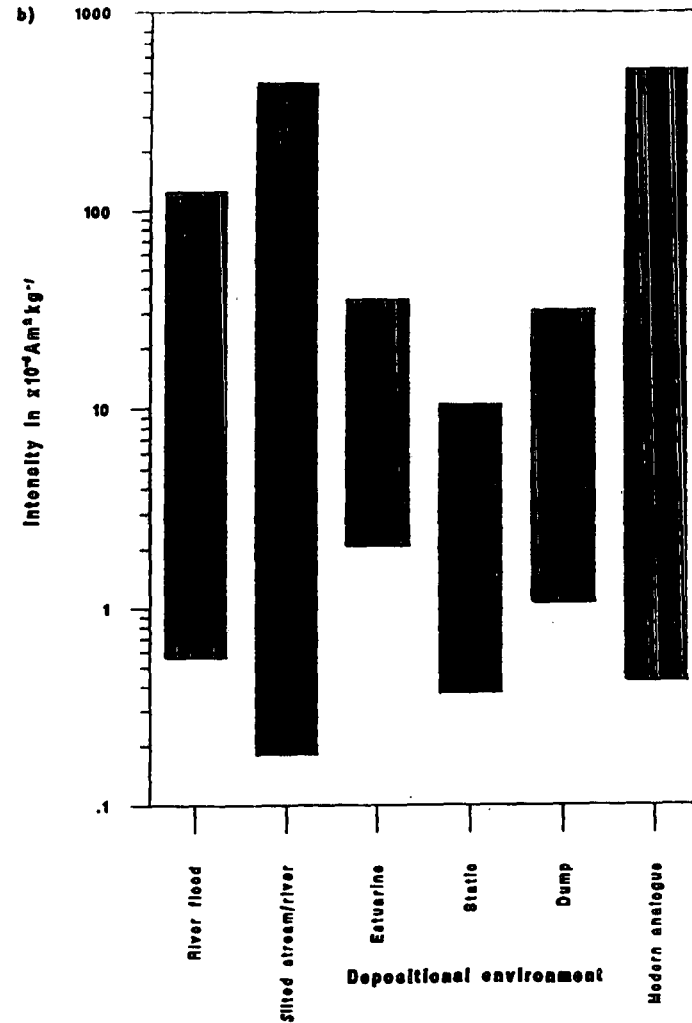
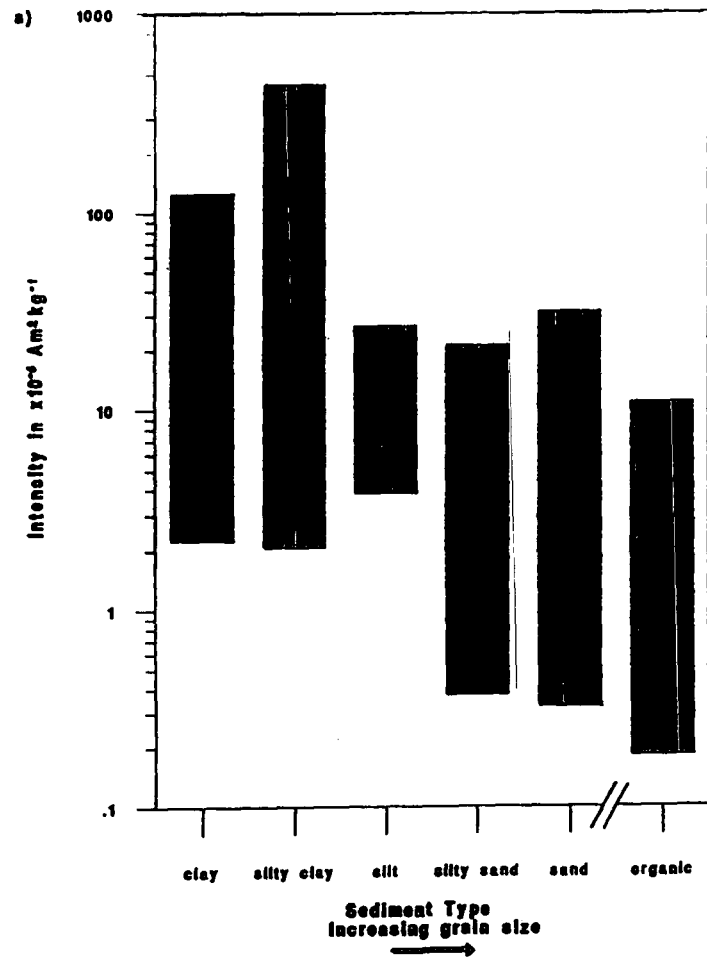


Figure 3.85: Range of values of intensity of magnetisation against a) sediment type and b) depositional environment. On this and subsequent plots 'Modern analogue' samples have been omitted from plot of sediment type and anomalous samples have been omitted from both plots of sediment type and depositional environment (see text). Numbers of samples in each category are as follows: clay=29, silty clay=152, silt=33, silty sand=113, sand=51, organic=45, river flood=189, silted stream/river=128, estuarine=29, static=39, dump=38, modern=19.

also showed that sediments with high organic content had noticeably lower intensities of magnetisation (e.g. A.B.C. Cinema, context 4006; Section 3.4.1), which might arise from lower concentrations of magnetic minerals or bioturbation. Grouping contexts according to their depositional environment must be done with caution (Fig. 3.85b) because the categories 'river flood' and 'silted stream/ditch' include 16 and 7 contexts respectively, whereas the categories 'estuarine', 'static', 'dump' and 'modern analogue' only include two contexts each. Such categorisations can only be of limited value with such an unevenly distributed number of contexts, but it is interesting to note the wide range of intensities of magnetisation from the modern analogue environment (Section 3.4.3) which indicated that this deposit does not appear to be representative of archaeological deposits from apparently similar depositional conditions, or that the remanent magnetisation measured in archaeological deposits develops over a period of time after deposition.

The stability index (Section 2.5.2) was used in the identification of the primary component of magnetisation and in assessing its stability. 62% of the pilot samples had stable or very stable magnetisations, with stability indices in excess of 4.0. There was often a small, soft overprinted magnetisation removed by demagnetisation in fields of 7.5-15mT. Such behaviour was consistent with a viscous overprint of a primary magnetisation. Lower stability indices (Fig. 3.86a) were generally associated with larger grained, sandy deposits (e.g. Prudhoe; Section 3.4.5) or deposits with a high organic content (e.g. Context 4006 at A.B.C. Cinema (Section 3.4.1)). Clays showed a particularly wide range of stability indices. It could be suggested that the magnetisation of sandy deposits was less stable as there was likely to have been less time for remanence acquisition during deposition, the magnetic carriers themselves may be less stable or the remanence may have changed as the sample dried out. Organic sediments, as might be expected, have a lower stability index, probably because the material of the deposit has been bioturbated. An examination of the relationship between intensity and stability index of the pilot demagnetisation samples (Fig. 3.86b) showed that samples with very low initial intensities ($<2 \times 10^{-6} \text{ Am}^2 \text{ kg}^{-1}$) had low stability indices (<2.5). This was likely to be a reflection of the difficulty of measuring the magnetic directions of very weak samples during demagnetisation, suggesting that for such samples a more sensitive magnetometer would have been appropriate. However, for all but these very weak samples there appeared to be no direct connection between strength of magnetisation and stability. The median destructive field was usually between 7.5 and 25mT and demagnetisation generally revealed little contribution to the remanence by harder magnetic minerals. A notable exception was the silt material from Farnley (Section 3.4.6) which appeared to have a much larger hard magnetic mineral component, discussed in further detail below.

The dispersion of the direction of the primary components of magnetisation (where it was possible to isolate them), quantified by the α_{95} value, was of particular

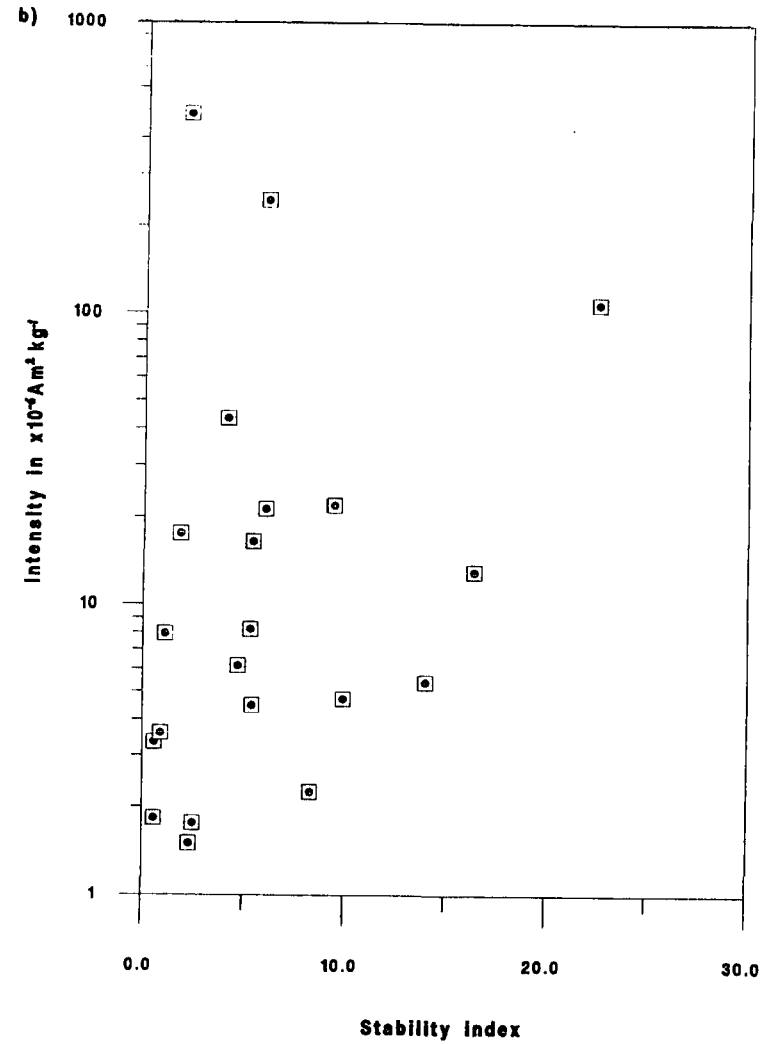
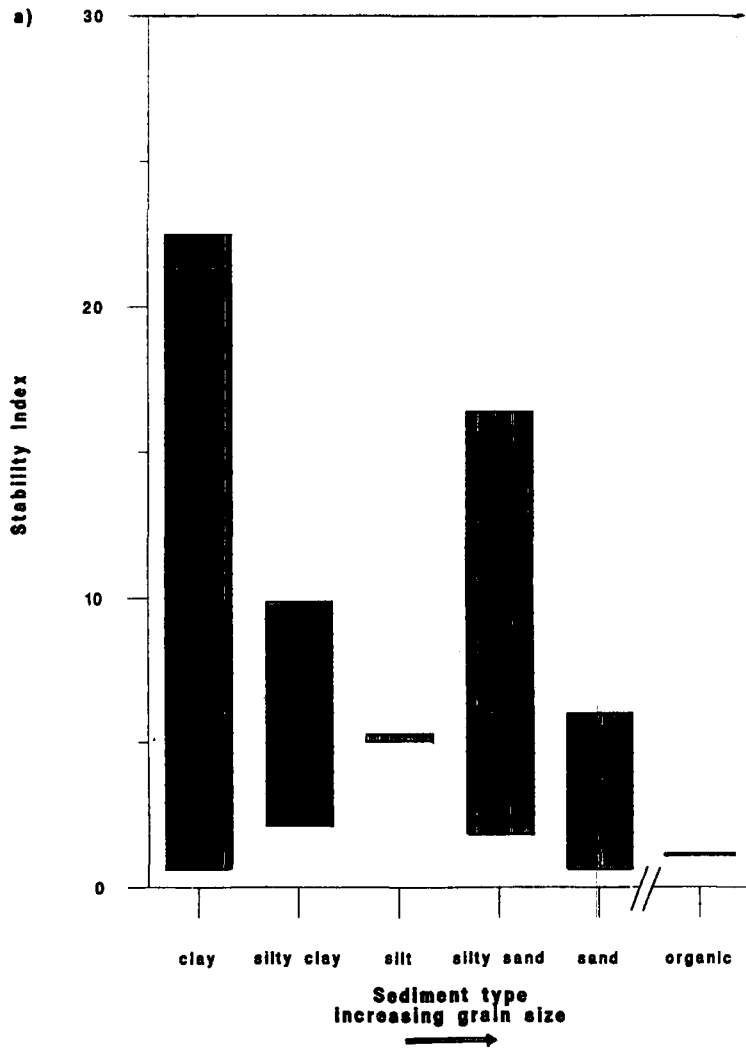


Figure 3.86a: Range of values of stability index against sediment type. Numbers of samples in each category are as follows: clay=3, silty clay=7, silt=2, silty sand=5, sand=3, organic=2.

b: Stability index against intensity for pilot samples.

importance as it could be taken as a crude measure of whether a group of samples was datable. A large α_{95} value indicated that the material was undatable, whereas a small α_{95} value meant that dating might be feasible, although the possibility of later overprinting had to also be considered. The broad indications (Fig. 3.87a) were that small α_{95} values were associated with the smaller grained deposits (clay, silty clay and silt). In some cases, the α_{95} values were extremely small (e.g. Stakis Hotel and A.B.C. Cinema sites), less than those commonly expected for fired materials (Chapter 4). Sands and deposits with high organic content had consistently higher α_{95} values, which corresponded to their lower stabilities. In fact all six contexts with α_{95} values under 4° were deposits of clay, silty clay or silt, whereas 17 of the 20 contexts with α_{95} values of 4° or above were silty sand, sand or organic deposits. A study of the relationship between the intensity and α_{95} value (Fig. 3.88a) indicated that low intensities were not necessarily associated with low α_{95} values, or high intensities with high α_{95} values, suggesting that the dispersion of the magnetic directions was not determined solely by the strength of magnetisation. However, it was clear that very low stability indices (<3) were associated with high α_{95} values ($>9^\circ$), whereas stability indices over 3 were usually, but not exclusively, associated with α_{95} values below 6° (Fig. 3.88b). It would seem reasonable to expect samples with low stability to have magnetic directions that were poorly grouped.

Bearing in mind the problems of grouping contexts according to their depositional environment detailed above, it appeared that a wide range of α_{95} values occurred in river floods; estuarine, silted river/stream and static deposits gave consistently low values; whereas dump and modern analogue deposits were generally significantly higher (Fig. 3.87b). These observations suggested that contexts where there had been least disturbance by bioturbation or water currents were most likely to yield a small α_{95} value.

Colour is a one of the most obvious properties to use when describing and categorising sediments suitable for archaeomagnetism. However, it is also very difficult property to measure objectively. Even when, as in this work, Munsell charts are used colour descriptions are dependent upon light, moisture content and the subjectivity of the person making the description. Given the usefulness of colour as a visual characteristic easily assessed in the field, an attempt was made to relate sediment colour to intensity of magnetisation. Fig. 3.89a shows that black/very dark grey sediments had the widest range of intensity of magnetisation, including some very high values, conversely, red/brown sediments had very low intensities of magnetisation. These observations suggested that an abundance of dark minerals is associated with magnetite. However, the apparent colour of the sediment may not necessarily reflect the magnetic minerals it contains.

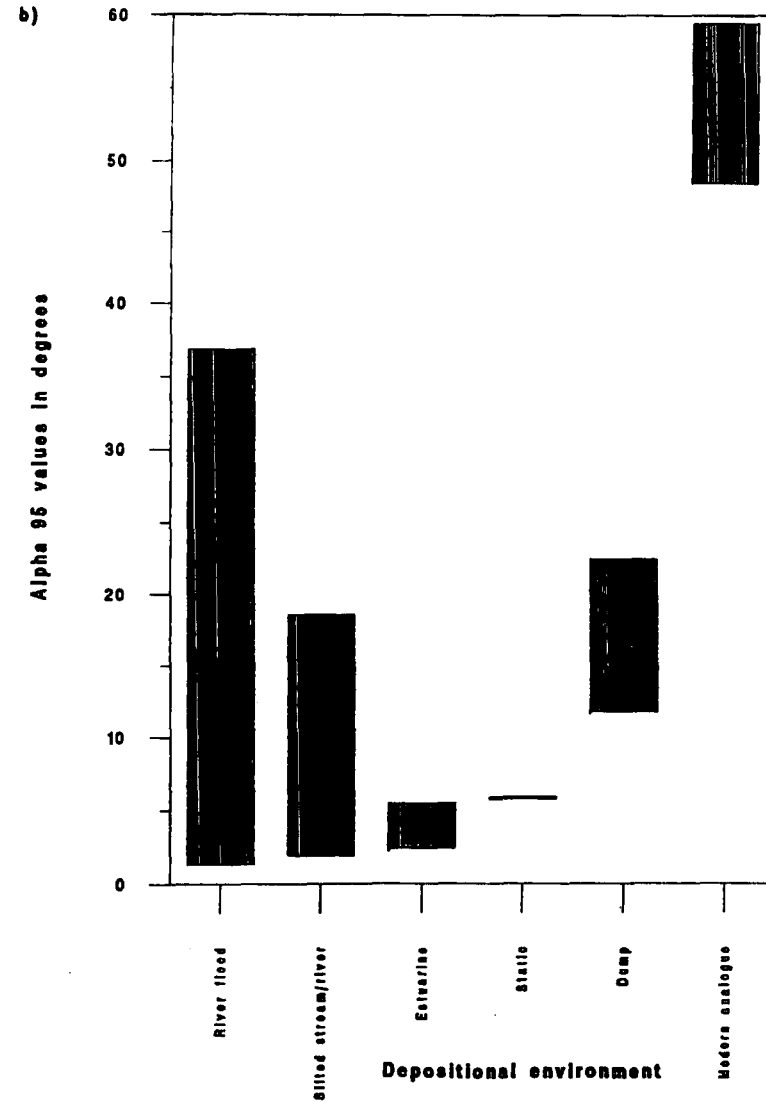
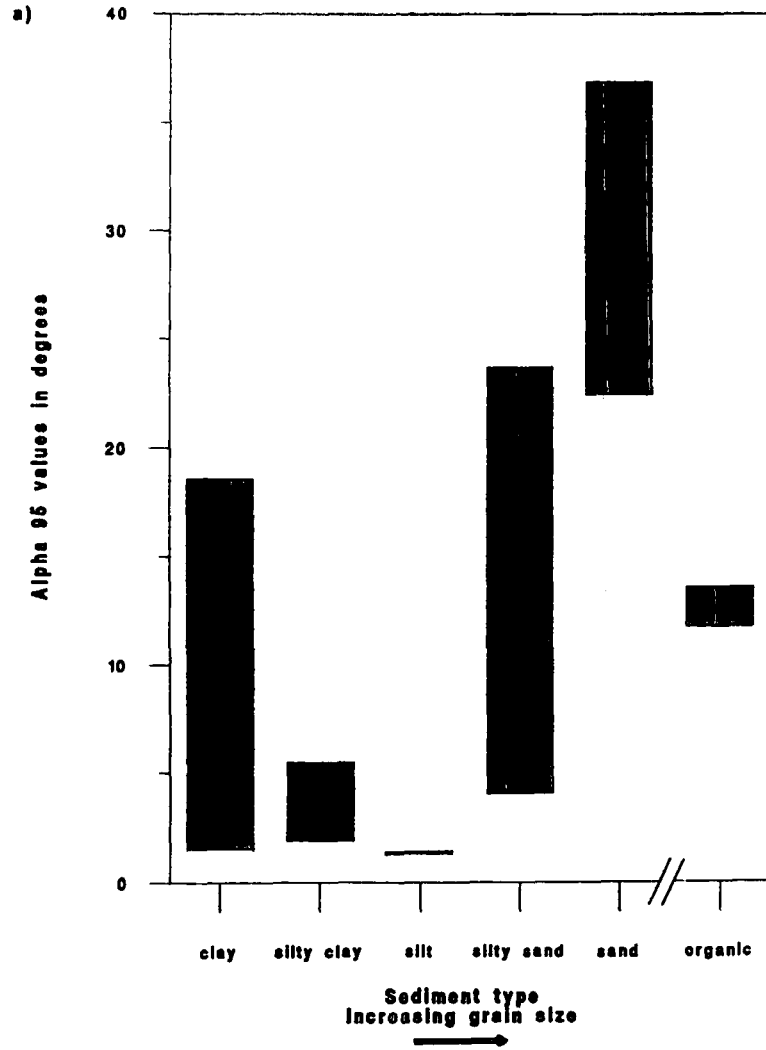


Figure 3.87: Range of values of Alpha95 against a) sediment type and b) depositional environment. Number of contexts in each category are as follows: clay=2, silty clay=5, silt=1, silty sand=10, sand=5, organic=2, river flood=16, silted stream/river=3, estuarine=2, static=2, dump=2, modern=2.

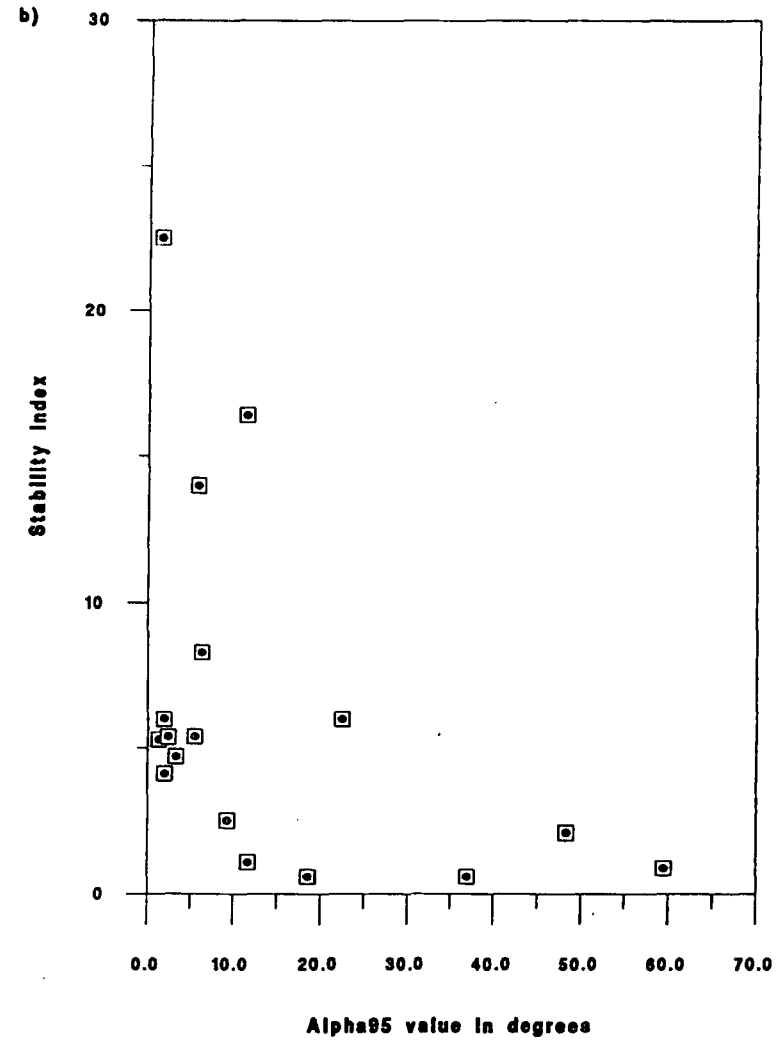
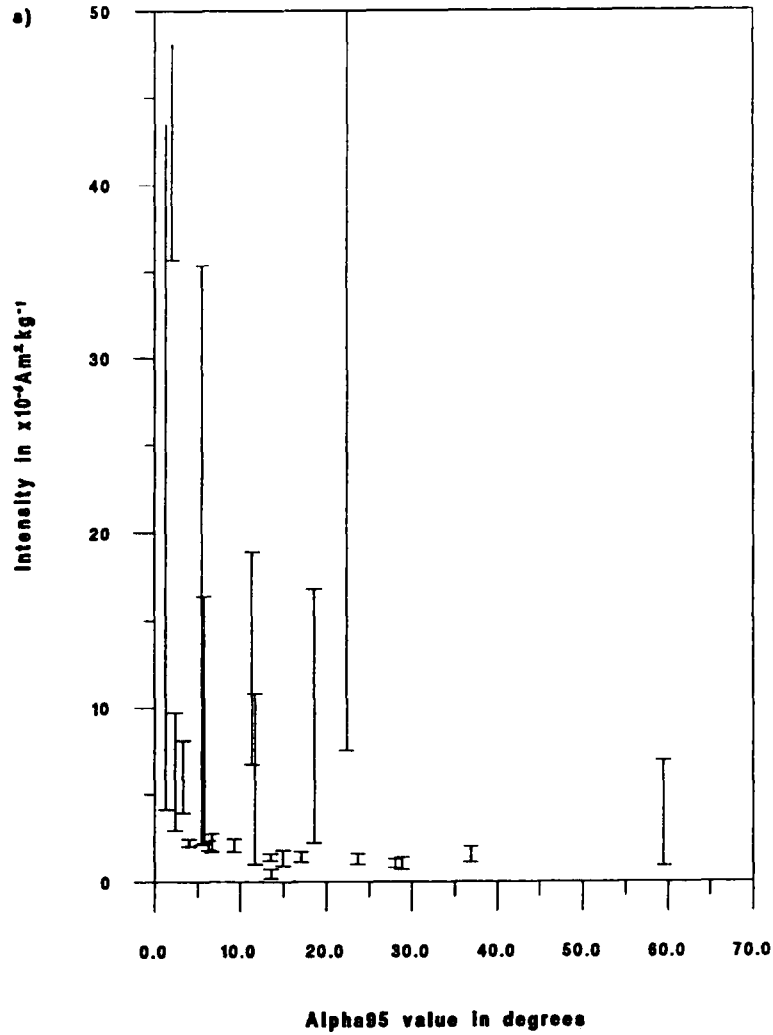


Figure 3.88a: Range of intensity values against alpha95 values for each context.

b: Alpha95 value for each context against stability index of a pilot sample from that context.

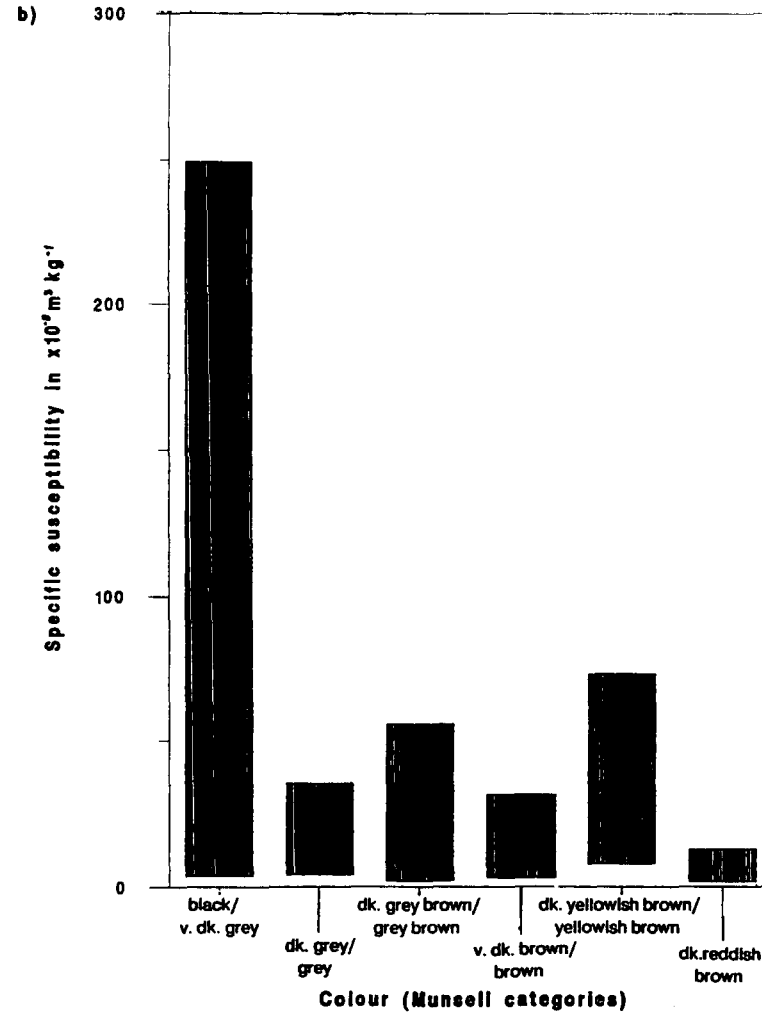
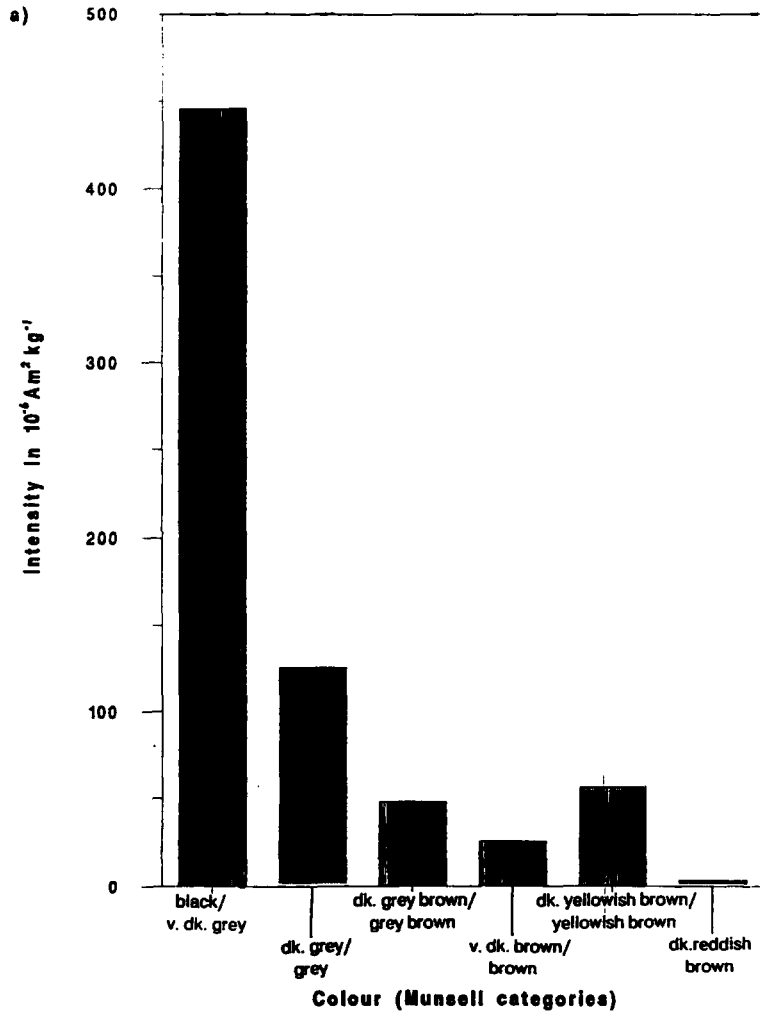


Figure 3.89: Sediment colour, as determined from Munsell chart, against range of values of a) intensity and b) specific susceptibility. Number of samples in each category are as follows: black/v. dark grey=95, dark grey/grey=67, dark grey brown/grey brown=94, v. dark brown/brown=37, dark yellowish brown/yellowish brown=88, dark reddish brown=23.

3.5.4 *Specific susceptibility and magnetic fabric*

All the sediment types appeared to cover similar ranges of specific susceptibility (Fig. 3.90a) with the exception of the silty clay grain size, which covered a very wide range. This range was probably explained by the wide variety of different contexts, arising in different depositional environments, which were included in this rather broad category, as discussed above. It might be expected that specific susceptibility would be largely unrelated to overall grain size, as it is dependent upon the magnetic mineralogy, which cannot necessarily be ascertained from an examination of the grain size of the material in general. There also appeared to be no clear relationship between specific susceptibility and source (Fig. 3.90b). Just as overall grain size may not be related to magnetic mineralogy, so the depositional environment may not indicate the magnetic mineralogy.

In many cases, for example Fig. 3.91, there appeared to be a linear relationship between specific susceptibility and intensity. The linear relationships were tested using a *t*-test (Miller & Miller, 1984) and visual inspection of the plot to ensure that there were no systematic deviations from linearity which would be undetected by the *t*-test. The gradient of the linear relationship varied from context to context (Table 1D in Appendix 1). Such a relationship would be expected because a high intensity of magnetisation indicates a high content of magnetic minerals and hence a high susceptibility (susceptibility can be seen as a rough indication of total magnetic content (Section 2.3.1)). However, the relationship would also be dependent upon the magnetic grain size and mineralogy, and would therefore vary from context to context. There were exceptions to the generally observed linear relationship (Table 1D), predominantly in those sediments which had already been shown to have unstable remanences. The lack of a clear relationship between specific susceptibility and intensity in those cases was likely to arise from inhomogeneity of the sediment, with the magnetic mineralogy or grain size varying within a single context.

It appeared from Fig. 3.89b that black and dark grey sediments generally had much higher susceptibilities than yellow, brown and red sediments, consistent with a greater magnetite content. However, apparent colour may be deceptive, as described above.

In the majority of cases, the magnetic fabric appeared to be similar to those previously found in natural environments and laboratory experiments (Section 2.3.2). The distribution of minimum and maximum axes of susceptibility provided a useful indication of the environment of deposition, even suggesting flow directions consistent with the archaeological evidence in some circumstances (e.g. Wood Hall, context 805;

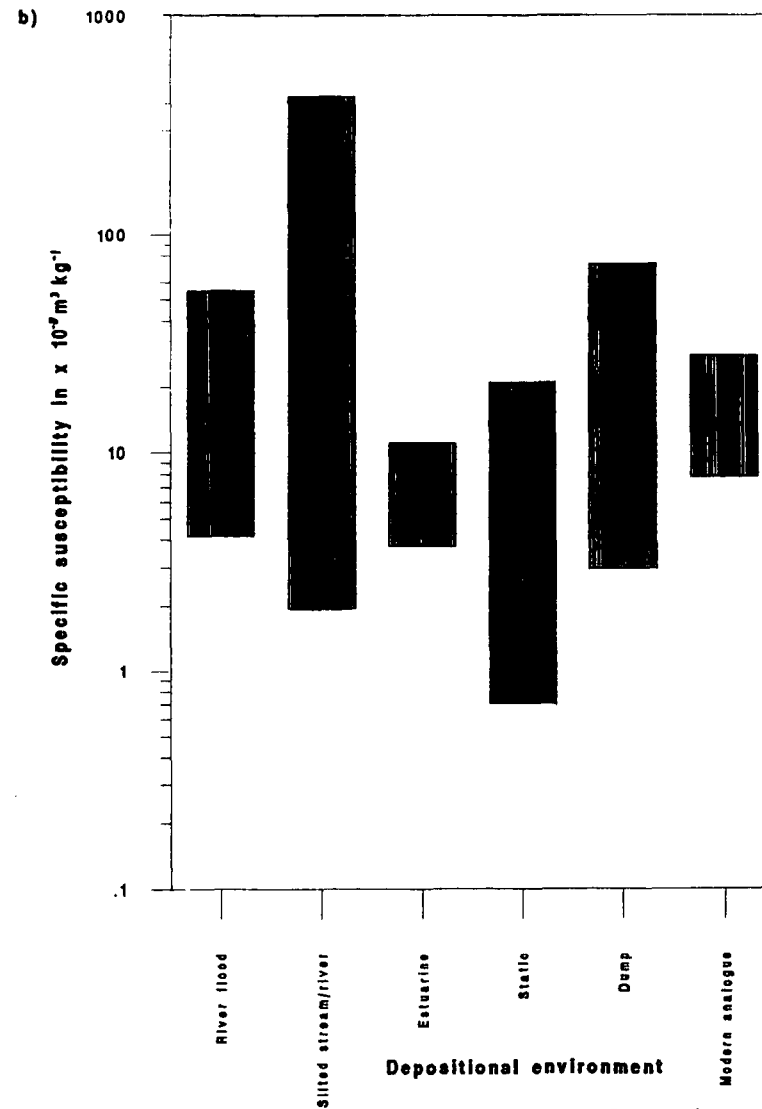
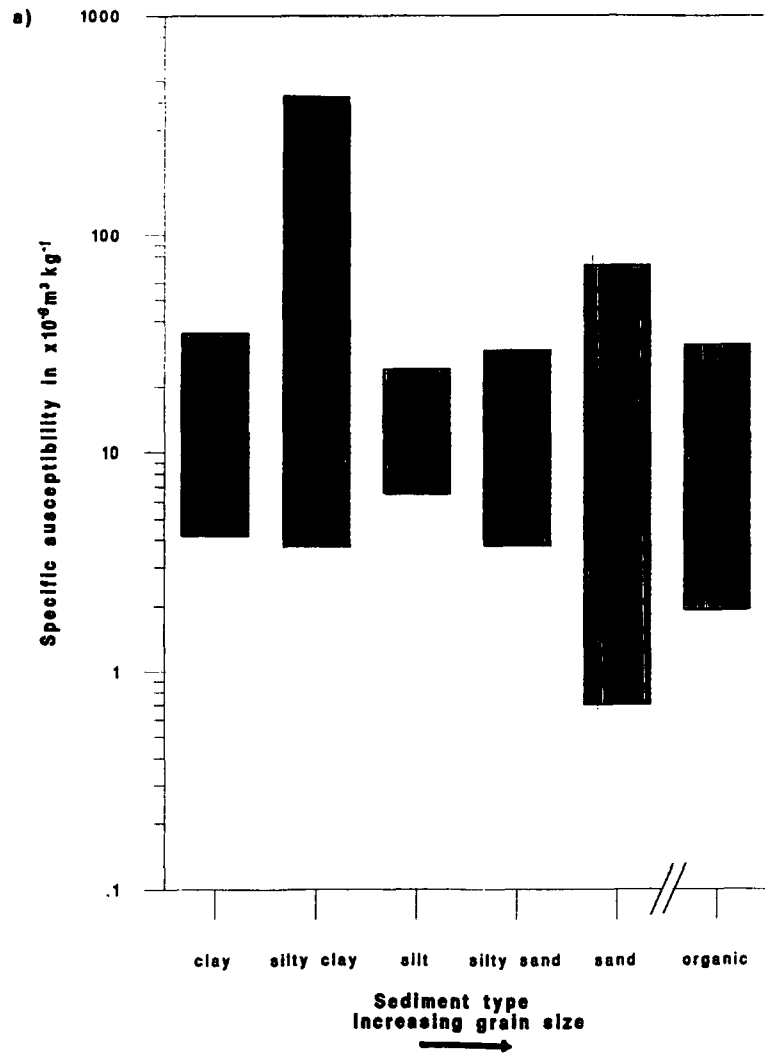


Figure 3.90: Range of specific susceptibility values against a) sediment type and b) depositional environment. Number of samples as Fig. 3.85.

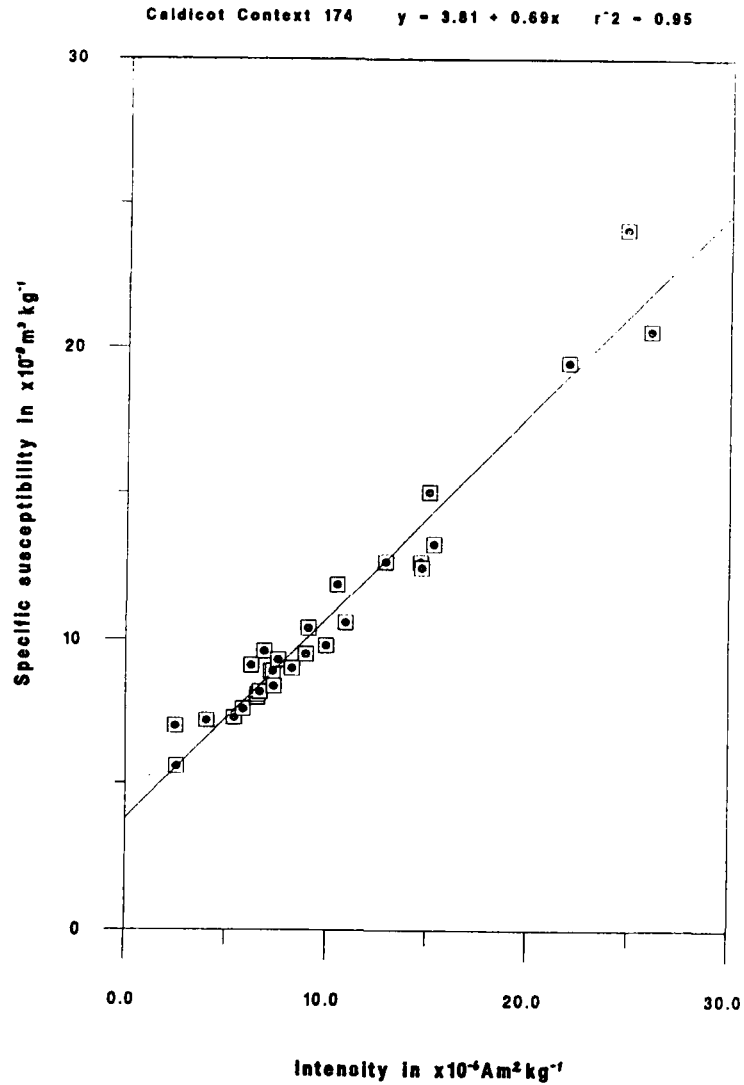


Figure 3.91: Specific susceptibility against intensity for all samples from Caldicot context 174, with linear regression.

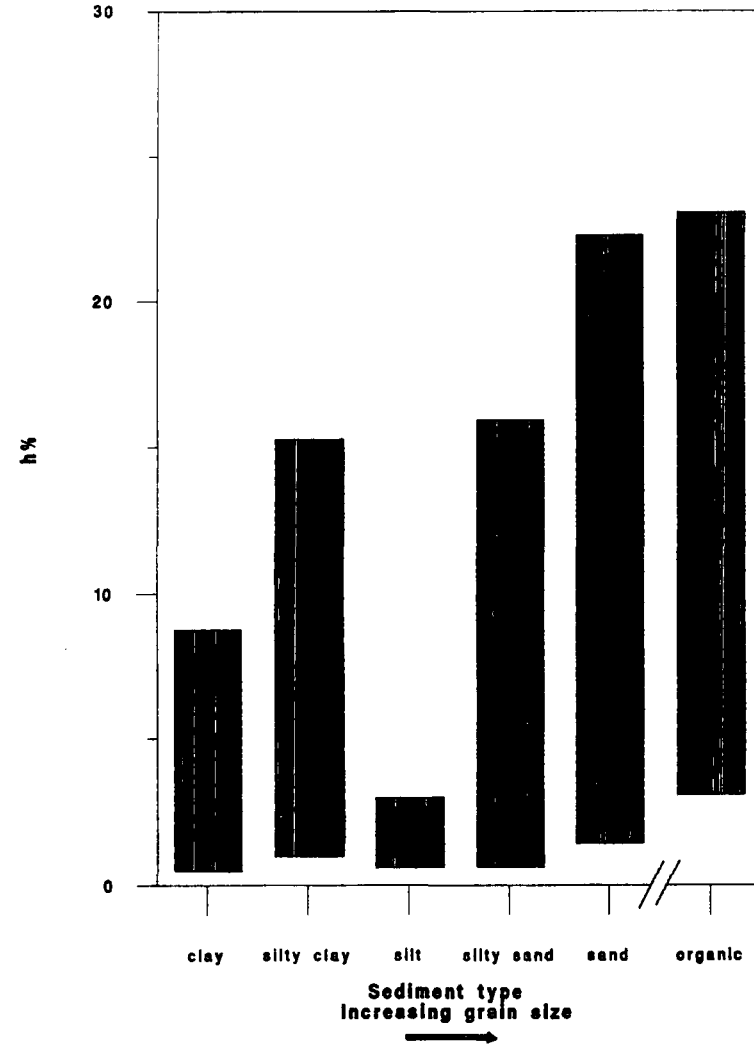


Figure 3.92: Range of values of h% against sediment type. Numbers of samples as Fig. 3.85.

Section 3.4.10). However, in some cases magnetic fabric results, including the distribution of the susceptibility axes, $h\%$ and q , were difficult to interpret.

The measure of the overall percentage degree of anisotropy, $h\%$, showed a much wider range (Fig. 3.92) than that expected from previous studies (Section 2.3.2). The highest values of $h\%$, in some cases over 20%, were found in sands and organic deposits. There appeared to be no simple explanation for these high values and further measurements of $h\%$ on a wider variety of deposits of this type would be necessary to establish the validity of these unusually high values.

The ratio of lineation to foliation, q , has a theoretical range of 0 to 2 and laboratory experiments have suggested that certain depositional conditions and sediment types give rise to particular ranges of q values (Section 2.3.2). However, there seemed to be no evidence of these relationships in the sediments examined in this study (Fig. 3.93a; Fig. 3.93b), with most sediment types and depositional conditions covering very similar ranges of q values. This might be attributed to the fact that overall grain size did not reflect the size or shape of magnetic grains within the sediment. Further clarification would be provided by a study of the properties of a magnetic extract, however these results would appear to show that q values are not related to overall grain size or depositional environment. Whilst silts appear to have a narrower range of q values, it must be borne in mind that all the silt samples were taken from a single context.

Laboratory experiments have been used to suggest that q values in the range 0.06–0.67 are characteristic of a 'primary depositional style' magnetic fabric (Section 2.3.2). To test this hypothesis a graph was plotted of percentage of samples with q values falling in this range against α_{95} value for each context (Fig. 3.94). There appeared to be no indication that small α_{95} values, which might suggest an undisturbed deposit, were associated with a large percentage of samples in the range indicated, or vice versa. Hence, it would appear that the definition of a sediment as having a 'primary depositional style' fabric on the basis of q values is inappropriate to the sediments investigated here. The percentage of q values falling in the given range varied widely for river flood and silted stream/river deposits (Fig. 3.95a), probably simply a reflection of the number of different contexts included in these broad categories. A lower proportion of estuarine samples fell in the range thought to be associated with undisturbed depositional conditions, whereas a much higher proportion of samples from static environments fell in the range, as might be expected. However, caution must be exercised when drawing conclusions of this type as, by the same arguments, a high proportion of samples from dump and modern analogue deposits appeared to exhibit characteristics of primary depositional conditions! Unexpected trends were also apparent when considering the relationship between percentage in range and sediment type, in order of increasing grain

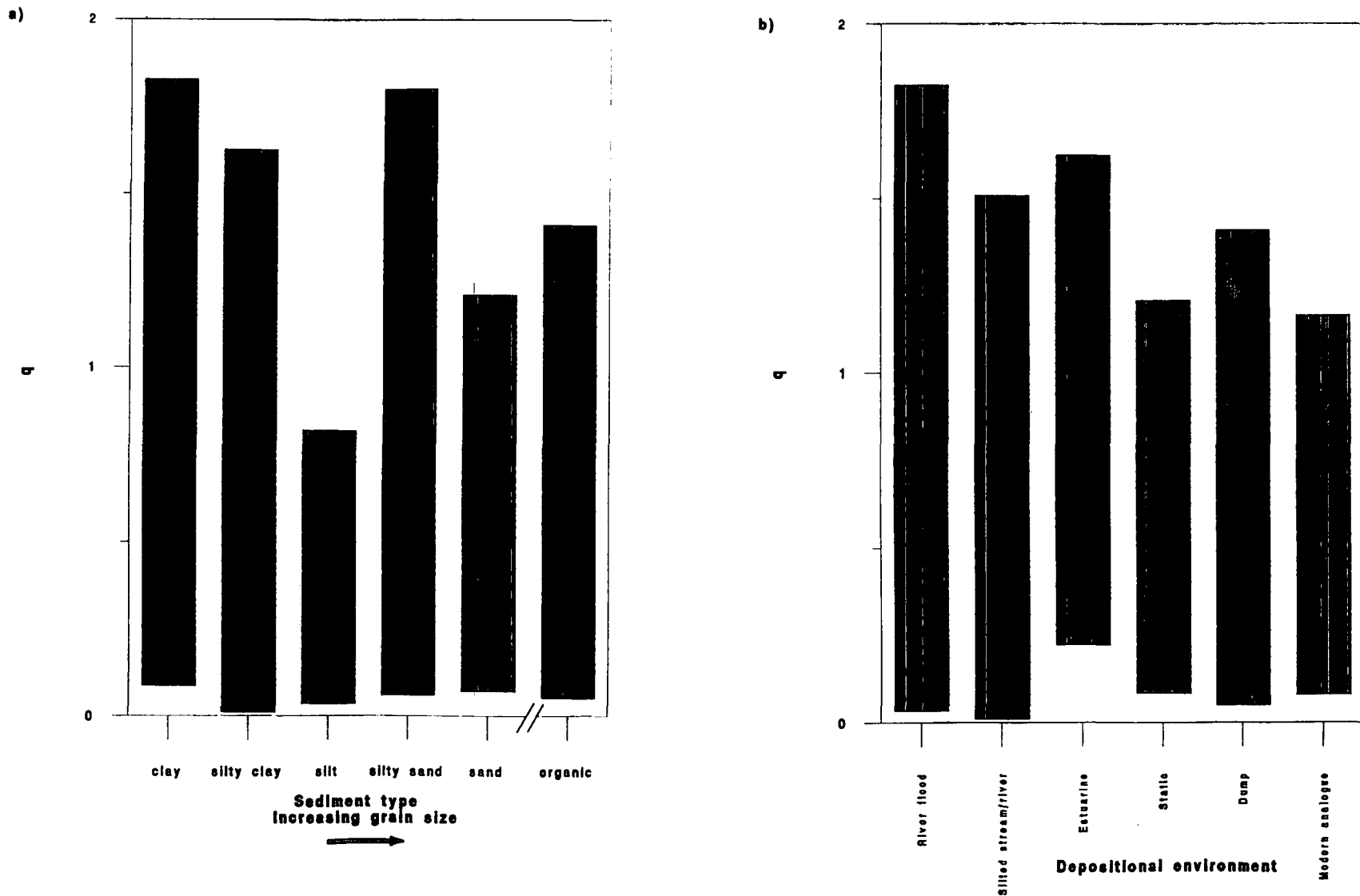


Figure 3.93: Range of q values against a) sediment type and b) depositional environment. Number of samples as Fig. 3.85.

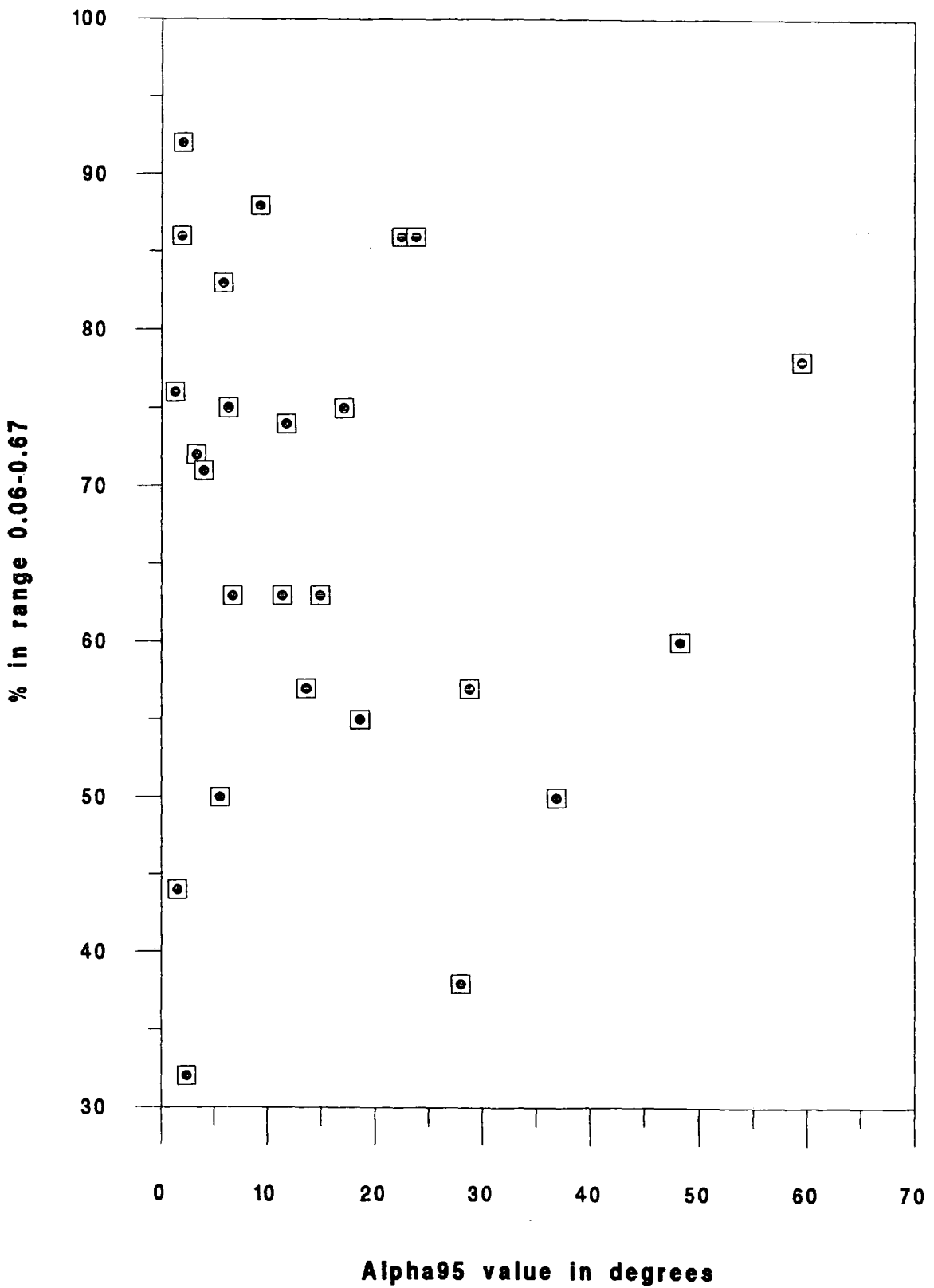


Figure 3.94: The percentage of samples falling in the range 0.06-0.67, characteristic of a primary depositional fabric, against Alpha95 for each context.

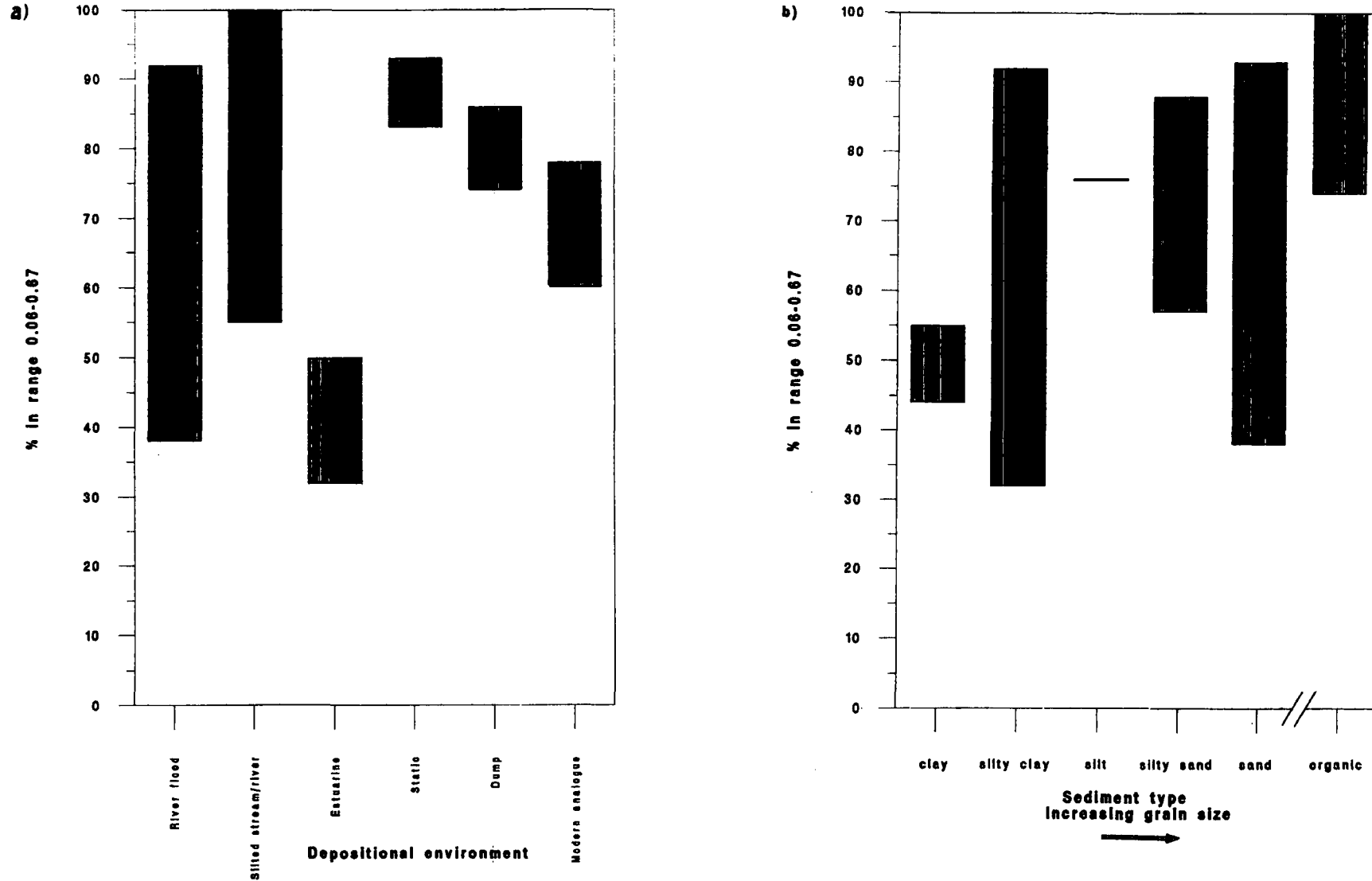


Figure 3.95: Range of % of samples with q values between 0.06 and 0.67, against *a*) depositional environment and *b*) sediment type. Numbers of samples in each category are as follows clay=2, silty clay=7, silt=1, silty sand=11, sand=6, organic=2, river flood=16, silted stream/river=7, estuarine=2, static=2, dump=2, modern=2

size (Fig. 3.95b). Particularly surprising was the apparent tendency for bioturbated organic materials to show the characteristics associated with a primary magnetic fabric rather than clay deposits.

These results illustrate that extreme caution must be used when characterising sediments on the basis of their q values. It must be borne in mind that the laboratory experiments and theoretical models are very simplistic. Archaeological sediments reflect particularly complex environments, with both natural and human influences acting on the sediment. The sediments themselves may be composed of a number of magnetic and non-magnetic minerals and a wide variety of grain sizes, and the magnetic fabric of such materials is, as yet, not well characterised. Before magnetic fabric studies can reach their full potential in archaeology it will be necessary to investigate the magnetic fabrics of material from a variety of modern analogue environments, where the depositional conditions are known, and from a much greater range of archaeological contexts.

3.5.5 *Magnetic mineral studies*

Magnetic mineral studies proved particularly useful in attempting to identify the remanence carriers and characterise their behaviour. The results of IRM acquisition tests often correlated well with demagnetisation behaviour. An example was the Farnley silts (Section 3.4.6) where both methods indicated the presence of a significant proportion of hard magnetic minerals.

SIRM reflected the concentration of magnetic minerals, their grain size and mineralogy (Section 2.4.1). There appeared to be no simple relationship between SIRM and intensity as measured on the pilot samples (Fig. 3.96). As expected, samples with very high intensities ($>50 \times 10^{-6} \text{Am}^2 \text{kg}^{-1}$) also tended to have high SIRM values. However, in other cases, contexts with similar intensities had very different SIRM values, because these values reflect the magnetic minerals permanently magnetisable in fields of 2.69T (Section 2.4.1) but these minerals were not necessarily aligned in the original material to give a high intensity of NRM. In circumstances where both the intensity of remanence and the SIRM were low (e.g. Wood Hall, context 803; Section 3.4.10), it was suggested that the low intensity arose from an overall absence of remanence-carrying minerals in the material, rather than non-alignment of existing magnetised grains. In contrast, the high SIRM value of the Prudhoe samples (Section 3.4.5) indicated the presence of a high proportion of remanence-carrying minerals in the matrix, and suggested that the low intensity in this case was caused by a lack of preferential alignment of the magnetised grains.

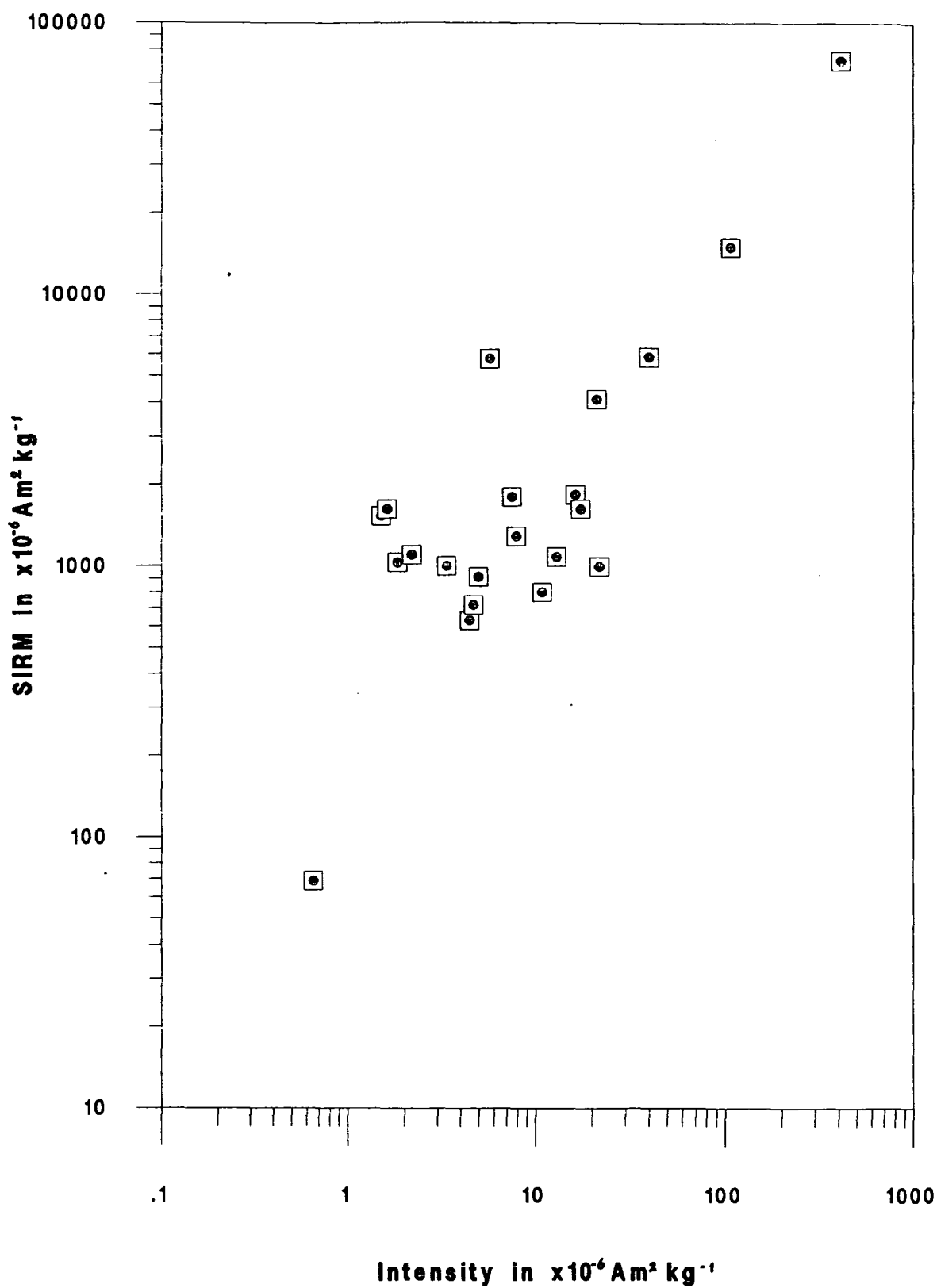


Figure 3.96: Intensity against SIRM values for pilot samples.

SIRM values are affected by so many factors, including magnetic grain size, concentration and mineralogy, that comparison between different contexts was difficult. A more informative measurement was the remanence ratio, S , which gave a normalised measurement of the concentration of magnetic minerals that saturated in low fields, in comparison with those that saturated in fields over 1T. In detrital material, this is likely to be a reflection of the ratio of concentration of magnetite to haematite/goethite, with a high S ratio indicating predominance of magnetite (Section 2.4.1). It was noticeable that in this study almost all of the samples had high S values (>0.75), suggesting magnetite to be the dominant magnetic mineral (Fig. 3.97a). The clays from Stanwick context 1384 (Section 3.4.7) and the silty sands from Farnley (Section 3.4.6) showed S values as low as 0.66. In both cases the demagnetisation behaviour also indicated the presence of haematite or goethite, supporting the mineralogy suggested by the IRM tests. It was difficult to relate S to source of sediment (Fig. 3.97b) because of the unequal number of contexts in each category, as described above. However, one would not expect a correlation between magnetic mineralogy and depositional environment, as magnetic mineralogy is more likely to depend directly on geological source and oxidation conditions. Black, grey and grey brown samples tended to have higher S values (Fig. 3.98) and lower values were associated with yellow, brown and red sediments; suggesting the presence of haematite in the latter samples. However, some dark grey samples also had low S values, indicating that the characteristic red colour of haematite might have been masked.

$(B_o)_{cr}$, the coercivity of the SIRM, is determined solely by magnetic mineralogy and magnetic grain size and therefore independent of concentration of magnetic mineral (Section 2.4.1). If there is a single magnetic mineral present $(B_o)_{cr}$ values can be used to indicate grain size. For example, if the magnetic mineral is magnetite, $(B_o)_{cr}$ values below 10mT characterise multidomain grains, whereas single domain grains can give values up to 100mT (Section 2.4.1). In this study $(B_o)_{cr}$ values ranged between 13mT and 37mT but there appeared to be no clear link between $(B_o)_{cr}$ value and overall sediment type (Fig. 3.99). As described above, this observation is unsurprising as overall sediment type may be unrelated to the grain size of the magnetic minerals, and in some cases there may be a mixture of magnetic mineral types.

3.5.6 *Dating contexts*

In all cases where the magnetisation was shown by demagnetisation to be stable and the magnetic directions were well grouped ($\alpha_{95} < 6^\circ$), an attempt was made to date the sediment by comparing the mean magnetic direction, and its error at α_{95} , with the archaeomagnetic calibration curve or, for earlier samples, the lake sediment secular variation record (Section 2.6). A number of problems with the conventional methods of

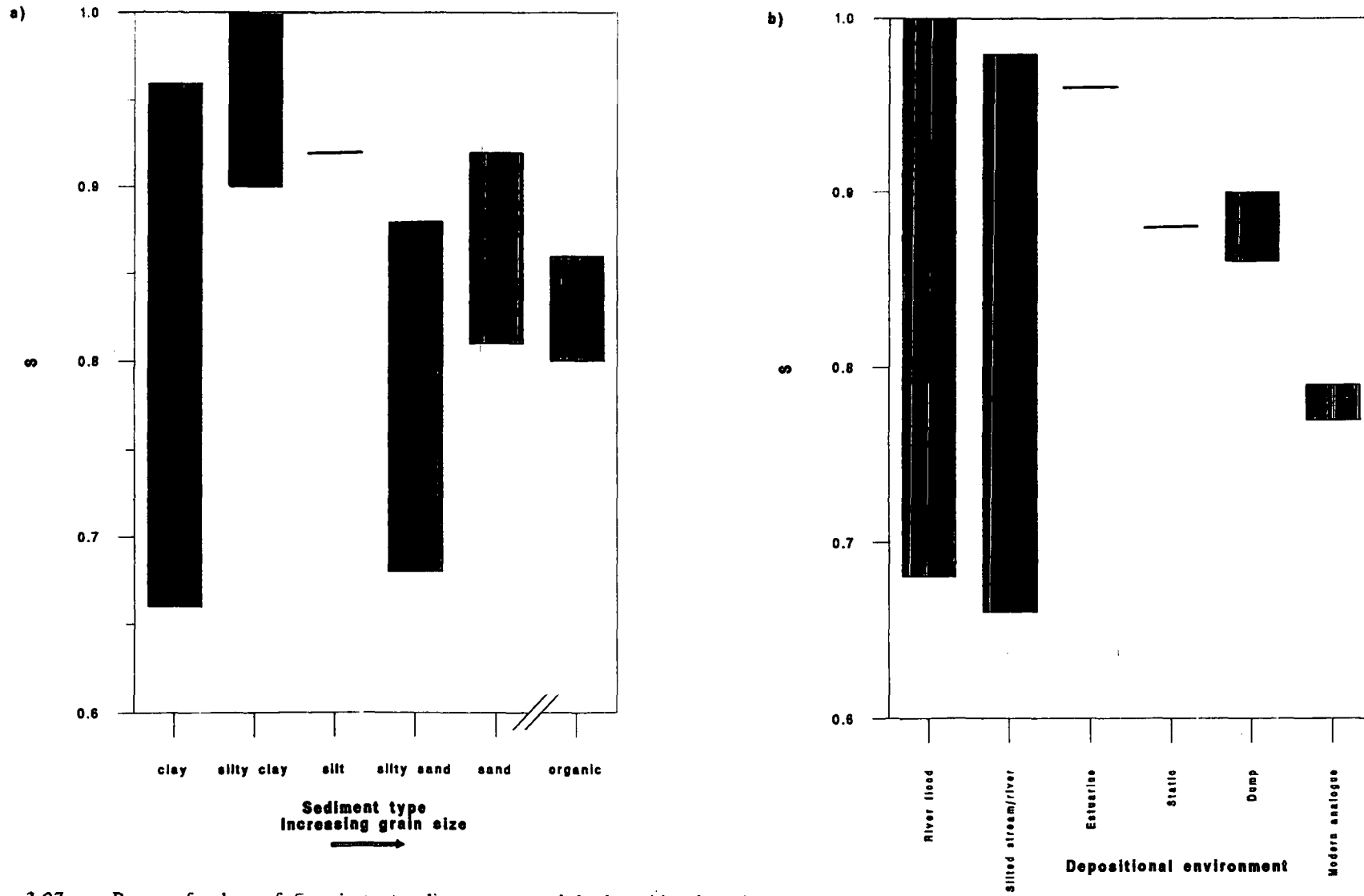


Figure 3.97: Range of values of S against a) sediment type and b) depositional environment. Number of samples in each category are as follows: clay=3, silty clay=7, silt=2, silty sand=5, sand=3, organic=2, river flood=8, silted stream/river=7, estuarine=2, static=1, dump=2, modern=2.

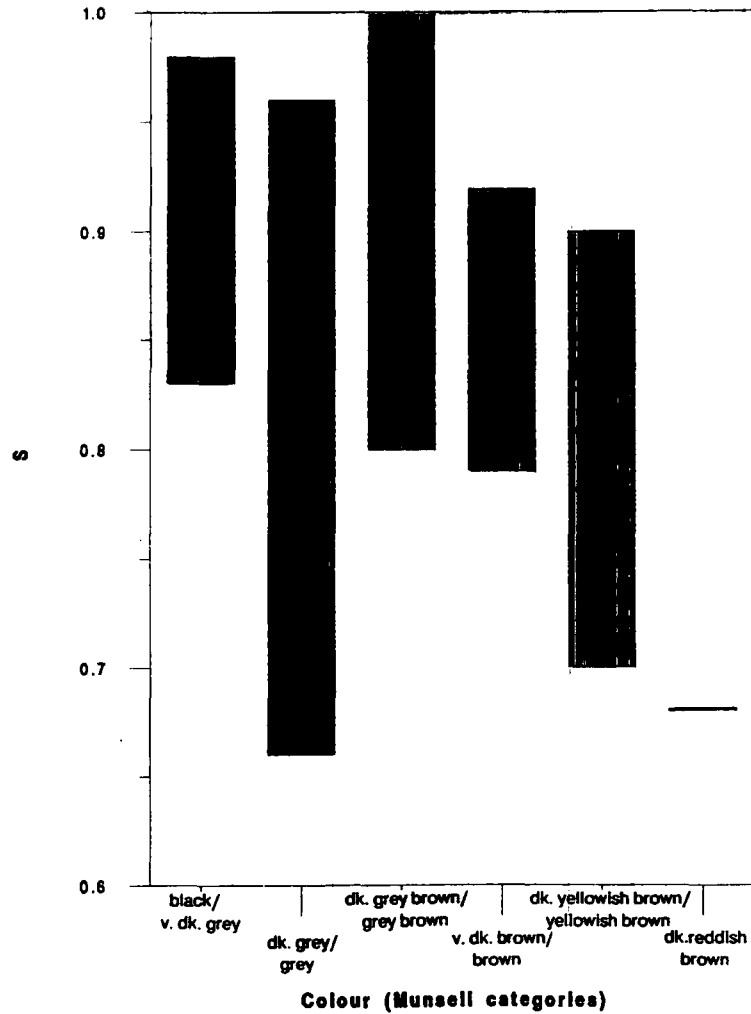


Figure 3.98: Range of S values against colour. Number of samples in each category are as follows: black/v. dark grey=5, dark grey/grey=3, dark grey brown/grey brown=5, v. dark brown/brown=3, dark yellowish brown/yellowish brown=4, dark reddish brown=1.

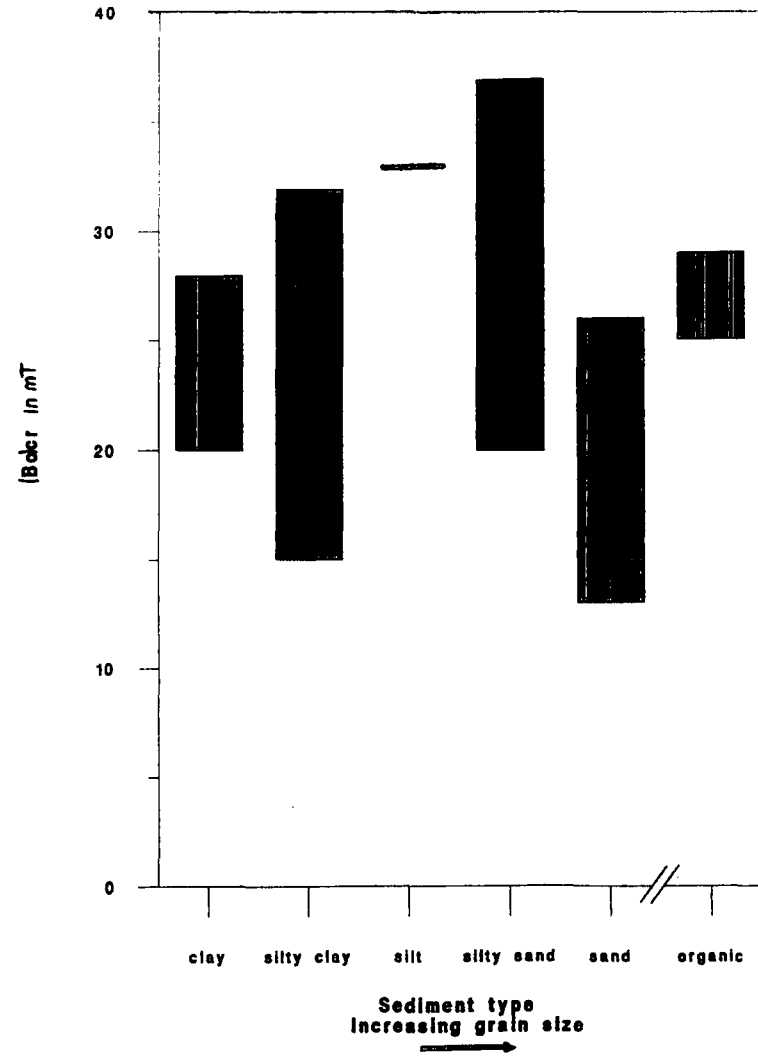


Figure 3.99: Range of values of (Bo)cr against sediment type. Numbers of samples as Fig. 3.86a

obtaining archaeomagnetic dates for both fired materials and sediments became evident at this stage, as discussed in each individual case. Mean magnetic directions from a context of a single date, in the period covered by the archaeomagnetic calibration curve, were compared visually with the calibration curve, as is common practice in archaeomagnetic dating (Section 1.2, 2.5.3 & 2.5.4; Clark *et al.*, 1988). While the dates obtained in this way often corresponded well with the dates indicated by the archaeological evidence, doubts about the objectivity of the calibration curve and the precision and accuracy of the dates obtained from it, prompted further detailed study of the subject (Chapter 5) and reconsideration of the dates obtained (Section 5.6.4). A single magnetic direction expected to date to before 10th century BC was dated by comparison with the lake sediment secular variation curve. There were a number of unsatisfactory aspects to this process, most notably that the absolute values of declination and inclination of the lake sediment curve are not well established, as discussed in Section 3.3. In the two cases for which dates were obtained in this manner, Farnley and Hartlepool (Section 2.4.6 and 2.4.8), the comparison could be justified since the remanence values were extreme and similar values were rare in the secular variation record. However, such comparisons are not to be recommended.

The comparison of a sequence of magnetic directions, recording secular variation with the lake sediment or calibration curve should be more satisfactory than using a single magnetic direction. Unfortunately, such sequences were rarely found in the archaeological record as sedimentary deposits were frequently short, often representing a single depositional event, or disturbed, with magnetic directions too dispersed for secular variation to be discerned. In only one case, Caldicot (Section 3.4.4), could secular variation be extracted from a sediment archaeomagnetic record. Even with this smooth, precise secular variation record, comparison with the lake sediment curve was extremely difficult as the deposition rate was unknown and hence the record of declination and inclination could be expanded or contracted over time, not necessarily uniformly. Visual fitting of records in this way is unsatisfactory as absolute values of declination and inclination are not well-established and the error determination is subjective; more quantitative methods exist but, because of limitations, have yet to be widely applied (Section 2.5.3).

Despite the difficulties mentioned, dates were obtained for nine of the contexts studied which closely matched those suggested by other archaeological evidence. These contexts included river floods, estuarine deposits, silted-up streams and primary silts in ditches and wells. There was no evidence of inclination or bedding errors (Section 1.4.2) as the mean magnetic directions fitted the calibration curve at the expected dates. However, it must be remembered that such systematic errors are difficult to identify, particularly in deposits of a single date (Section 1.4.2). The apparent absence of such

errors and the anomalous magnetic properties of the modern analogue flood deposit (Section 3.4.3) suggested that the remanence might have been acquired post-depositionally (Section 1.4.2). If this was the case, the dates would represent the date of immobilisation of the remanence, not the archaeological event of deposition. This study, therefore, adds information to the debate within palaeomagnetism and archaeomagnetism as to the exact mechanism of deposition, but further studies of this nature, particularly of a greater number of archaeological sediments from known environments, would help to elucidate some of the unknown factors.

3.5.7 Suggestions for future work

This study has indicated that sediments can be dated by archaeomagnetism and may provide valuable sequences of magnetic directions to aid the construction of the calibration curve. It has also indicated areas in which improvements can be made. The process of sampling and the precision of field measurements would be greatly aided by the development of an orientation system which combines the ease of use of the magnetic compass, with the reliability of the sun compass or gyro-theodolite. A hand-held laser gyroscope with an accuracy of 1° would be ideal and is likely to be available in the foreseeable future. A way of consolidating sandy deposits before sampling would increase the range of materials that could be studied, as would the development of a coring system that enabled oriented cores to be obtained, eliminating the need to cut a section. The methods seemed to be most suitable for fine-grained, undisturbed, minerogenic deposits, laid down under slow-moving or static water conditions (discussed fully in Section 6.2), but there is also scope for further study of less common depositional environments. The detailed process of sediment deposition in archaeological environments is extremely complex and laboratory redeposition experiments are less than ideal because they cannot re-create such complex environments. A study of modern analogue deposits might enable the factors influencing deposition to be examined in a known environment of known date. Such modern analogue studies could be assisted by detailed sedimentological information, such as that provided by scanning electron micrographs of detrital grains, on the physical nature of the sediment and its mode of deposition. The study of dated, long sediment sections recording secular variation would help to determine if inclination and bedding errors occur, but such sections are rare on archaeological sites. In Chapter 4 a different range of archaeological materials are examined, to enable comparison between this study of sediments and the fired materials conventionally studied. Perhaps the most crucial step in archaeomagnetic dating is to re-examine the calibration curve and the process of obtaining dates from it, as these factors underpin the validity of dates obtained by archaeomagnetic studies from all materials. Chapter 5 addresses this fundamental issue.

In summary, this chapter has demonstrated the potential of archaeomagnetism to date water-lain archaeological sediments and to determine their environment of deposition and magnetic mineralogy. However, it has also revealed a number of problems with the underlying methodology of archaeomagnetic dating of both fired materials and sediments which must be addressed if the technique is to reach its full potential. The following chapters attempt to clarify and address some of these problems.

Chapter 4

Archaeomagnetic Studies Near Xi'an, China

4.1 THE OBJECTIVES OF THIS INVESTIGATION

In this study samples were taken from six fired structures and a sequence of sediments from archaeological sites in the vicinity of Xi'an, Shaanxi Province, China, in co-operation with the Xi'an College of Geology. The objective was to measure the direction of the ancient field, as recorded by a variety of dated archaeological contexts. It was intended that these measurements would contribute to the knowledge of the behaviour of the geomagnetic field in the region, adding to the information already provided by direct measurements of the geomagnetic field and previous archaeomagnetic studies. Many such dated archaeomagnetic measurements are required if an archaeomagnetic calibration curve for the Xi'an area is to be constructed.

Xi'an and its environs are ideal for archaeomagnetic studies because they provide a large quantity of fired remains, dating from the Neolithic to the present day. The earliest Chinese settlements developed on the rich, loessic soils bordering river valleys in the province and the first capital of unified China, Chang'an, was established in this area, under the rule of the Qin (221BC-207BC). Chang'an remained the capital city for several Dynasties, until the 10th century AD. In later periods, the Yaozhou Yao area of Shaanxi Province became a centre of pottery production. The long and varied history of human occupation of Shaanxi has been extensively investigated through excavation, revealing numerous features suitable for archaeomagnetic dating. These can often be closely dated by their archaeological associations. In this study the features sampled included a fireplace, kilns, a fire damaged funerary monument and ditch sediments. These had been dated by a variety of methods; documentary sources, pottery typology or radiocarbon dating. The locations of the sites sampled are shown in Fig. 4.1.

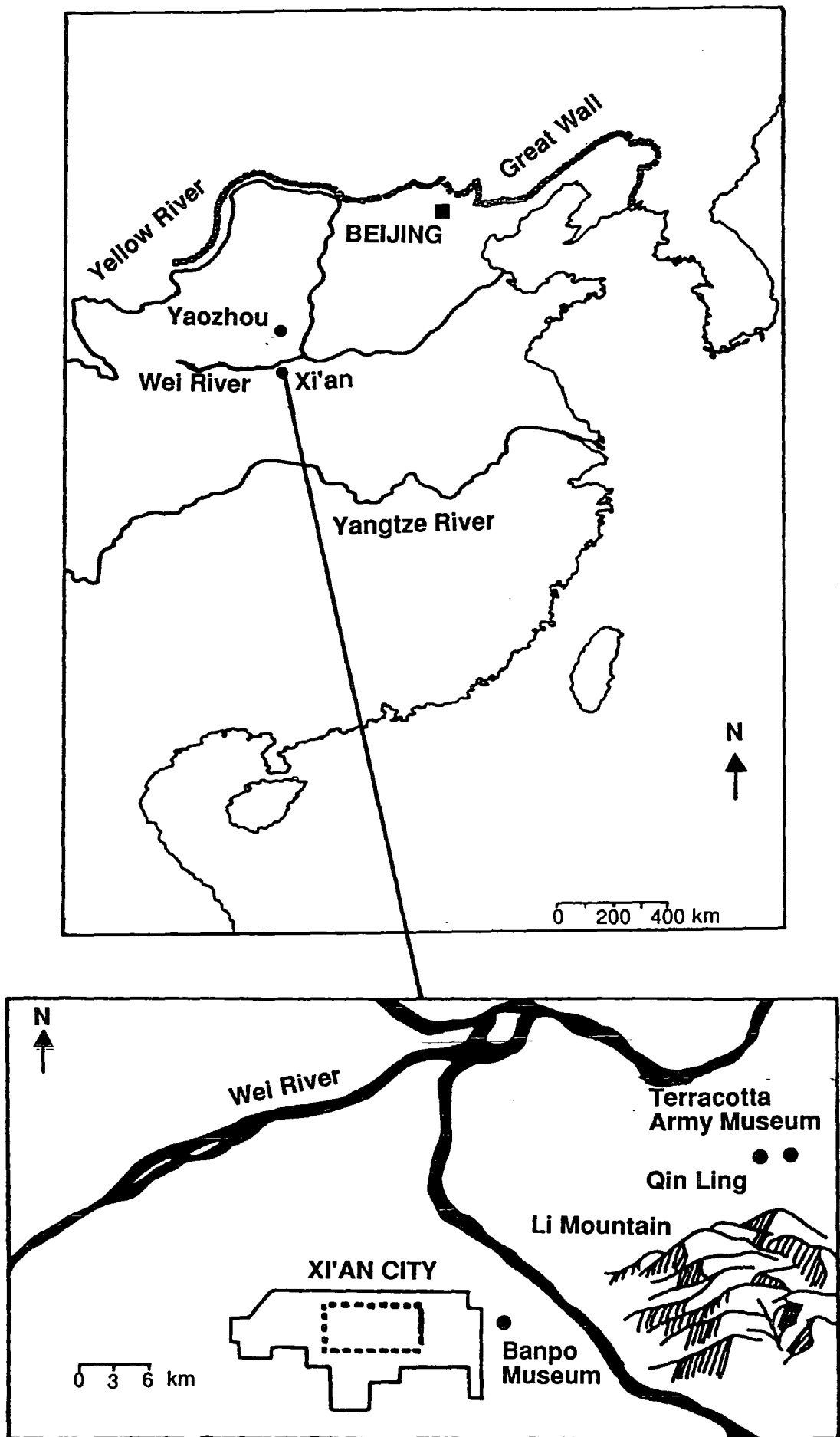


Figure 4.1: Map of China, showing location of Xi'an and the sites sampled in this study.

4.2 DIRECT OBSERVATIONS OF THE GEOMAGNETIC FIELD IN CHINA

Historical references to the discovery of magnetism and observations of magnetic direction are of great interest when compiling a record of the time-dependent behaviour of the geomagnetic field in a region. Chinese literature contains the earliest references to the construction of a magnetic needle compass, appearing in well authenticated texts at least as early as AD1086. Magnetic declination was first discovered sometime between the 7th and 10th centuries AD. These are the earliest recorded direct observations of the geomagnetic field, considerably before the Europeans had even registered the existence of the North and South poles. A detailed study of these early texts is provided by Needham in Vol. 4 of his comprehensive work, 'Science and Civilisation in China' (Needham, 1962 pp229-334).

The magnetic compass was originally used in divination and the earliest ones probably consisted of a type of spoon carved from lodestone, revolving on the smooth surface of a diviner's board. Pieces of diviner's board have been recovered from Han tombs, one of which may be dated as early as AD69 (Ronan & Needham, 1986 p19), but they may have been used even earlier by the Han court magicians in secret rituals. The board, known as the 'heaven-plate' was made from two pieces of lacquered wood, the lower piece was square, symbolising the Earth and the upper piece was round, symbolising heaven. The upper plate rotated around a central pivot and was marked with 24 compass points. The spoon was carved from lodestone; the ends of the bar were magnetic poles and hence oriented themselves along the axis of the Earth's field. The spoon may have been heated and cooled to intensify its magnetisation, but experiments have shown that this is not essential (Ronan & Needham, 1986 p20). The progression to the use of a floating magnetised needle as a compass was made at least by between AD1040 and AD1160.

Once historians had understood the operation of the early geomagnetic compass, Medieval texts containing observations of declination could be interpreted. A table of early declination measurements from texts dating from AD720 to AD1829 has been compiled by Needham (1962 p310). All direct observations of declination so far interpreted are presented in Table 3A in Appendix 3 (J. Needham, pers. comm. & Needham, 1962 p310) and in Fig. 4.2. The values given by Needham are from geographically separated sites, with a latitude range of 23°N-40°N and longitude range of 98.5°E-120.5°E. Before plotting they were corrected to Xi'an using the 'Inclination correction' (Section 5.5), with an inclination value based on the site's latitude, assuming the field to be an axial geocentric dipole. The declination observations were unevenly distributed over time, but appeared to indicate a trend from easterly to westerly

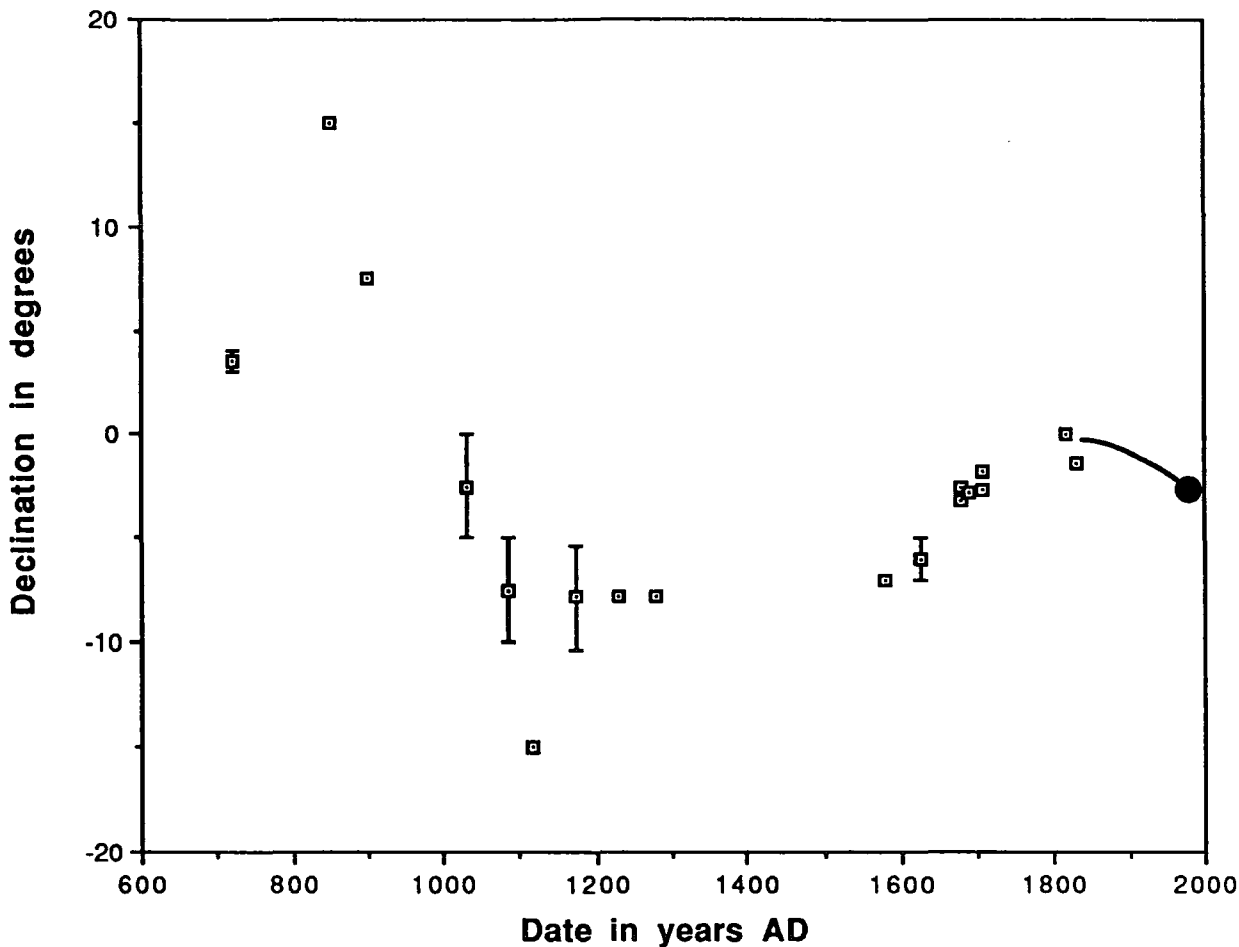


Figure 4.2: Graph of declination vs. time, showing direct observations of declination of the geomagnetic field in ancient China. The continuous line represents regular measurements of declination (Jenny, 1933) and the dot indicates the present declination at Xi'an. All values have been converted to Xi'an and the error bars are defined by the uncertainties in the original texts (Section 4.2).

declinations between AD850 and AD1115, followed by a period in which there was little change in declination, until a small movement eastwards after AD1650. There may be inaccuracies in the dates given, owing to difficulties in dating the Medieval Chinese texts (Smith & Needham, 1967) and there is the possibility of mistakes in the interpretation of the texts, which are difficult to assess. Despite this, the record is remarkable in its extent and apparent accuracy, giving invaluable information for comparison with archaeomagnetic measurements and for construction of a secular variation curve.

The earliest observation of declination, in circa AD720, was credited by Wylie (1897) to Yi-Xing, a Buddhist monk. Although the original text referred to by Wylie has not subsequently been found, later accounts of the observation in other texts have convinced sinologists of the validity of this measurement (Smith & Needham, 1967). A definite statement showing a clear knowledge of magnetic declination has been found in Meng Qi Bi Tan (Dream Pool Essays), written in around AD1086 by Shen Gua, astronomer, engineer and high official (Needham, 1962 p249):

'Magicians rub the point of a needle with the lodestone; then it is able to point to the south. But it always inclines slightly to the east and does not point directly to the south.'

These essays give the earliest clear description of the magnetic needle compass in any language. In the 5th century AD, the Chinese were making quantitative measurements of magnetic force, distinguishing lodestone from non-magnetic iron ore for medicinal purposes (Lei Gong Pao Zhi: (Handbook based on the) Venerable Master Lei's (Treatise on) the Preparation (of Drugs) in Needham, 1962 p234). The compass' original association with divination processes by Imperial magicians, and the fact that Chinese civilisation was more agrarian than maritime, led to the use of the compass being confined to Taoist geomancy for centuries. Use in navigation in the Medieval period was limited because river and canal traffic was preferred to ocean voyages. Whilst there is a long surviving literature on geomancy and the compass, there are still gaps and obscurities, including information recorded in books burnt by Jesuit converts in the 17th century.

It is interesting to note that by the 12th century AD scholars were not only measuring declination but also attempting explanations for it. Thus in Ben Cao Yan Yi (The Meaning of the Pharmacopoeia Elucidated) which dates from AD1115 (Needham, 1962 p251):

'Again if one pierces a small piece of wick (pith or rush) transversely with this needle (i.e. the magnetic needle), and floats it on water, it will also point to the south, but it will always incline (to the east) towards the compass point Bing (i.e. S15°E). This is because Bing belongs to the principle of Fire, and the points Geng and Xin (in the west) which belong to Metal (the needle being of metal), are controlled by it. Thus its (declination) is quite in accord with the mutual influences of things.'

To put these observations in their historical context, the knowledge of magnetic declination is not evident in Europe until the middle of the 15th century. The first evidence is from around AD1450 when German portable sundials, which included a compass for setting the noon line, had a special mark on the dials to indicate where the needle should point.

The explicit understanding that declination changed with time was only consciously held from the Manchu Dynasty in the 18th century, but it is evident that by the 15th century the Chinese had realised that declination varied from place to place. In Xing Cha Sheng Lan (Triumphant Visions of the Starry Raft) of AD1436 (Needham, 1962 p313) Fei Xin wrote:

'There is a seamen's saying 'To the north we are afraid of the Seven Islands; to the south we fear the Kunlun'. At these places the needle may err, and if that happens, or the steering is inaccurate, both men and ships will be lost.'

As far as can be ascertained, magnetic inclination was never discovered by the Chinese (Needham, 1962 p314). Regular measurements of declination and inclination were initiated by the Jesuits in the 17th century (Wylie, 1897) and continued under the influence of Europeans working in China (Jenny, 1933; Vestine *et al*, 1947).

4.3 PREVIOUS ARCHAEOMAGNETIC STUDIES IN CHINA.

Direct historical observations of the geomagnetic field in China extend back over a thousand years, but are irregular until the middle of the 17th century. In order to investigate changes in the field previous to direct observations and to fill in the gaps between them, indirect measurements must be used, including the study of the ancient field recorded by dated archaeological baked clays and sediments.

One of the earliest studies in archaeomagnetism was an attempt to date Chinese Yüeh pottery using the inclination of its magnetisation (Section 1.5; Aitken, 1958).

Subsequently, the most comprehensive studies in Chinese archaeomagnetism have been carried out by Wei and collaborators, with the investigation of fired remains from Loyang (34°42'N, 112°40'E) in central China (Wei *et al.*, 1981 & 1982) being the most detailed. Loyang was the ancient capital of nine Dynasties and measurements were made of the direction of magnetisation of baked earth from the abundant kilns and ovens. Bricks were also used for inclination determinations because their orientation in the kiln could be deduced from the excavation of a complete, abandoned kiln of Wei Jin Period (around AD300) in the suburbs of Loyang. Samples were taken from the wall and floor of the structures and measured in an astatic magnetometer. The samples' remanent magnetisation was shown to be stable in direction and intensity in applied fields of up to 25mT. The viscous remanent magnetisation acquired over two weeks was less than 5%, so the NRM values were taken to be the direction of the ancient field. The dates assigned to each feature were the midpoints of the commonly accepted archaeological dates for each Dynasty which, from 840BC, were based on continuous archives, anchored in time by recorded astronomical observations. The results (Fig. 4.3a) indicated substantial changes in inclination in the last 2500 years with a decrease from 39° in around 350BC to a minimum of 33° in about 100BC. This was followed by a rapid increase to a maximum of 61° in about AD800, towards the end of the Tang Dynasty. There was a subsequent shallowing of inclination to a minimum of 41° and then a rise to 50°30' in 1970. From this it might be inferred that the geomagnetic pole drifted towards Loyang from 100BC, or earlier, until around AD800 and then drifted away until AD1500, when it started drifting towards the region again (Wei *et al.*, 1981). Declination had a maximum of 11° east and a minimum of more than 23° west, being eastwards from 100BC to AD350 and westwards from AD350 to AD1040.

A magnetic direction from a much earlier feature was obtained from baked earth specimens from Jiangzhai (34°22'N, 109°12'E) in the Lintong region of Shaanxi Province, north-east of Xi'an (Wei *et al.*, 1980 & 1983). The site was from the Yanshao culture, similar to Banpo (Section 4.4.2), and is Neolithic, dated to 3950±90calBC by radiocarbon (details of radiocarbon measurements were not available). The mean archaeomagnetic direction obtained from 37 samples taken from two pottery stoves and an oven is also shown in Fig. 4.3a.

Archaeomagnetic samples have been taken from other sites in the Xi'an area dating from 1500BC to AD1900 (Wei *et al.*, 1983). Unfortunately, the numerical values were not available for detailed analysis, but a general impression of geomagnetic field changes can be gained from the published graphs (Wei *et al.*, 1983). Inclinations ranged between 40° and 60°, but the 15 values obtained were too scattered to show a clear trend. Declination results from 1500BC to 900BC indicated a change from positive to negative inclinations at around 1200BC. More detailed conclusions could not be drawn,

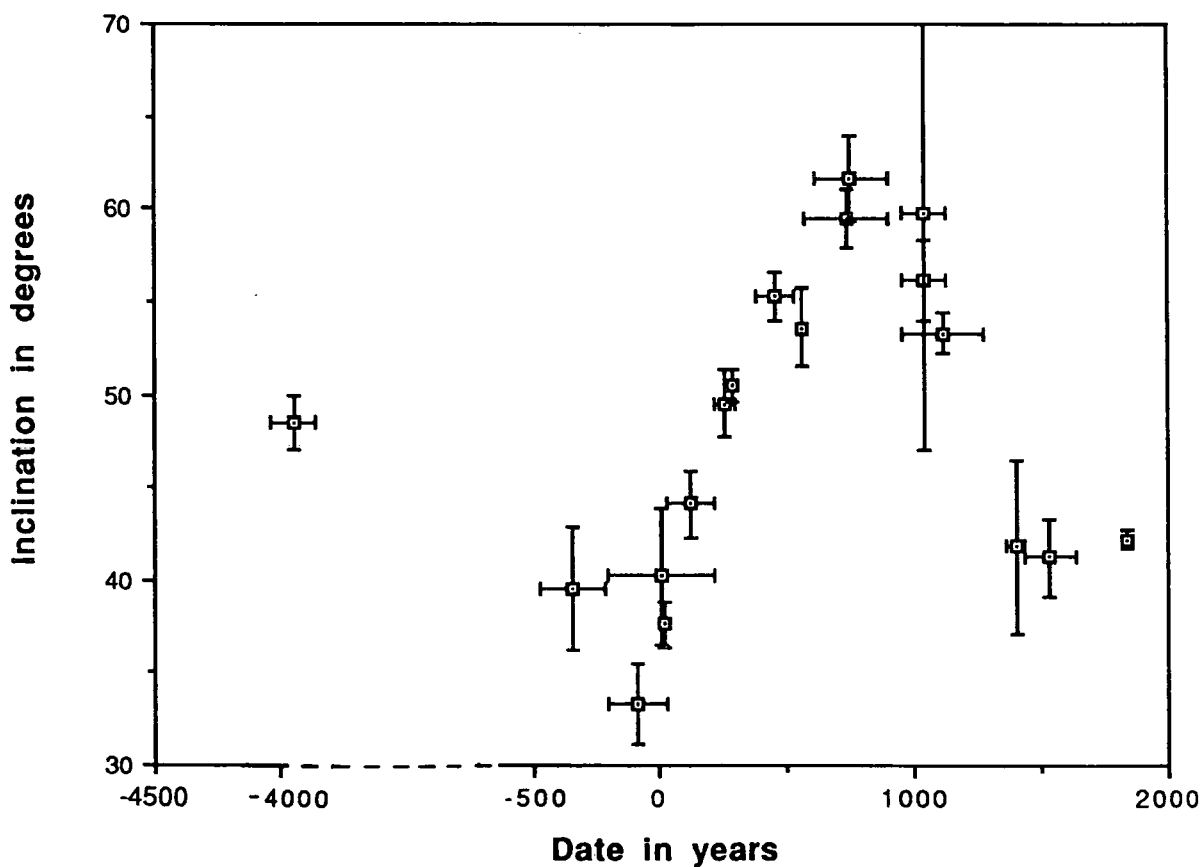
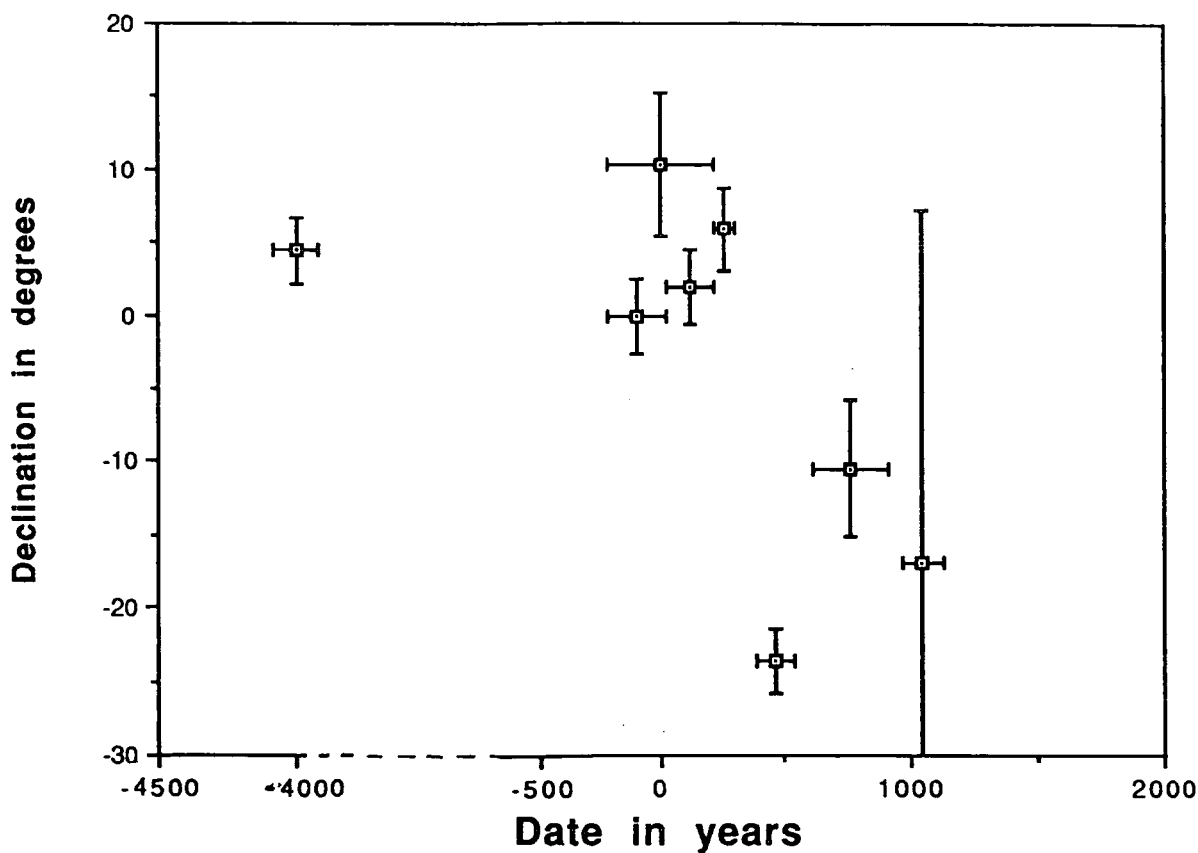


Figure 4.3 a: Graphs showing archaeomagnetic measurements of declination and inclination over time from samples taken at Loyang and Jiangzhai by Wei. Data taken from Wei *et al.* (1980 & 1981). Dates are taken to be the mid-point of the archaeological age range for the relevant Dynasty and errors in magnetic measurements are at 95% confidence. All magnetic directions are corrected to Xi'an. Note the discontinuous time axes.

owing to the scarcity of data and the absence of error estimation. A number of studies into the intensity of the ancient field have been made using a wide variety of Chinese pottery (Wei *et al.*, 1982, 1983 & 1987; Tang *et al.*, 1991)

Recent work (Fig. 4.3b; Cong & Wei, 1989) has examined the correlation between the geomagnetic field recorded in marine sediments and that recorded in baked clays. The marine sediments were obtained from the mouth of the Yellow River (37°49'N, 119°26'E), using a piston corer. 194 specimens were taken from a single core of the clayey fine sands and measured in a spinner magnetometer. The sediments were dated with two radiocarbon dates and by a study of the palynological and microfossil record. The magnetic directions were then compared with the magnetic directions of samples of baked clays from archaeological sites in the eastern part of China (34-38°N, 107-120°E). The sediment record of inclination showed a variation from around 80° at 1350calBC to only a few degrees at 450calBC and a variation in declination from about 38°E at 2650calBC and 2050calBC to 37°W at calAD50 and 950calBC. The variations are similar to those found in baked clays, particularly at the extreme values. Wei compares this record with that of Hirooka (1983) for Japan, suggesting a good correlation, particularly at extreme values despite a 20-30° separation in longitude. However, as the results are based on only one core, it is difficult to make detailed conclusions without further information. The comparison of archaeomagnetic results with the remanence directions from continuous sediment cores may prove to be as vital in defining the form of the Chinese archaeomagnetic curve as it has been in British archaeomagnetism (Section 5.2), although there are a number of attendant problems (Section 2.5.3).

4.4 THE FEATURES EXAMINED AND THE MAGNETIC RESULTS OBTAINED

The numerical results of the measurement of NRM, bulk demagnetisation and magnetic fabric on the groups of samples from each archaeological context are given in Table 3B in Appendix 3. The results of the stepwise demagnetisations and IRM acquisition tests of typical pilot samples from each context are given in Table 3C in Appendix 3.

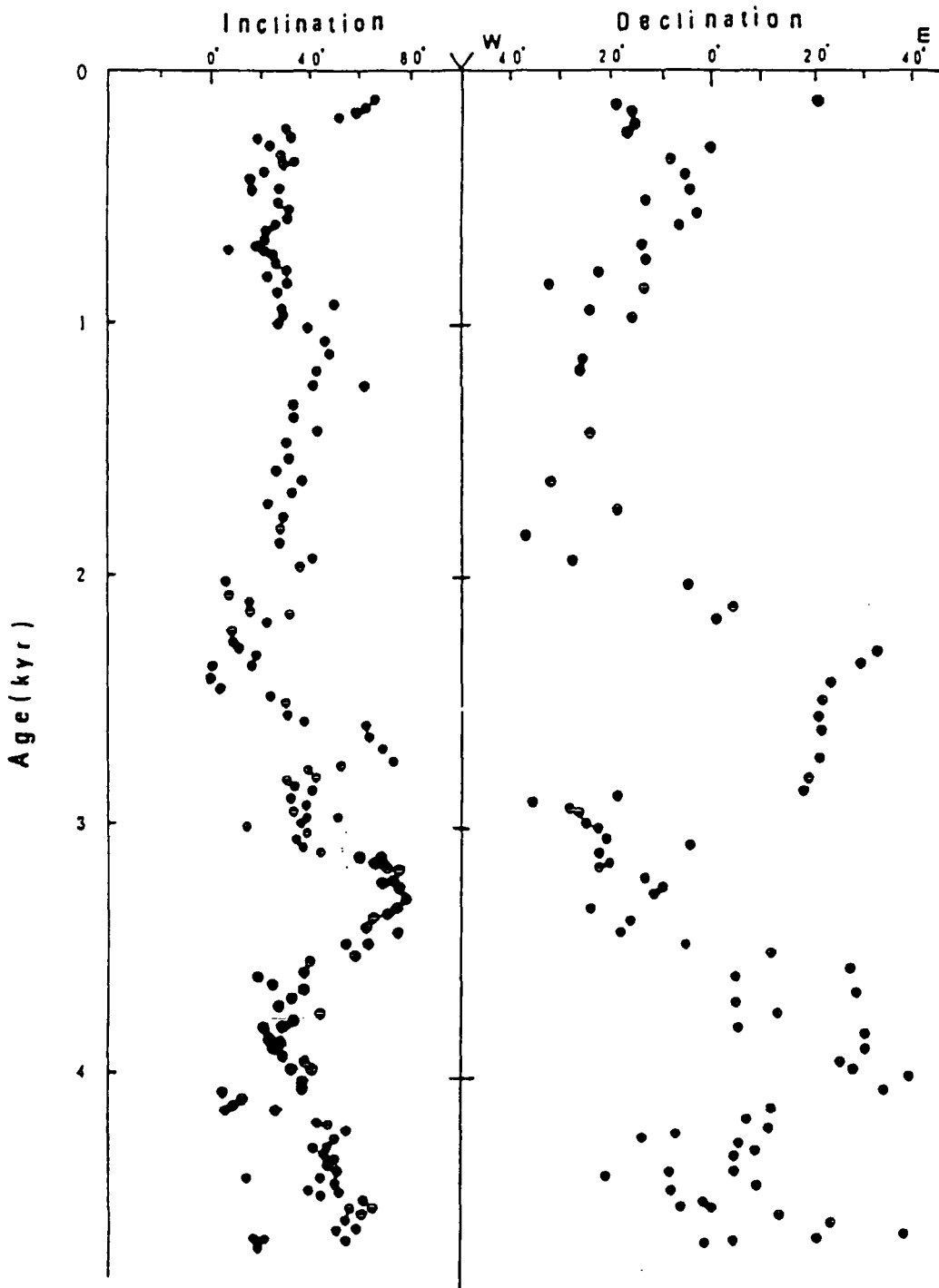


Figure 4.3b: Graphs showing palaeomagnetic measurements of declination and inclination against age (from radiocarbon in cal BP) for cores taken from mouth of Yellow River (from Cong & Wei, 1989).

4.4.1 The Terracotta Army Museum, Lintong County, Shaanxi.
(34°20'N 109°15'E)

Historical introduction to the site.

Towards the end of the aptly named 'Warring States' period (475-221BC), the Qin (Ch'in) state became dominant and its superiority was established under the first Qin emperor, Qin Shihuangdi. He came to the Qin throne at 13 years old and spent the first twenty-five years of his reign in battles with other states. He finally conquered them 'like a silkworm devouring a mulberry leaf', according to Ssu-ma Ch'ien, who wrote 'The Historical Records', China's first large-scale work of history, about a century after the fall of the Qin (Topping, 1978). The rule of Qin Shihuangdi was the first to unify China and he radically altered the political and social structure, destroying the ancient feudal system and creating a centralised empire. Laws were codified, weights and measures standardised, and a uniform Chinese written language was established. During his reign a vast network of roads and canals were built and the Great Wall was constructed to protect the northern frontier of the newly formed empire from the 'barbarians' of the Asian Steppes. This was achieved by joining walls and ramparts erected previously by contending feudal states (Topping, 1978). China's first standing army, possibly numbering into millions, was created to guard the Wall. However, Qin Shihuangdi's rule was severe; prisoners of war and forced labour were used on the construction of the Wall and thousands died in the process. He saw the Confucian ideas prevalent before his reign as a threat and reacted by burning books and burying scholars alive. Many suffered under his rule and revolts soon followed his death in 210BC.

Obsessed with a fear of death, Qin Shihuangdi began the construction of his funerary monuments when he came to the throne in 246BC. Over 700,000 conscripts worked for 36 years on his tomb and a vast army of soldiers, modelled in terracotta, possibly intended as his escort on the journey to the afterlife (Hollidge, 1988 p55). Skeletons from royal tombs of the Shang Dynasty (1700-1100BC) show that warriors, women, servants and horses were buried alive alongside kings and high ranking officials. The practice of live burials had been stopped for centuries but Qin Shihuangdi revived it symbolically with the Terracotta Army (Topping, 1978). The Emperor himself was buried at Qin Ling, in a tomb under a vast artificial hill, 30km east of modern Xi'an (Fig. 4.1). Whilst his mausoleum has not yet been excavated, there are detailed historical descriptions of its contents (Hollidge, 1988 p59).

During the disturbances after the Emperor's death, troops of the General Xiang Yu looted the imperial tomb at Qin Ling. This attack in 206BC is recorded in Shui Jing Zhu (The Water Classic) and quoted here from City of Edinburgh Museums and Art Galleries (1985).

'After Xiang Yu entered the pass, he opened the mausoleum. After 30 days of plundering they still could not exhaust the contents of the mausoleum. Bandits from the east of the pass melted the coffins for bronze as well as setting fire to it. The fire burned for more than 90 days'

It is clear from excavations that the Terracotta Army also came under attack from the rebel army. The timber framework was set on fire and part of the construction collapsed, smashing the Terracottas *in situ* and covering them in mud and ash. There is extensive scorching on the corridor walls, indicating a fire of great ferocity, making the event ideal for study by archaeomagnetism.

Site description

The Terracotta Army was discovered in 1974 by farmers sinking a well less than 1.5 km from the Emperor's mausoleum, 30km from modern Xi'an (Fig. 4.1), although legends of ghosts who 'lived under the ground' may indicate some earlier discoveries. Part of the site was opened to the public in 1979 and while only three pits, representing a fraction of the pits located, have been excavated, they have revealed 100 chariots, 600 horses, 7000 figures and numerous weapons.

The main vault (Pit 1) is 5-7m below the present ground surface and measures approximately 210m by 62m (Fig. 4.4), covering 12,000m², of which 2000m² has been excavated revealing 1087 soldiers, 10 chariots and 32 horses. The vault is divided into 11 parallel corridors, oriented east-west, by earth walls and paved with cord-impressed pottery bricks (City of Edinburgh Museums and Art Galleries, 1985). A wooden construction of pillars and cross beams had enclosed the corridors and protected the figures when the topsoil was replaced to totally conceal the Army (Fig 4.5). The figures themselves are 1.8m high and were originally painted. They adopt various postures and have different features and facial expressions, which leads to the suggestion that they were intended to be realistic portraits of individuals (Museum of Qin Terracotta Figures, 1987). The figures are arranged in the formation adopted by the Emperor's guard before commencing a military campaign. They have their backs to the Emperor's tomb, reinforcing the suggestion that they are intended to defend the tomb.

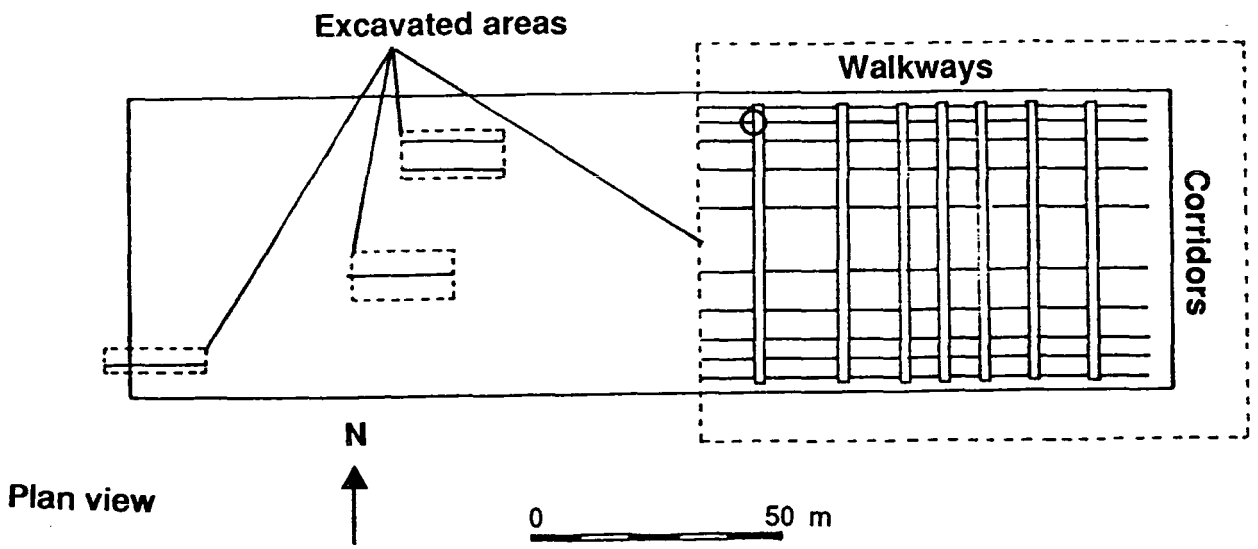


Figure 4.4: Sketch of Pit 1 of the Terracotta Army Museum; the circle indicates the sampling location.

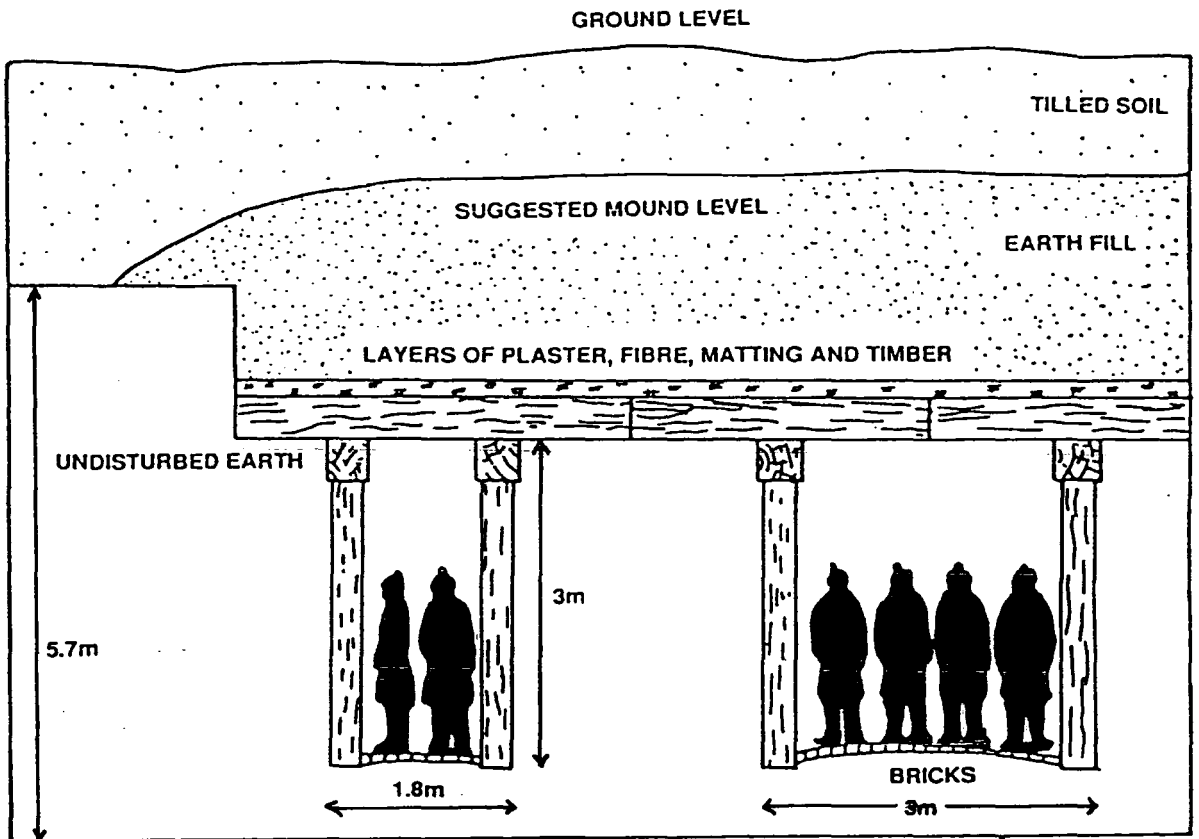


Figure 4.5: Schematic diagram showing the construction of the vault for the Terracotta Army (after City of Edinburgh Museums and Art Galleries, 1985).

Pit 2, an L-shaped vault, was found in 1976, 20m to the north-east of Pit 1. It is 96m by 84m and contains chariots, cavalry and infantry. A smaller pit (Pit 3), beside Pit 2, was also excavated in 1986. Containing one chariot and 68 warriors, it is suggested that this represents the command post (Museum of Qin Terracotta Figures, 1987). More sites of archaeological interest are certain to exist in the vicinity. For example, in building a motorway to link a new airport with Xi'an, 24 vaults of terracotta figures were discovered, covering an area five times that of the Qin Dynasty pits. These statues are 50cm high and appear to be associated with the tombs of the emperor, Liu Qi (188-144BC) at Yangling, 22 km northwest of Xi'an (Bahn, 1991). Further details of this discovery are awaited with interest.

Description of the samples taken

14 samples were taken by the button method from the burnt clay on the top of one of the corridor walls in Pit 1. The detailed location is shown in Fig. 4.4. The buttons were attached to a roughly horizontal shelf cut into the wall, where it joined with the main walkway. Whilst it would have been desirable to have sampled a number of areas in the vault, to compare directions of magnetisation, in view of the importance of the monument sampling had to be restricted to one small area. The material of the wall was very hard and well fired to a depth of several metres down the sides of the walkway. It was a uniform reddish brown (Munsell No. 5YR 4/6) fired clay, with no visible inclusions and the material of all the samples appeared identical. Whilst some cracks were visible at the edges of the walkway, the area sampled appeared to be stable.

Orientation was determined using a magnetic compass with a stand-off, since the entire site was inside a building and a gyrotheodolite was not available. The magnetisation of the feature itself did not appear to affect the compass readings. In the laboratory it was possible to carry out limited sub-sampling, in order to check the uniformity of the direction of magnetisation within material from a single location with the same orientation.

Archaeological interpretation of the deposit sampled

It is believed that the well-documented burning of the site in 206BC, described above, caused the extensive scorching of the corridor walls, thus providing a precise date for the acquisition of TRM.

Results of magnetic measurements

Natural remanent magnetisation

The NRM directions were well grouped (Fig. 4.6a) with a very small α_{95} value of 2.5° and high intensities in the range $69.0\text{--}873.3\mu\text{Am}^2\text{kg}^{-1}$ (Table 3B).

Demagnetisation

4 of the 14 samples were demagnetised in increasing alternating fields. A typical example (Fig. 4.7), showed the demagnetisation of a very small viscous component of magnetisation, followed by a single component vector with a stability of 31.4 (extremely stable) over a range 10–90mT. Initially the intensity fell sharply, with a median destructive field of 12.5mT, but a much harder component was revealed in demagnetisation fields over 25mT. 11% of the original magnetisation still remained after demagnetisation at 100mT. After partial demagnetisation at 10mT to remove the small viscous component the grouping of magnetic directions improved slightly (Fig. 4.6b), giving an α_{95} of 2.4° and small changes in average declination and inclination. The sub-samples had very similar directions and behaved in the same way as the original samples.

Magnetic mineralogy

Applying a series of isothermal remanent magnetisations to a selected sample (Fig. 4.8 a & b) showed that it had a very high SIRM of $20.7\text{mAm}^2\text{kg}^{-1}$, 93% of which was acquired in applied fields up to 1T. $(B_o)_{cr}$ was reasonably high at 22mT and the S ratio was 0.72. These results suggested that there was a significant contribution to the remanence from hard magnetic minerals, confirming the evidence of the demagnetisation behaviour.

General conclusions

The samples from the Terracotta Army Museum clearly had a strong, extremely stable magnetisation, with contributions from both soft and hard magnetic minerals. It was possible that the harder magnetic mineral, which may be haematite, was formed by the intense heat of the fire. The remanence would appear to be a TRM, reflecting the magnetic field in 206BC when the Army was attacked. As the date of heating is known so precisely and the scatter in the determination of magnetic direction is small, this study provides an excellent reference point for the archaeomagnetic calibration curve (Section 4.5).

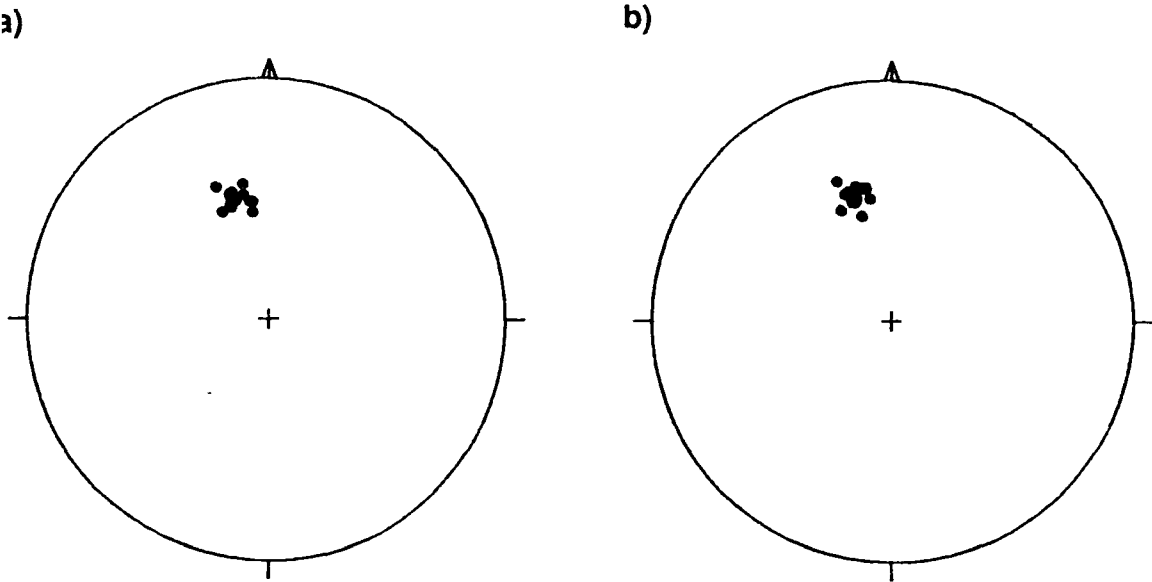


Figure 4.6: Stereographic plot of the directions of magnetisation of samples TERR1-14 a) NRM values and b) after partial demagnetisation.

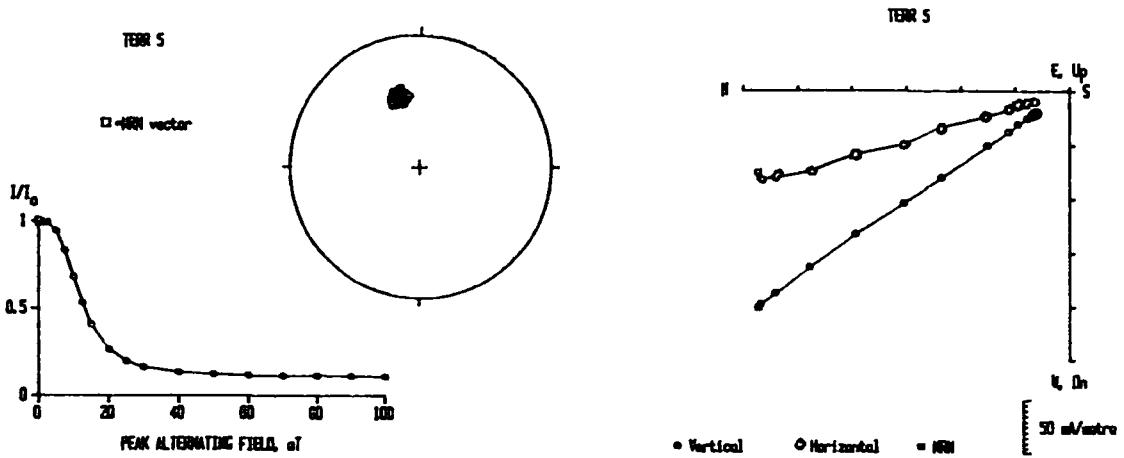


Figure 4.7: Stereographic, intensity and Zijderveld plots of the behaviour of a typical sample (TERR5) on alternating field demagnetisation.

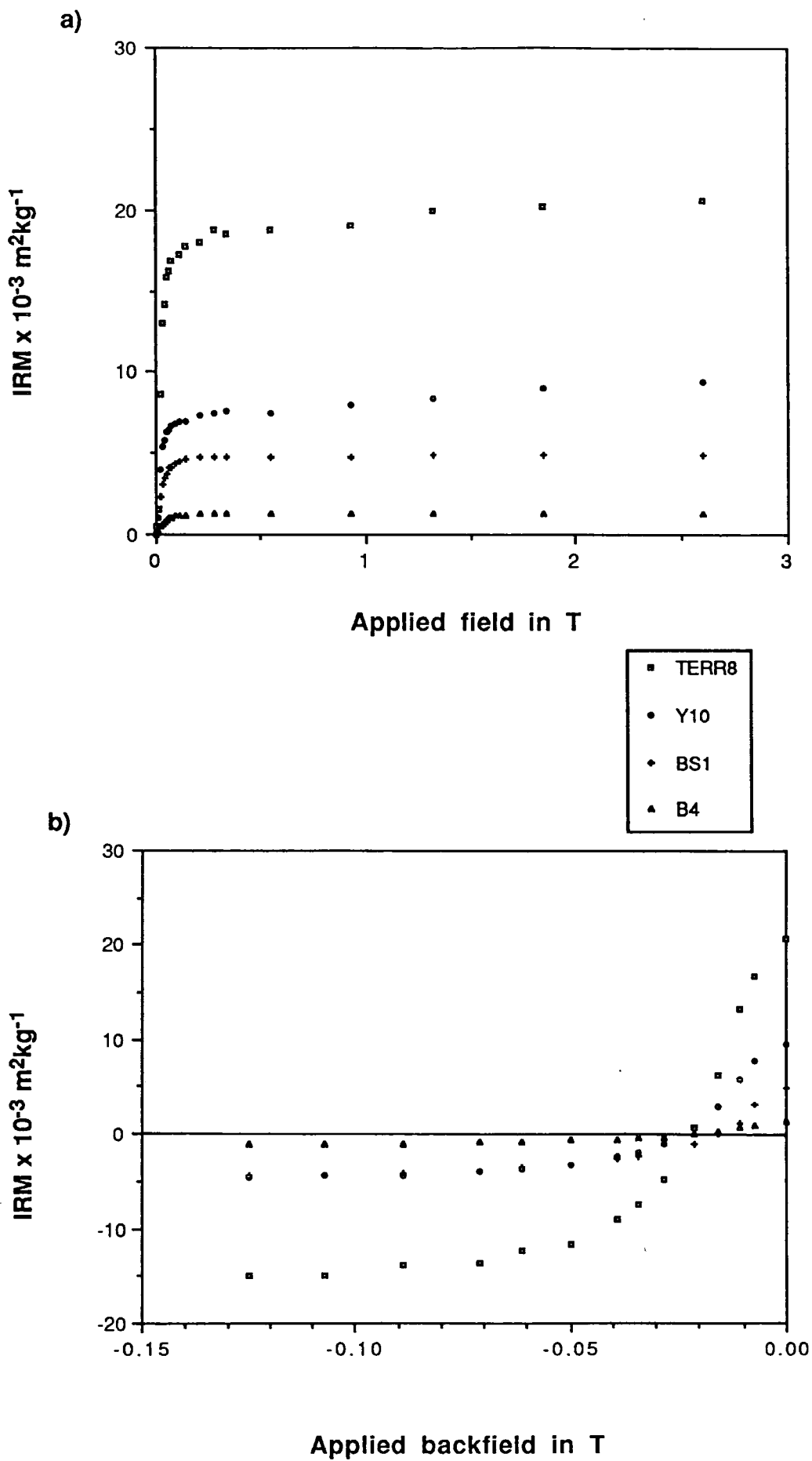


Figure 4.8 a: IRM build-up curve for samples TERR5, B4, BS1, Y10.
 b: Plot of back coercivity for TERR5, B4, BS1, Y10.

4.4.2 Banpo, near Xi'an, Shaanxi (34°16'N 108°54'E)

Historical introduction to the site

The Wei Valley in Shaanxi Province is known as the cradle of Chinese civilisation (Hollidge, 1988 p50). The early ancestors of man lived in the region, even before the present landscape was created by aeolian sand from the Mongolian Plateau. In 1963 the bones of Lantian man (*Sinanthropus lantianensis*) were found in the area. They displayed the thick skull and pronounced jaws characteristic of *Homo erectus*, an early stage of human evolution (Cotterell, 1988 pp3-4). These remains were dated to 600,000-700,000 years old on the basis of their stratigraphic relationship to neighbouring sites which had been dated by magnetostratigraphy (Day, 1986, pp376-379). At the end of the last Pleistocene glacial, a layer of loess was deposited over large areas of northern China, up to 100m deep in places. This yellow soil is easy to work and self-fertilising if it is well watered. Hence, by the Neolithic period, the Wei and middle Yellow River valleys provided an ideal environment for the development of agriculture and the earliest settlements, known as the Yangshao culture, were established in the 5th millennium BC. The site at Banpo is a typical example of one such Neolithic community, representative of the settlements on the loess terraces of the Wei River Valley, of which over 400 have been found.

Site description

The settlement at Banpo is situated 7km east of Xi'an on the Chanhe River (Fig. 4.1). It was discovered in 1954, 3-4m below present ground level when foundations were being laid for a factory. Excavations were carried out between 1954-57, covering an area of 10,000 m² and have been described as 'the greatest single contribution to prehistoric archaeology in east Asia' (Hay, 1973). The site is one of the most complete examples of an agricultural Neolithic settlement in the world and is remarkably well preserved.

The area fully excavated and exhibited covers 4000m² and includes the remains of 45 houses, a pottery making centre and a cemetery. Both square and round houses of various sizes have been found. These were mainly semi-subterranean and inside them the loess had been shaped into fire-holes, storage pits, seats and bed platforms. Most of the house floors were plastered and the low wattle and daub walls were covered by reed roofs, supported by wooden posts. At the final stage of occupation there may have been as many as 100 houses and 500-600 inhabitants in the village (Cotterell, 1988 pp7-8). Agricultural implements found included hoes, spades, cutters and digging sticks and the

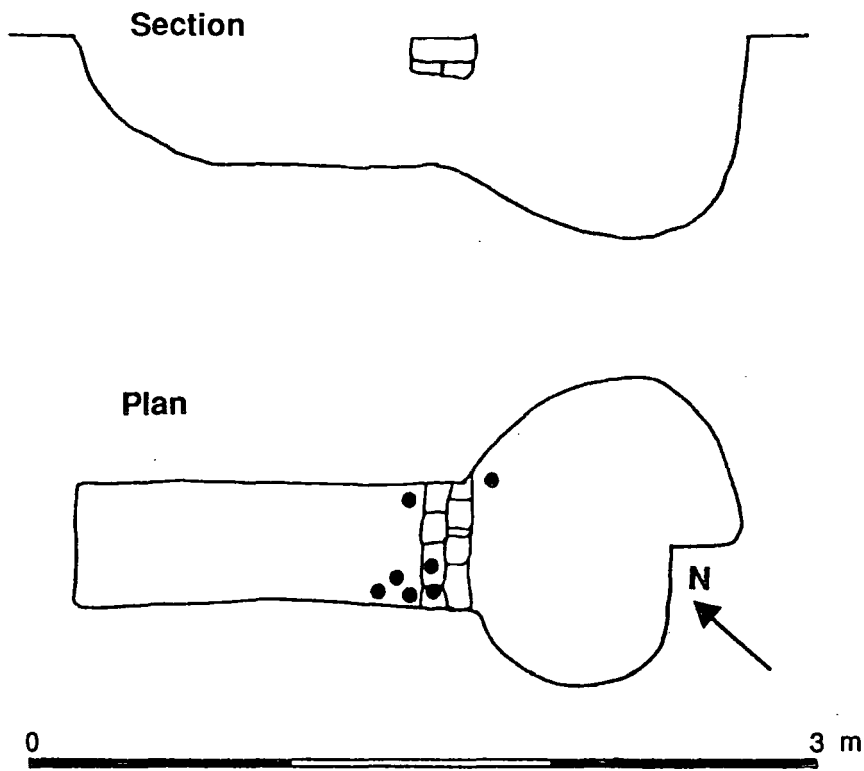


Figure 4.9: Section and plan views of the fireplace sampled at Banpo, showing the location of samples (samples not to scale).

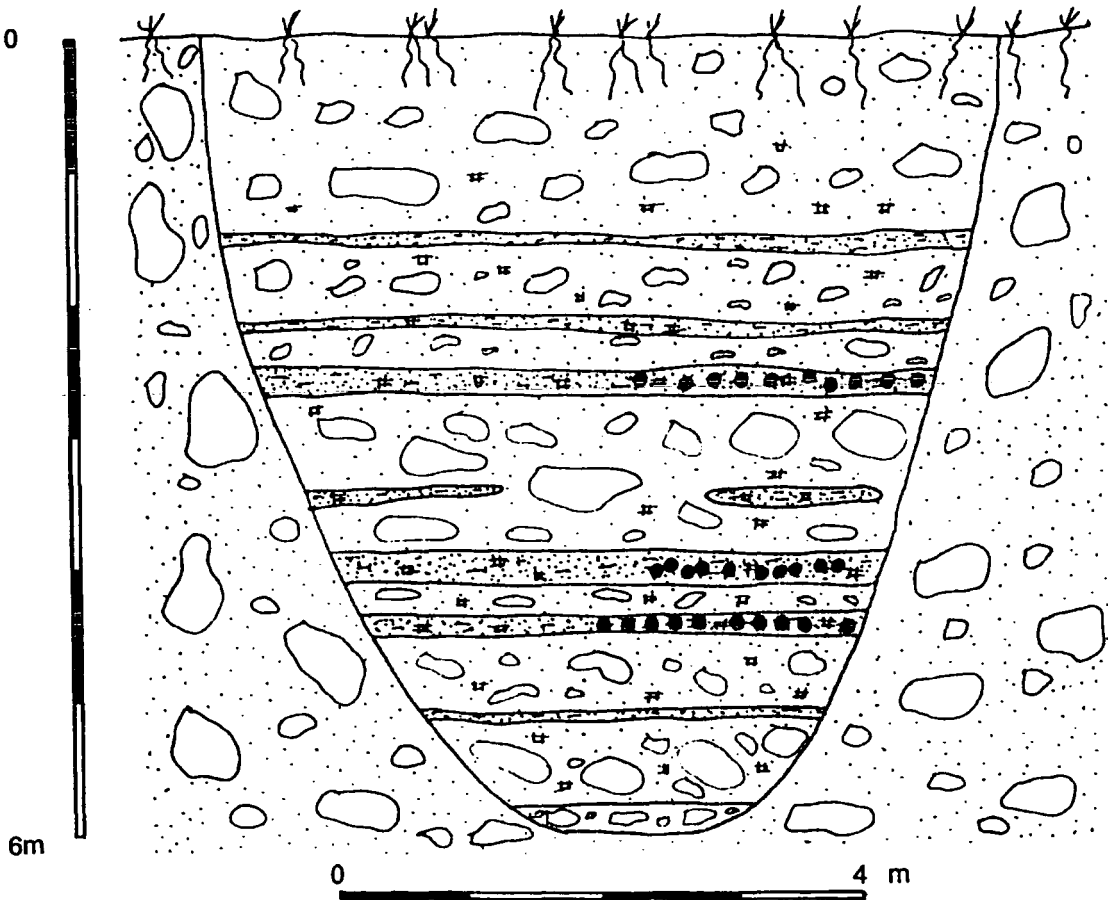


Figure 4.10: Section drawing of the moat at Banpo, showing the location of samples, using the notation of Appendix 2 (samples not to scale).

discovery of grinding stones indicated that the main crop, millet, was prepared and preserved as flour. Fishing tackle was also found and the importance of fishing to the settlement was shown by the frequency with which fish designs appeared on pottery (Watson, 1974 p26-27). Animal bones indicated that pigs, dogs and possibly chickens were kept and that hunting was used to supplement the diet (Hollidge, 1988 p51).

The cemetery outside the settlement contained at least 130 adult burials and several child graves. None of the adults appeared to have lived beyond 30 years old (Elisseeff & Elisseeff, 1983 p18) and the fact that women were buried with more grave goods has led Chinese archaeologists to suggest that the settlement was matriarchal (Banpo Museum, 1987; Elisseeff & Elisseeff, 1983 p19), although this interpretation has been questioned (Watson, 1974 p27).

The habitation area of the site was enclosed by a deep trench or moat (6m deep, 300m long and 6-8m wide) which was still in a usable condition when the site was discovered. This may have been for protection from wild animals (Elisseeff & Elisseeff, 1983 p16), although no stockade has been found, or to collect run off water during the heavy rains (Watson, 1974 p26). While inside the museum the moat has been fully excavated, outside the moat fill has been left intact and several episodes of sedimentation were visible in the section.

The Yangshao culture is also known as the 'Painted Pottery' culture and is characterised by the production of polished and painted ceramic ware (Elisseeff & Elisseeff, 1983 p16-18). Over half a million pot sherds were recovered from Banpo, including fine-grained ware with geometrical designs in black, red and brown and coarse grey vessels, decorated with cord or basket impressions. The initial designs on the pottery were of fish or human faces, but they became increasingly abstract over time. Six kilns were excavated in the pottery making centre, one still containing unfired pots. These kilns could reach temperatures of 1000°C and produced extremely well baked earthenware (Watson, 1974 p27).

Description of the samples taken

Samples were taken from a fireplace in the main excavated area and from 3 deposits in the ditch section. The fireplace (No. 18) consisted of a pair of chambers, one round, one oval, connected by a flue (Fig. 4.9). Wood was pushed into the fire-place along the long channel, with flames and smoke expelled from the other end. The inner walls and floor consisted of a layer of friable, pale brown (Munsell No. 10YR 6/3) burnt clay, 3-5cm thick. Samples were taken by the button method from apparently stable areas

of fired material on the floor and walls around the entrance to the chambers. Permission was only granted to take 7 small samples from areas of the hearth that were not visible from the public viewing gallery and so no sub-sampling was possible. Trimming the material in the laboratory proved to be difficult as it was so friable and several samples crumbled, thus the samples used for measurement were smaller than would be desirable. Samples were consolidated before measurement.

The fill of the ditch was visible in a section just outside the museum. At this point it was very narrow, only 6m wide, and at least 6m deep. In general, the fill was mixed, containing many stones and large quantities of pottery and charcoal (Fig. 4.10); six or seven distinct horizons of a light brownish grey (Munsell No. 10YR 6/2) sandy silt were evident. The latter material was dry and loose, crumbling when sample tubes were inserted. 30 samples were taken by the tube method from the three most distinct horizons, but only 23 of them survived the return journey.

Orientation was carried out using a magnetic compass with stand-off as the samples were taken inside the museum or in its shadow, and a theodolite was not available.

Archaeological interpretation of the deposits sampled

Radiocarbon dates indicate that the site was occupied between 4500-2500calBC, although these dates are still under discussion by archaeologists (Elisseff & Elisseff, 1983 p16). It was suggested by archaeologists at the Banpo museum that the hearth sampled was situated in one of the earliest parts of the site and that it had later been abandoned. On this basis, they dated the last use of the fireplace to 4000±150BC. Dates for the ditch deposits from radiocarbon and thermoluminescence are awaited, but pottery from the deposits suggested that they accumulated whilst the site was occupied rather than after its abandonment.

Results of the magnetic measurements of the fireplace samples

Natural remanent magnetisation

The samples from the fireplace proved to have a rather weak magnetisation of 7.6-67.6 $\mu\text{Am}^2\text{kg}^{-1}$ and to have dispersed directions of magnetisation with an α_{95} of 13.8° based on all seven samples (Fig 4.11a). Although the magnetisation was not unusually weak, the samples were very small and hence the value of the magnetisation to be measured was not far above the noise level of the magnetometer.

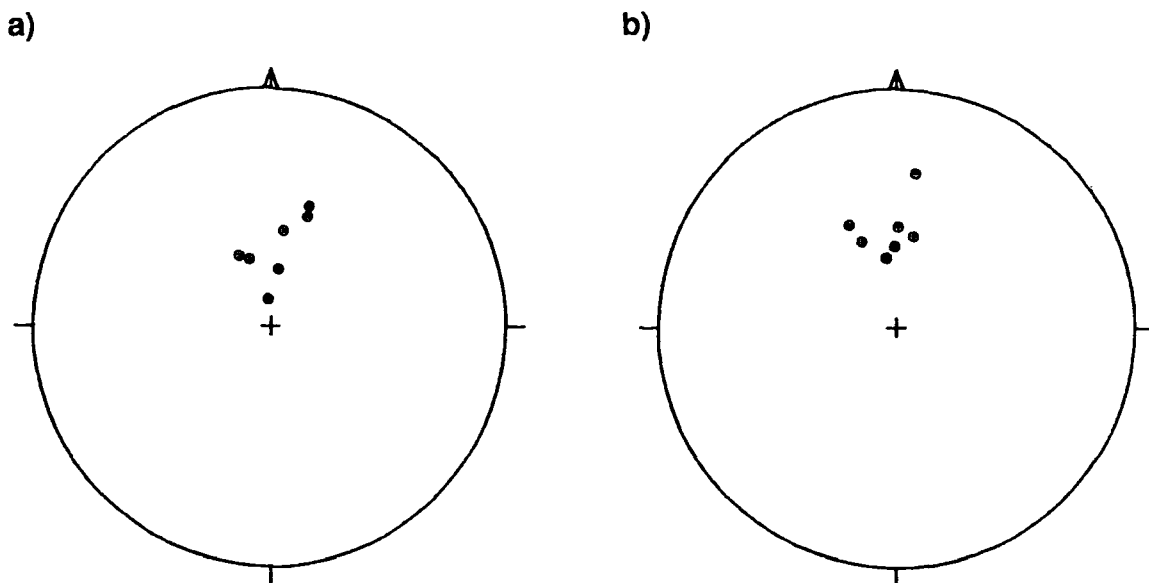


Figure 4.11: Stereographic plot of the directions of magnetisation of samples B1-7 a) NRM values and b) after partial demagnetisation.

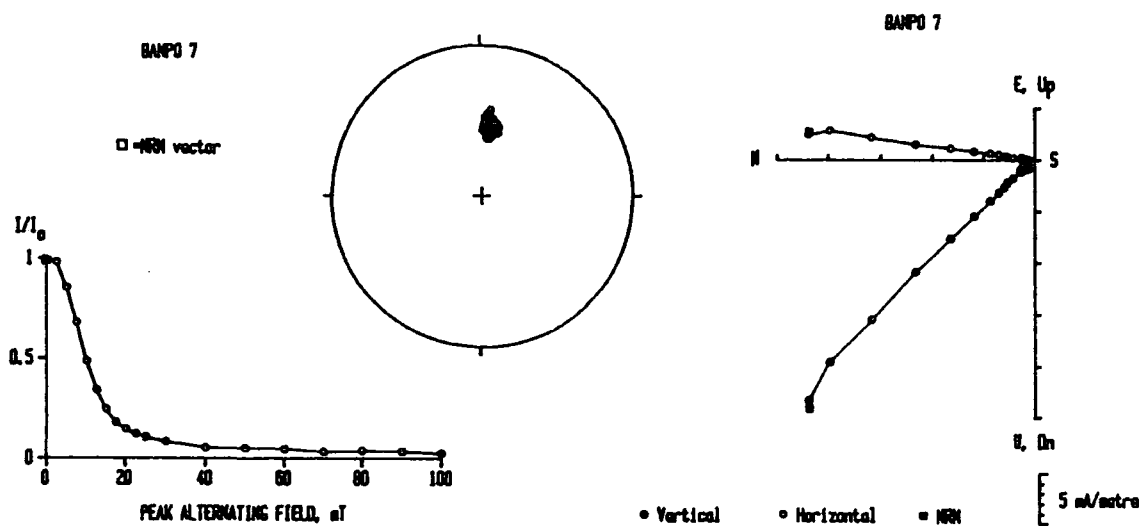


Figure 4.12: Stereographic, intensity and Zijderveld plots of the behaviour of a typical sample (B7) on alternating field demagnetisation.

Demagnetisation

Stepwise alternating field demagnetisation of the sample with the highest intensity of magnetisation (B7 shown in Fig 4.12) revealed the magnetisation to be very soft, with a median destructive field of 10mT and only 5% remaining after demagnetisation in fields of 40mT. However, it did appear to be stable (once a soft, possibly viscous, component had been removed) with a stability index of 6.5 (very stable) over the range 10-70mT. All the samples were subjected to pilot demagnetisation and selection of the most stable components gave a slightly improved α_{95} of 9.3° (excluding one outlier with anomalous demagnetisation behaviour). The rather large dispersion of even the most stable component (Fig. 4.11b) can be attributed, at least in part, to the small number of samples and to the fact that the samples were so small, their magnetisation was close to the noise level of the magnetometer. It was not possible to relate magnetic direction to sample location, because the samples were closely grouped in the few stable areas.

Magnetic mineralogy

IRM acquisition tests (Fig. 4.8) on a representative sample showed that it had a low SIRM, $1.29\text{mA}\cdot\text{m}^2\cdot\text{kg}^{-1}$, 99% of which was acquired in fields of 1T. $(B_0)_{\text{cr}}$ was 20mT and S was 0.81. These results were somewhat conflicting, with the IRM build-up indicating that the magnetic mineral was almost entirely a soft magnetic mineral and the S ratio suggesting that there was a significant contribution from a harder magnetic mineral, possibly produced by weathering.

Curie temperature

Measurements of induced magnetisation vs. temperature were made on small chips of material using a Curie balance (Section 2.4.2), in an attempt to determine Curie temperature (Fig. 4.13a). Induced magnetisation appeared to reduce almost linearly up to temperatures in the range 580-600°C, when the induced magnetisation had reduced to zero. This behaviour is consistent with magnetite being the magnetic carrier. The linear decrease in induced magnetisation, rather than a sharp change in magnetic properties at the Curie point, can be attributed to the dominance of the curve by paramagnetic minerals in the sample, since there was a low concentration of other magnetic minerals. The low intensity of magnetisation of the sample would also explain the slight scatter in measurements of induced magnetisation; it might have been advisable to prepare a magnetic extract for the Curie temperature determination. The heating and cooling curves followed similar paths, indicating that there was no chemical change on heating. There was no evidence for a material of higher Curie temperature, such as haematite, but this may be because haematite has a much weaker spontaneous magnetisation and will therefore cause a smaller deflection in the Curie balance or because haematite may not be saturated in the fields available. These problems indicate that IRM experiments are more suitable for determining the contribution of haematite.

Saturation Magnetisation in arbitrary units

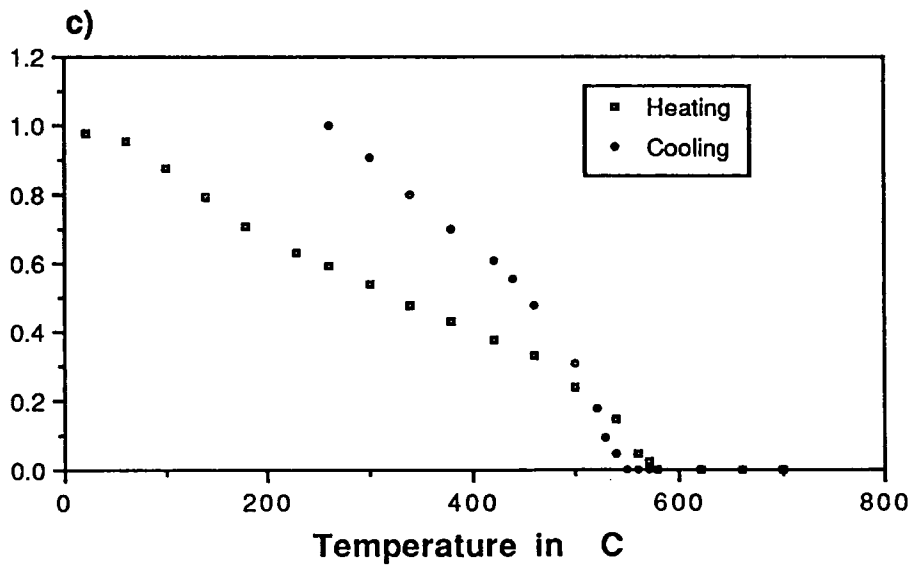
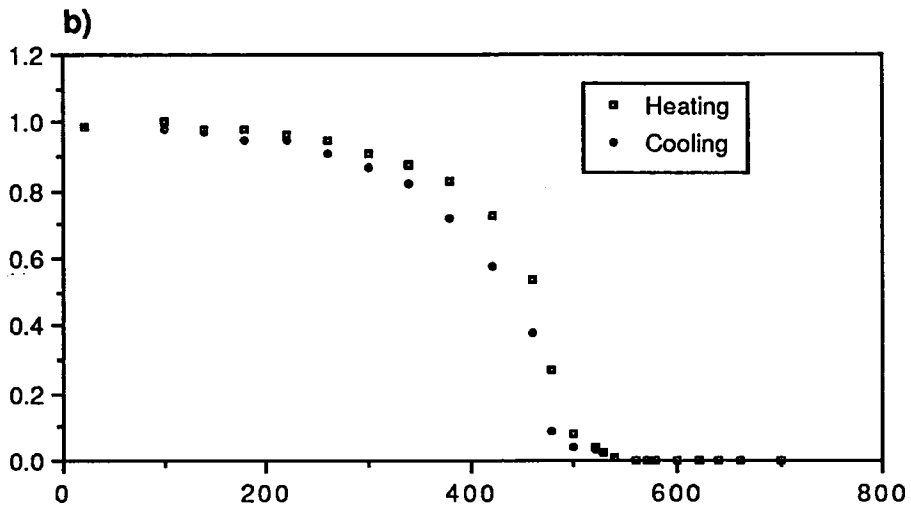
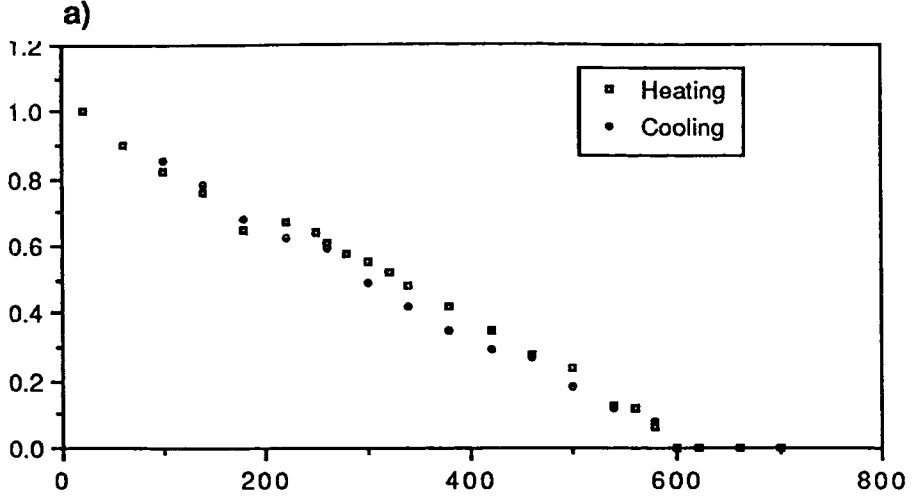


Figure 4.13: Curie temperature determinations of a) Banpo sample, B4; b) Yaozhou sample, Y28 and c) Yaozhou sample, Y32

Results of the magnetic measurements on the ditch samples

Natural remanent magnetisation

The sediment samples from all 3 horizons had well grouped directions of magnetisation with relatively shallow inclinations, with α_{95} values of 4.7° (excluding a reversely magnetised outlier), 9.5° and 5.5° , for the upper, middle and lower horizons respectively (Fig. 4.14). The intensities of magnetisation were quite high compared with other sediments (Chapter 3), in the range 11.0 - $60.1 \mu\text{Am}^2\text{kg}^{-1}$, with the upper horizon having the highest intensity and the bottom horizon, the lowest.

Demagnetisation

All of the 7 samples subjected to pilot demagnetisation (e.g. Fig 4.15a) showed a similar, rather surprising trend (Fig. 4.15b). The intensity of magnetisation fell sharply, with a low median destructive field of 10mT, but a harder component of magnetisation was also indicated as 10% of the magnetisation remained even after demagnetisation in fields of over 40mT. The direction of magnetisation changed considerably, always moving in an easterly direction but never appearing to reach a stable endpoint (stability index was 2.4, poorly stable). Although all directions of magnetisation of the samples moved in roughly the same direction on demagnetisation, the dispersion of the directions increased on demagnetisation. Therefore it was impossible to deduce whether the demagnetisation paths converged to a single magnetic field direction and hence a common, stable remanence direction could not be identified.

Magnetic fabric

Specific susceptibility fell in the range 48.2 - $117.3 \times 10^{-8} \text{m}^3\text{kg}^{-1}$ which is higher than normally found in sediments (Section 3.5). In the upper two horizons, 88% of the q values fell in the range expected for an undisturbed magnetic fabric and the axes of susceptibility were indicative of a primary magnetic fabric (Fig. 4.16). $h\%$ for these horizons was in the range 0.54-2.05. In addition to having lower intensity of magnetisation and susceptibility, the bottom horizon had a lower $h\%$, 0.26-0.67 and the axes of susceptibility were scattered, possibly indicating that the susceptibility anisotropy was too weak to be measured on the instrument available. q values for this horizon were in the range 0.42-1.27.

Magnetic mineralogy

The SIRM value for a typical sample was $4.89 \text{mAm}^2\text{kg}^{-1}$ (Fig. 4.8), 92% of which was acquired in fields up to 1T. $(B_0)_{\text{cr}}$ was very low at 17mT and S was 0.89. These results suggested that the magnetisation was dominated by soft magnetic minerals, such as magnetite, with some contribution from a harder magnetic mineral.

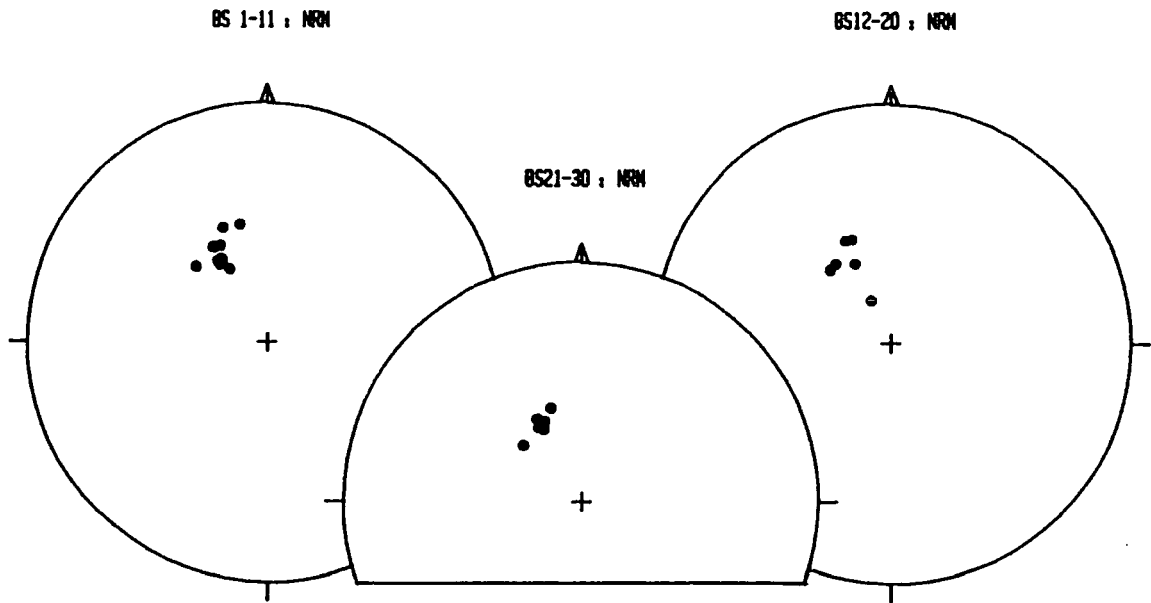


Figure 4.14: Stereographic plot of the NRM directions of Banpo sediment samples BS1-11, BS12-20 (excluding 14, 18, 20) and BS21-30 (excluding 23, 24, 26, 29). Samples excluded did not survive transportation.

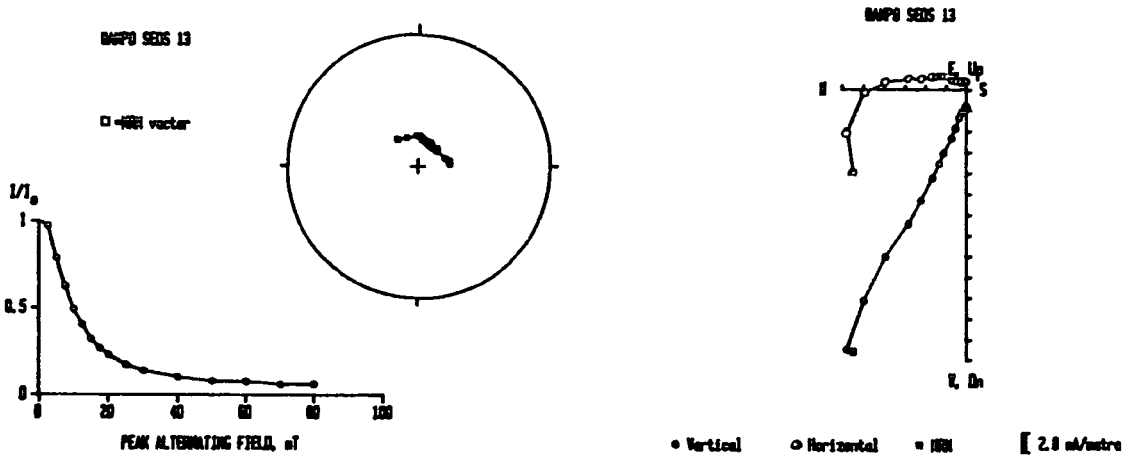


Figure 4.15 a: Stereographic, intensity and Zijderveld plots of the behaviour of a typical sediment sample (BS13) on alternating field demagnetisation.

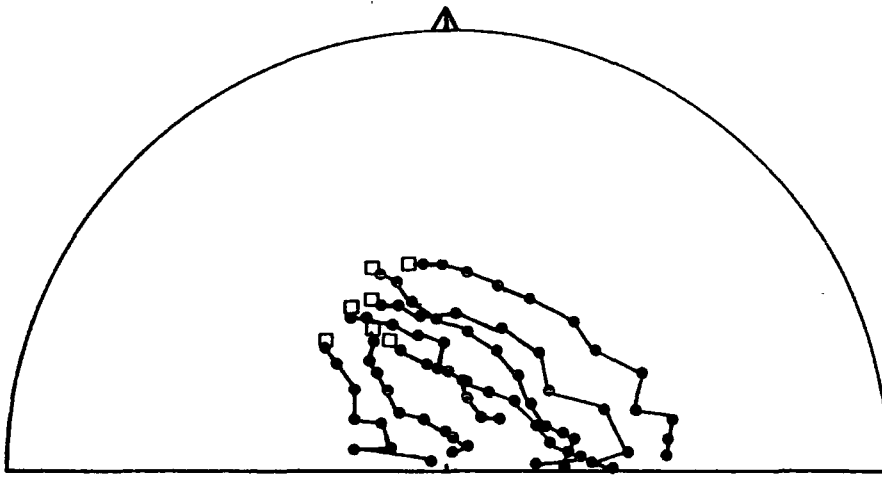


Figure 4.15b: Stereographic plot showing behaviour on stepwise demagnetisation of the 7 pilot samples from BS1-11. Squares represent NRM directions.

BS 1-11 : FABRIC

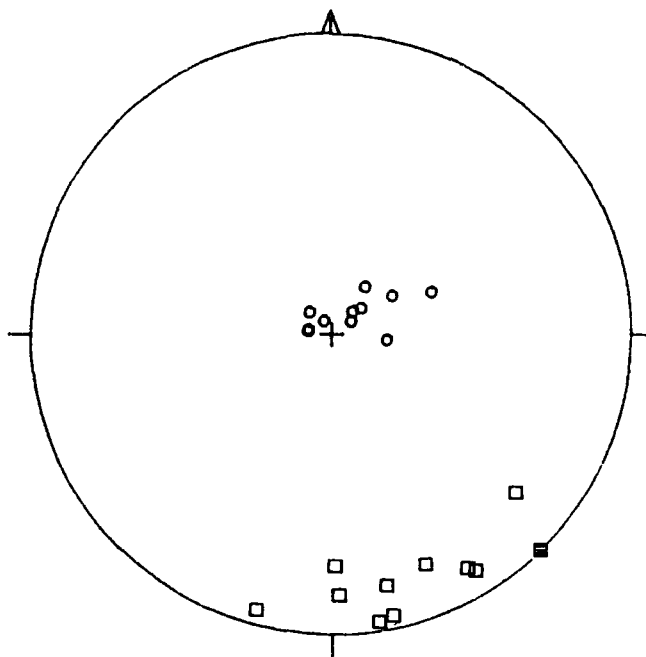


Figure 4.16: Magnetic fabric of samples BS1-11 from one of the Banpo sediment contexts.

General conclusions

The fired samples appeared to have a stable magnetisation. This might reflect the field at the time of last cooling. However, the magnetisation was very soft and the analysis was difficult as the samples were so small that their intensity of magnetisation was close to the noise level of the magnetometer, particularly during demagnetisation in high fields. If it had been permissible, areas of the fireplace would have been consolidated prior to sampling and a larger number of samples taken.

The sediment samples had a much higher magnetisation and SIRM value than the samples from the fireplace, indicating the presence of more remanence-carrying minerals than in the fired clay. However, the magnetisation was very soft and appeared to be overprinting another, possibly stable, magnetisation, which was too weak to be isolated. This small, stable component might be attributed to the harder magnetic mineral, possibly haematite, revealed in the IRM acquisition tests. The behaviour was consistent with remanence-carrying grains reflecting changes in the geomagnetic field as it moved from east to west. However, it was impossible to deduce when this remanence was acquired. Although the NRM inclination was similar to that of the present field, the declination was too westerly. The magnetic fabric was consistent with a water-lain deposit, suggesting that the sediments had accumulated when there had been water in the ditch, but that any magnetisation acquired at the time of deposition was subsequently overprinted by a PDRM or CRM.

Although the uncertainty of these results means that they do not contribute much detail to the calibration curve (Fig. 4.24), there is clearly considerable scope for an extensive sampling program on the hearths and kilns of Banpo. However, a greater number of samples per feature would be required, features might need consolidating before sampling and more precise archaeological dating control within the wide range given by the radiocarbon dates must be attained.

4.4.3 Yaozhou Yao, near Tongchuan, Shaanxi (35°05'N 109°02'E)

Historical introduction to the site

China has a strong tradition of ceramic manufacture going back 8000 years and was responsible for the invention of porcelain. In the last 40 years thousands of kilns and tens of thousands of pots from different regions and periods have been recovered by Chinese archaeologists. The important kiln sites in Shaanxi Province are dominated by those at Yaozhou (Hughes-Stanton & Kerr, 1982 p94-97), which consist of a number of groups of kilns situated along the west bank of the Chi (meaning 'Lacquer') River, near Tongchuan City (Fig. 4.1). Some of these have been fully excavated (Zuo, 1987). Pottery production in the region commenced in the Tang Dynasty (AD618-AD906), reached its peak in the Northern Song Dynasty (AD960-AD1279) and continued on a limited basis into the 14th century. However, the area is best known for the diversity and quality of the products from the Song period, which included characteristic carved and moulded green glazed wares, black and white glazes and urns with a 'belt' decoration, that is a different colour on the belly to the neck and base (Elisseeff & Elisseeff, 1983 p96). In the eight localities that have been excavated, the remains of twelve Song Dynasty kilns for stoneware and three Tang Dynasty kilns for three coloured ware have been found (Zuo, 1987).

Site description

Yaozhou Yao, the site investigated in this study, has been under excavation since 1984 by Prof. Zuo Zhenxi of the Institute of Archaeology in Xi'an. The site consists of a number of features associated with the ceramic industry, including kilns and workshops from various periods (Fig. 4.17). Significant innovations in the technology of ceramic manufacture can be seen in the pottery and kilns at Yaozhou Yao, particularly in the regulation of temperatures by alterations to the internal layout of the kiln.

The Song Dynasty kilns were roughly 3m long and 1.5m wide. An example of one is shown in Fig. 4.17a. They were horseshoe shaped in plan and consisted of a kiln entrance, a fuel chamber, a platform on which the ceramics were placed and two large chimneys, all constructed from heat resistant bricks. The entrance to the kiln platform was connected to the fanshaped fireplace by a duct and between the platform and the chimneys was a wall, the lower portions of which contained holes to permit combustion gases to escape. Opening and closing these holes changed the air flow over the kiln and hence provided the temperature control that was vital for the manufacture of the blue-

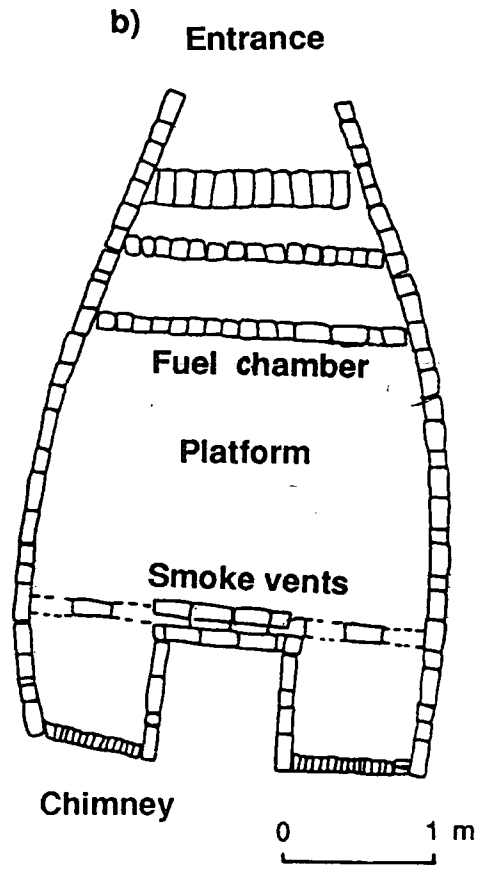
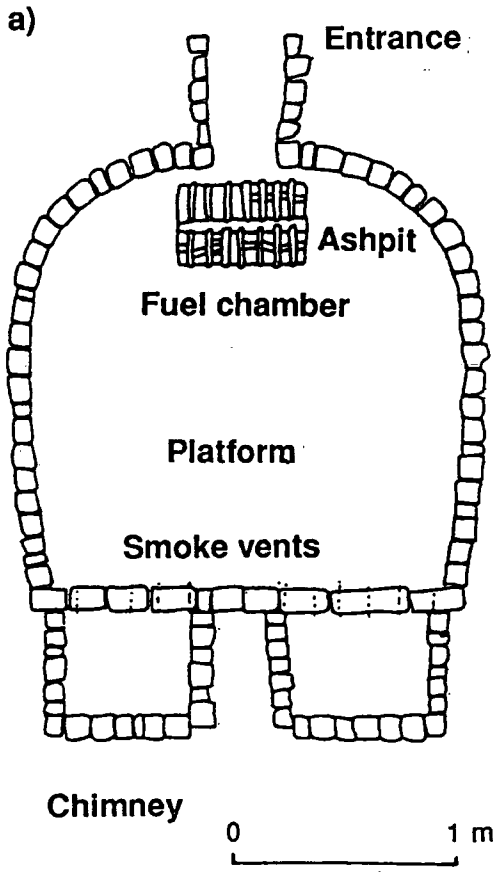
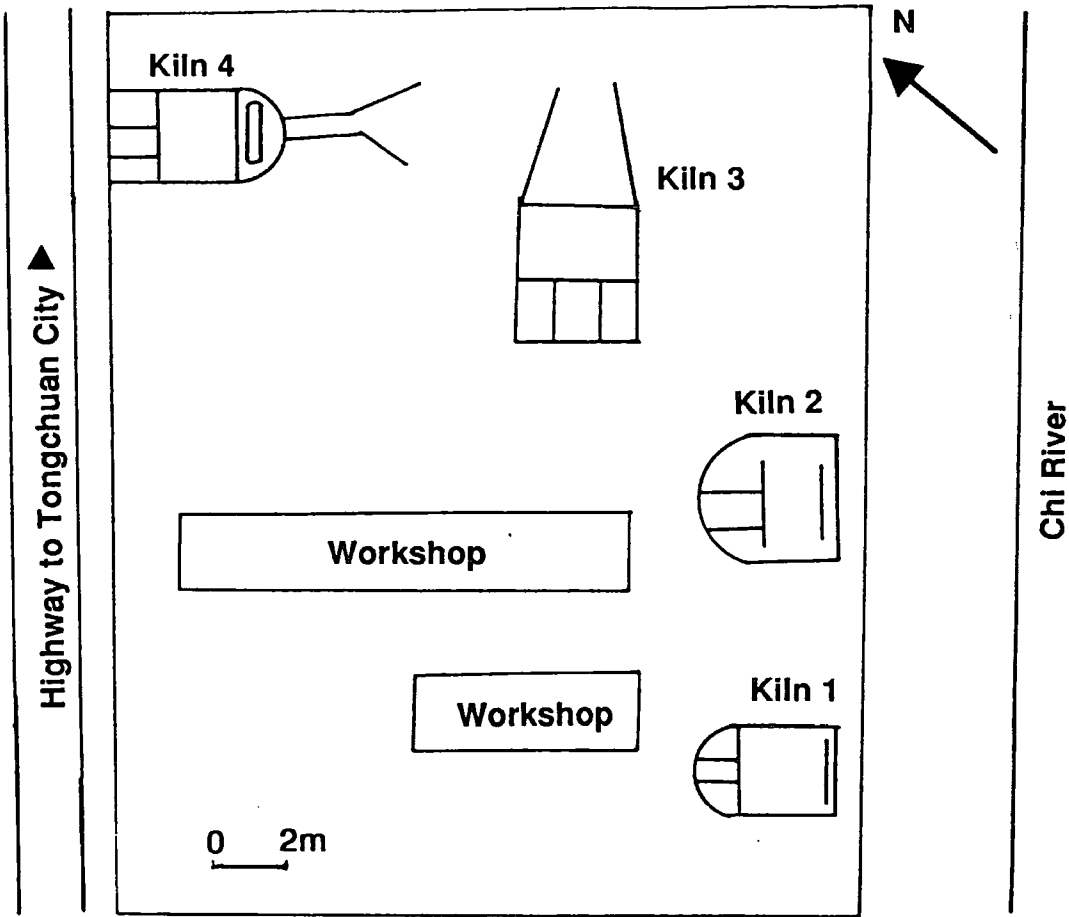


Figure 4.17: Diagram of site at Yaozhou Yao, showing details of a) a Song Dynasty kiln and b) a Tang Dynasty kiln.

green wares for which the area was renowned in the Northern Song Dynasty. In the centre of the fuel chamber of one of the Song Dynasty kilns (Kiln 4; Fig. 4.17a) was a rectangular ashpit of heat resistant bricks, covered by a grating made of lengths of stone, through which ashes would fall. On excavation ashes, coal cinders and unincinerated coal fragments were found in the ashpit (Zuo, 1987), indicating the use of coal as a fuel in the Song Dynasty. The kiln platform was spread with a fire-resistant grit under which the earth was burnt red, as were the bases of the chimneys, indicating a high firing temperature.

The Tang Dynasty kiln was larger (approximately 4m by 2m) and again of horseshoe shape, with similar kiln entrance, fuel chamber, kiln platform and double chimney. An example is shown in Fig. 4.17b. There was no ash pit so the draught must have entered through the stoking opening. In this case, the fire resistant grit had turned red-yellow as a result of the high temperature firing. Archaeological finds of ashes and uncarbonized firewood indicate the use of wood as a fuel in the Tang Dynasty. A study of the pottery itself (Elisseeff & Elisseeff, 1983 p197) also indicates technological changes; in the Tang Dynasty wares were fired on triangular supports which left recesses on bowls and plates of that period. By the 10th century potters had begun to use small studs which left only slight imprints and allowed hot air to circulate more freely over the pottery.

The evidence for dating the kilns was provided by Prof. Zuo from documentary sources and a study of ceramic typology. It is hoped that radiocarbon and thermoluminescence dates will be available in the near future. The four kilns sampled were dated as follows:

- 1) A kiln in use towards the end of the Song Dynasty; ceramic study suggests AD1200-1300, thus dating last use to AD1300±50. The features in use at this time consisted of a kiln, with associated workshop for preparing the clay and glazing the ceramics.
- 2) Another kiln from the Song Dynasty, last used in AD1100±50.
- 3) A Tang Dynasty kiln, in use between AD800 and AD900, with the last use being in AD900±50. Excavations in 1990, subsequent to sampling, suggested that there may have been a Song Dynasty kiln built directly over this feature and thus later heating may have affected the magnetisation of the lower kiln (Z. Meng, pers. comm.).
- 4) A kiln from the early Song period with final use in AD1000±50, perhaps 50-100 years earlier than 2), although they may both have been in use at the same time; their relationship is not clear.

Description of the samples taken

10-12 samples were taken by the button method from each of the four kilns and, where possible, these were later sub-sampled to ascertain the repeatability of the magnetisation. Samples were taken from the parts of the floor and walls considered to be most stable and to have reached a high temperature. The area around the firepit appeared to be the most suitable, as it was most likely to have reached the highest temperature and was generally undisturbed. The kiln floors consisted of a layer of burnt red earth, overlain by grit which had to be removed before sampling. The walls were constructed from burnt firebricks or clay. Samples were mainly very hard red (Munsell No. 5YR 4/6) fired clays, but also included some sandy, looser material, black shiny material and very hard white material. Parts of the kilns had been reconstructed for display purposes and these areas, indicated by the archaeologists, were avoided during sampling. The material sampled was generally very robust and hence easy to transport. Because of the incomplete survival of the kilns and their partial reconstruction, it was not possible to distribute samples in a systematic way.

Results of magnetic measurements for the Yaozhou Yao kilns

Natural remanent magnetisation

The intensity of magnetisation of all the samples fell in a wide range, from 2.1-3674.6 $\mu\text{Am}^2\text{kg}^{-1}$, with the highest intensities associated with the samples of red fired clay. The directions of magnetisation from all four kilns were well grouped with occasional outliers. For Kiln 1, α_{95} was 3.6°, excluding one outlier. α_{95} for Kiln 2 was 5.6° (excluding two obvious outliers, one of which had a reversed magnetisation) and α_{95} for Kiln 3 was 3.8°, with no outliers. When a small, weak sample with an outlying direction of magnetisation was eliminated, the α_{95} was 6.2° for Kiln 4 (Fig. 4.18a). Because samples were clustered in the few stable areas, no investigation could be made of magnetic refraction effects.

Demagnetisation

18 pilot samples were demagnetised in a stepwise fashion in alternating fields and Y10 showed typical behaviour (Fig. 4.19a). The intensity plot revealed a soft component, with a median destructive field of 20mT, and a much harder, persistent component, with over 20% of the magnetisation remaining in fields over 100mT. The Zijderveld plot suggested that the soft component was a viscous magnetisation and the main, harder component was very stable over a wide range of demagnetising fields (stability index was 60.0 (extremely stable) over a range of 10-100mT). All the pilot samples from the main groups showed similar behaviour, varying only in the proportion

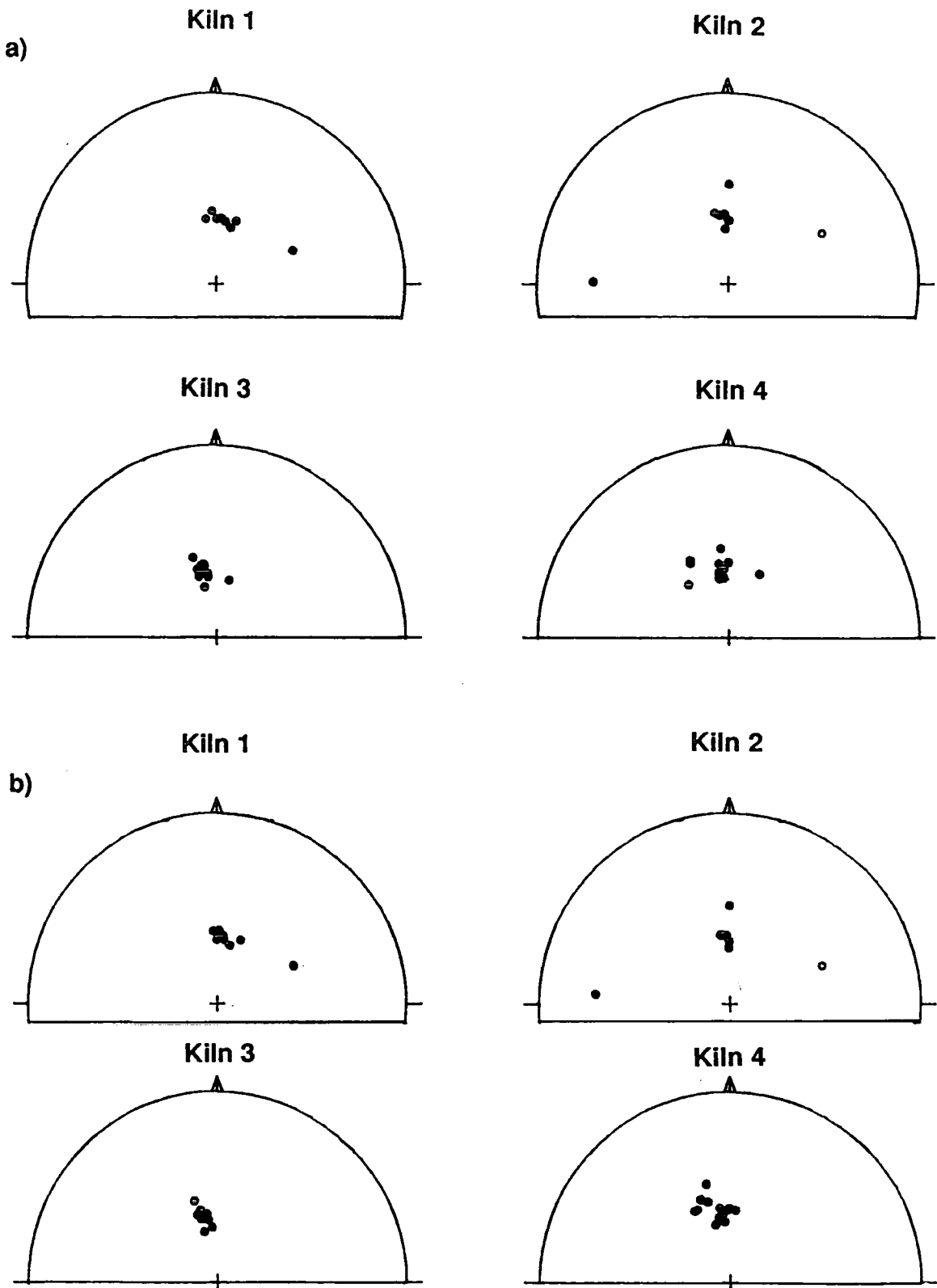
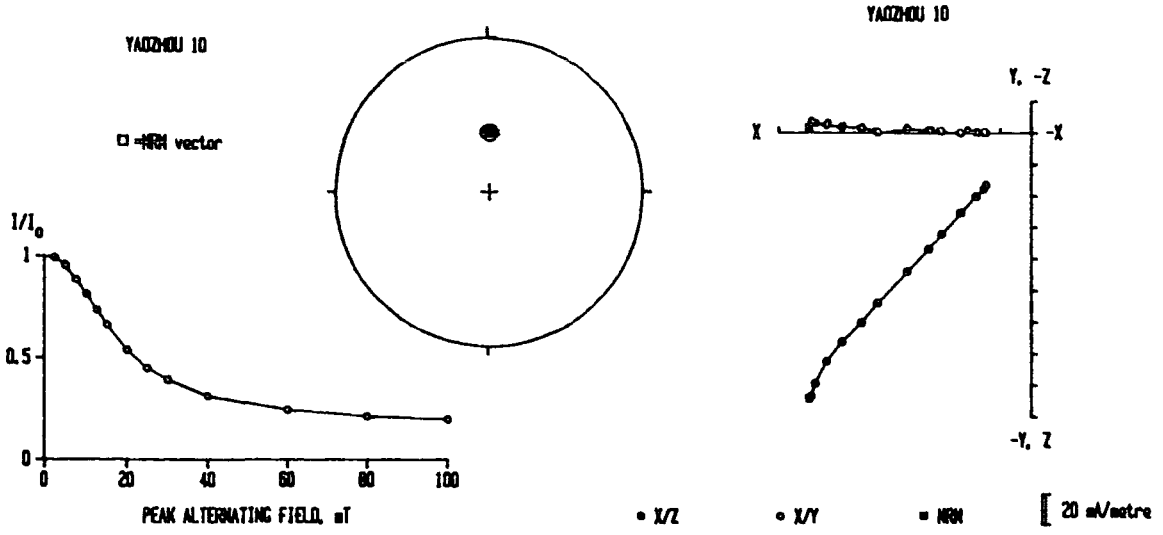


Figure 4.18: Stereographic plot of the directions of magnetisation of samples from Kilns 1-4, a) NRM values and b) after partial demagnetisation.

a)



b)

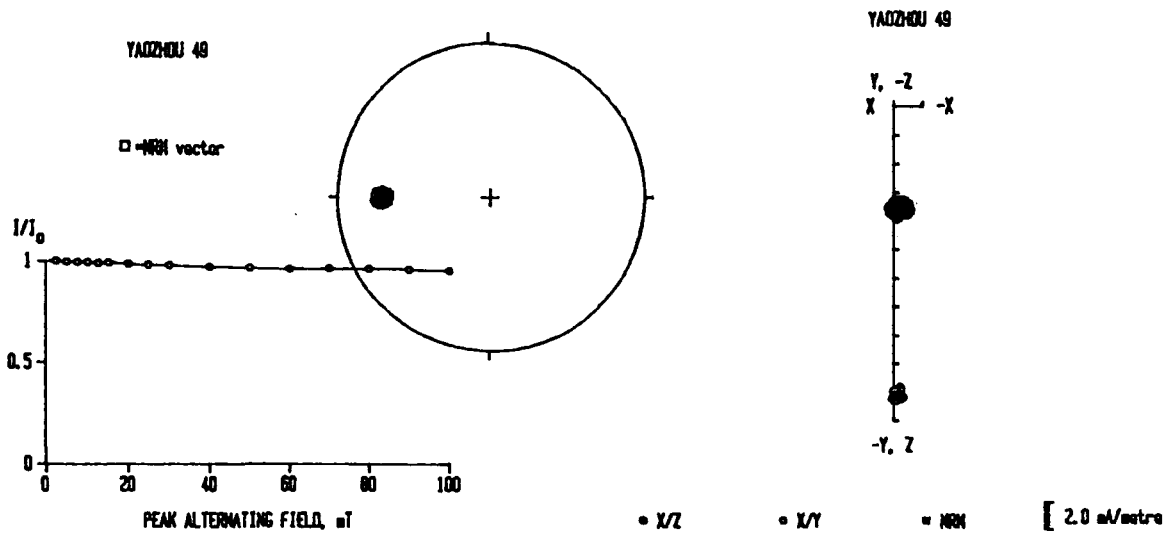


Figure 4.19: Stereographic, intensity and Zijderveld plots of the behaviour of a) a typical sample (Y10) and b) an anomalous sample (Y49) on alternating field demagnetisation.

of magnetisation contained in the soft component. When the outlying samples were demagnetised in a stepwise manner they also appeared to be very stable and their direction of magnetisation remained separated from the main group throughout. One particularly unusual sample was Y49 (Fig. 4.19b), whose anomalous direction was extremely stable and whose intensity was unaffected by demagnetisation, even in fields of 100mT. This would imply an unusual magnetic mineralogy for this sample, consisting only of very hard magnetic minerals. The 5 outlying samples were all of different materials, with a variety of intensities and from different areas of the kiln. In the absence of a common link, it was suggested that the outliers were from unidentified areas of the structure which had been rebuilt or had moved and so did not reflect the geomagnetic field at the time of last firing. The demagnetisation of samples from the Tang Dynasty kiln did not reveal two episodes of heating, thus suggesting either that Kiln 3 had been unaffected by the firing of the later kiln, or that it had been heated to a high enough temperature on the later firing to realign the direction of magnetisation completely.

The remaining samples were demagnetised in fields of 7.5-20mT to remove the soft component, which resulted in a slight improvement or no apparent change in the dispersion of magnetic directions, giving α_{95} values of 3.7, 5.3, 3.0 and 4.5 for kilns 1 to 4 respectively (Fig. 4.18b), excluding the above mentioned outliers. The sub-samples all showed similar behaviour to their parent samples.

Magnetic mineralogy

A typical sample (Fig 4.8a & b) had an SIRM of $9.4\text{mAm}^2\text{kg}^{-1}$, 85% of which was attained in fields of up to 1T. $(B_D)_{cr}$ was quite high at 25mT and the S ratio was very low, 0.49. The low S ratio and the fact that 15% of the magnetisation was acquired in fields over 1T, suggested that there was a very significant hard magnetic mineral contribution to the magnetisation, probably in the form of haematite, which may have caused the characteristic red colour of the samples.

Curie temperature

Curie temperature determinations were carried out on a number of chips of Yaozhou samples and two typical examples are shown in Fig. 4.13b and c. The sample in Fig. 4.13b showed a slight decrease in induced magnetisation with temperature, followed by a rapid decrease to zero at around 500-550°C. The curve was smooth, indicating the presence of only one magnetic mineral. The Curie temperature was rather less than that of magnetite (580°C). This might be attributed to thermal lag, with the thermocouple not registering the temperature at precisely the point when the changes in magnetisation occurred. Heating and cooling curves followed very similar paths suggesting that there had been no mineralogical changes on heating, which was expected as the material had already been fired to a high temperature. As with the Banpo sample (Section 4.4.2) there

was no evidence of the presence of haematite, but this might be attributed to the limitations of the experiment.

Other thermomagnetic curves for Yaozhou material (e.g. Fig. 4.13c) demonstrated slightly different behaviour, consistent with the inhomogeneity of the material. The induced magnetisation reduced to zero between 550 and 600°C, indicating the presence of magnetite, but there was an inflexion at around 500°C, which might indicate the presence of another magnetic mineral with a lower Curie temperature, possibly a titanomagnetite (Thompson & Oldfield, 1986 pp14-15). The shape of the thermomagnetic heating curve appeared to be dominated by paramagnetic minerals, possibly because there was a much lower concentration of magnetic minerals than in the sample discussed previously. The induced magnetisation on cooling was consistently greater than that on heating, suggesting that there had been a chemical change in the sample's constituents. The change in magnetisation could not be attributed to change in sample mass, as each measurement was corrected using the measurement on the Curie balance in the absence of an applied field.

General conclusions

The samples from the four kilns at Yaozhou Yao provided an important sequence of magnetic directions. The archaeological dating control was excellent, with the dates being known to within 50 years, and the directions of magnetisation were well grouped, giving fairly small errors in magnetic directions (Fig. 4.24). The dispersion in directions was slightly higher than might have been hoped for, but it was impossible to test for systematic variations depending on the position of the samples within the feature because of the clustering of sample locations. The uncertainty may arise from sampling errors (Section 2.1.2). The magnetisation appeared to be very stable, mainly residing in hard magnetic minerals which may have been created during heating to high temperatures. The remanence would appear to be associated with the date of last firing. The wide variations in intensity might be due to uneven heating of the structure and hence varying conversion of magnetite to haematite.

4.5 DISCUSSION OF THE RESULTS

4.5.1 *Introduction*

This pilot study investigated the magnetic properties of samples taken from six fired structures and a sequence of sediments from the Xi'an region of Shaanxi Province, China. The objective was to assess the potential of archaeomagnetic studies in China by measurement of the direction of the ancient geomagnetic field, as recorded by dated archaeological contexts. This information was then used in a number of ways: to investigate the suitability of such materials for archaeomagnetic studies (Sections 4.5.2, 4.5.3 & 4.5.4), to test the validity of earlier archaeomagnetic measurements and direct observations of the geomagnetic field (Section 4.5.5), to contribute to the dataset available for constructing the archaeomagnetic calibration curve for the region (Section 4.5.5) and to enable comparison of the properties of fired materials with sediments from both China and Britain (Section 6.3).

4.5.2 *Sampling, orientation and storage methods*

Samples of fired material were taken by the button method (Section 2.1.2), which was particularly suitable as, owing to the importance of the features under investigation, sampling was required to be minimally destructive. The method was very successful with the more robust materials (e.g. the Terracotta Army, Section 2.1.2), but with friable materials (e.g. the Banpo fireplace, Section 2.1.3) samples tended to crumble. Ideally, such materials would be consolidated before sampling (Section 2.1.2), but in these circumstances such a procedure was archaeologically unacceptable. The number of samples that it was permissible to take was restricted to reduce damage to the structures. It was also not possible to sample throughout the structures or select sample sites freely as there was often imperfect preservation and reconstruction of the feature, and the areas to be sampled were limited to those not visible to the public.

The sediments were sampled with 2.5cm cylinders (Section 2.1.3). Although this method was quick and enabled obstructions to be avoided, problems arose because the sediment was a dry, sandy silt, which crumbled on insertion of sample holders. Very careful sampling enabled 30 samples to be taken, but 7 did not survive transportation. Hence a method of consolidating such sediments needs to be developed.

Orientation in all cases was determined using a magnetic compass with a stand-off. There are inherent difficulties with this method (Section 2.1.4) but a gyrotheodolite was not available and the features were indoors, or in the shadow of a building, making a sun compass useless. There appeared to be no strong local anomalies in the geomagnetic

field which might affect the magnetic compass. The fired samples were successfully consolidated (Section 2.1.5) and all samples were stored in sealed boxes in a cool environment, away from strong magnetic fields.

4.5.3 *Remanent magnetisation*

The samples obtained by the small-scale sampling methods generally had sufficient magnetisation to be measured in conventional spinner magnetometers (Fig. 4.20a). The range of magnetisations of the fired materials was very wide, from $2.1\text{-}3674.6 \times 10^{-6} \text{Am}^2\text{kg}^{-1}$, reflecting considerable changes in magnetic mineral concentration and composition even within a single structure. The intensity of magnetisation of the sediments was generally much lower, in the narrow range $11.0\text{-}60.1 \times 10^{-6} \text{Am}^2\text{kg}^{-1}$, but still easily measurable in the spinner magnetometer. As expected, TRM's generally had higher intensity of magnetisation than DRM or CRM's; although concentration, type and grain size of magnetic minerals will also be influencing factors. It is interesting to note that the sediments and fireplace samples from Banpo have similar intensities of magnetisation, suggesting that firing has not enhanced the material's magnetisation, possibly because that particular area had not been heated to a high temperature or the magnetisation acquired on firing was not preserved over archaeological time. As explained in Section 4.5.2, no investigation could be made of the best location for samples as the sample sites were decided by non-archaeomagnetic criteria. Whilst it appeared that kilns were characterised by wider ranges of intensity of magnetisation than accidental fires or fireplaces, there are too few sites included for generalisations of this type to be made. It was also not possible to investigate the effects of magnetic refraction because samples were not distributed throughout the structure, as detailed above (Section 4.5.2).

Colour is one of the most obvious properties to use when identifying fired material suitable for archaeomagnetic studies. The colour of fired materials is less dependent on moisture content than the colour of sediments, although the problems of observer subjectivity and changing appearance in different light conditions still remain (Section 3.5.3). There tended to be much greater variety of colour in a fired structure than a sediment, related to firing temperature, conditions and duration, and the mineralogy of the material. This suggests that colour might be a sensitive indicator of the areas that should be sampled. However, a plot of sample colour against intensity (Fig. 4.20b) does not reveal any clear trends except to show that reddish brown and reddish yellow material frequently had the highest magnetisations. From this information it is difficult to recommend certain areas of a feature or colours of material that are more suitable for archaeomagnetic sampling than others. The general conclusion is that particular colours are not indicative of particular extremes intensities of magnetisation;

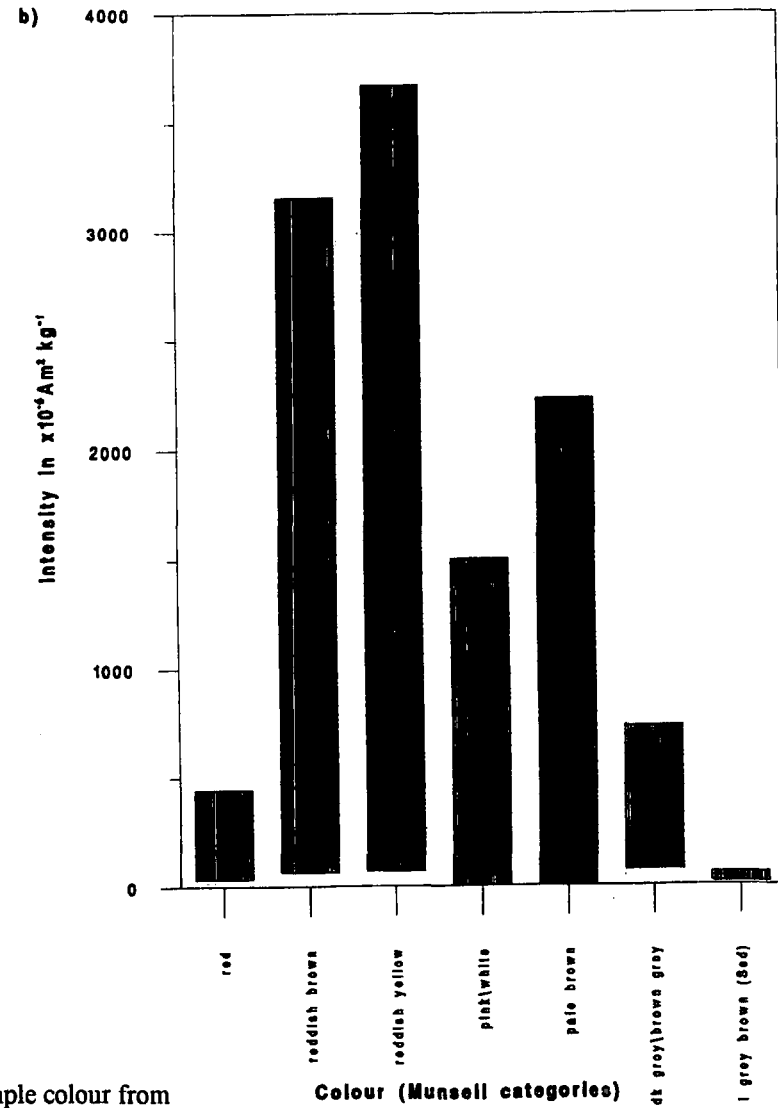
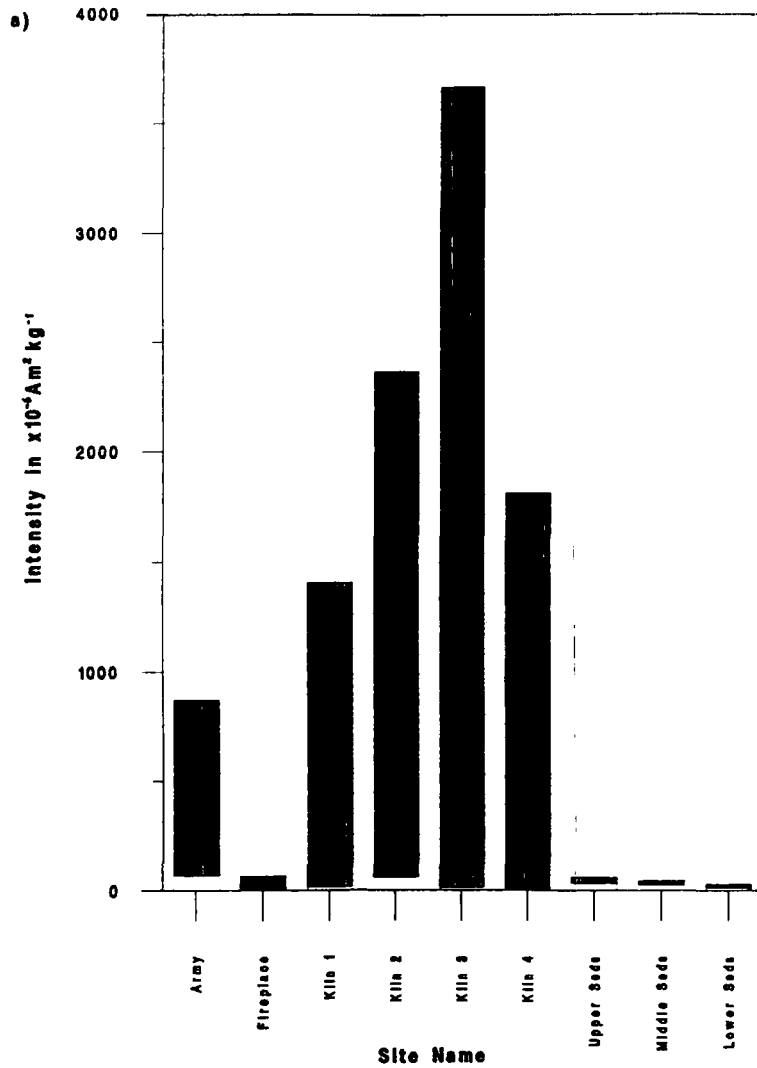


Figure 4.20: Range of values of intensity of magnetisation against a) feature and b) sample colour from Munsell chart. Numbers of samples in each category are as follows: Army=14, Fireplace (Banpo)=7, Yaozhou Kiln 1=10, Kiln 2=9, Kiln 3=12, Kiln 4=12, Banpo Upper sediments=11, Middle sediments=6, Lower sediments=6, red=9, reddish brown=11, reddish yellow=18, pink/white=6, pale brown=12, dark grey/brown grey=8, light grey brown (sediment)=23.

there are clearly many more complicated factors of magnetic mineral concentration, grain size and type to consider, which may not be reflected in sample colour.

Stability indices (Section 2.5.2) were used to identify the primary component of magnetisation and assess its stability. All the fired materials had stability indices over 6, and some were as high as 60 (Fig. 4.21a). The Banpo fireplace samples had the lowest stability, 6.5 (very stable), probably reflecting the difficulty of measuring the relatively weak magnetisation of these small samples. There were often softer components of magnetisation overprinting the most stable component. These components were small enough to be consistent with a viscous magnetisation. Unfortunately, the pilot samples were all from different materials and so no general conclusions concerning the relationship between stability and colour or location could be made. In contrast the sediments had a stability index of 2.4 (poorly stable) and demagnetisation did not reveal a stable remanence direction.

Using α_{95} values as a measure of the dispersion of primary components of magnetisation (Fig. 4.21b) revealed that the three Yaozhou Yao kilns and the Terracotta Army had α_{95} values $<5.5^\circ$, whereas the Banpo fireplace had an α_{95} value of 9.3° . The high α_{95} value for the fireplace is likely to be due to the low intensity of magnetisation of this material and the small sample size, rather than a general indication that fireplaces are less reliable recorders of the ancient magnetic field than kilns or accidental fires. It is interesting to note that even with 12 samples from a feature with a high intensity of magnetisation and high stability of primary component, the α_{95} value is still as high as 4.5° (Terracotta Army, Section 4.4.1). This suggests that there are factors other than the strength and stability of the primary component which affect the dispersion of magnetic directions. These might include magnetic refraction, sampling errors, differential movement of the structure and inadequacies in the material as a magnetic recorder (Section 2.6). As no stable primary component of magnetisation could be identified in the sediments, α_{95} values could not be calculated. There did not appear to be a direct relationship between α_{95} values and the range of intensities of samples from that context (Fig. 4.21c), although the Banpo fireplace had the largest α_{95} and the smallest intensities as discussed above.

Conclusions from the magnetic measurements in this study were limited by the diversity of the features. The six fired structures were constructed of different materials, for different purposes and existed in different states of preservation. The sediments came from a single archaeological feature, which may have been post-depositionally disturbed. Hence, any generalisations must be treated with caution. However, this investigation has demonstrated that a number of archaeological features from the Xi'an area of China have stable remanent magnetisations which appear to reflect the geomagnetic field at the time

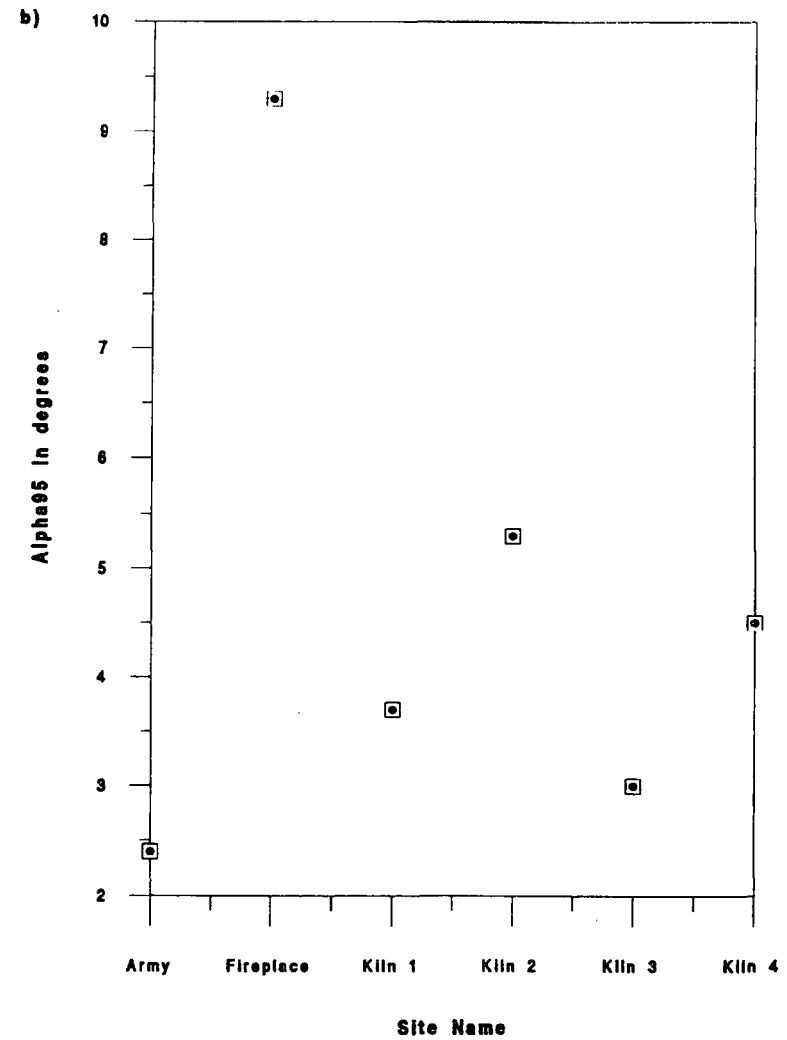
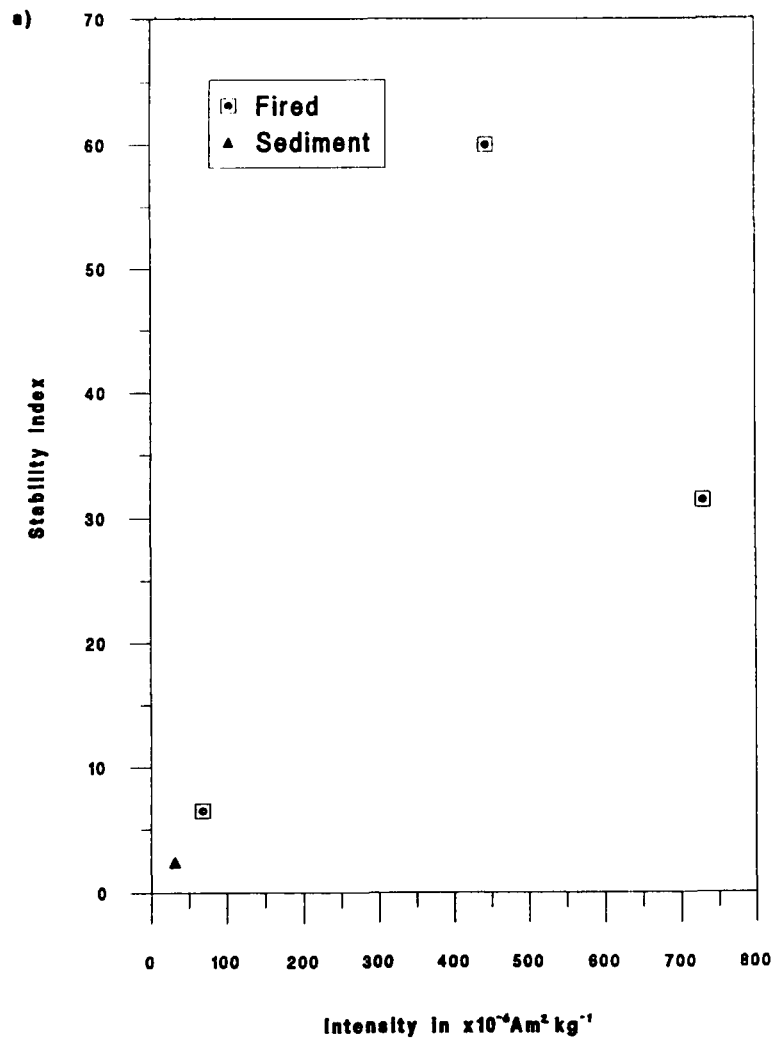


Figure 4.21a: Stability index against intensity for pilot samples of fired materials and sediments
 b: Alpha95 values for each feature. (The sediments showed no stable magnetisation.)

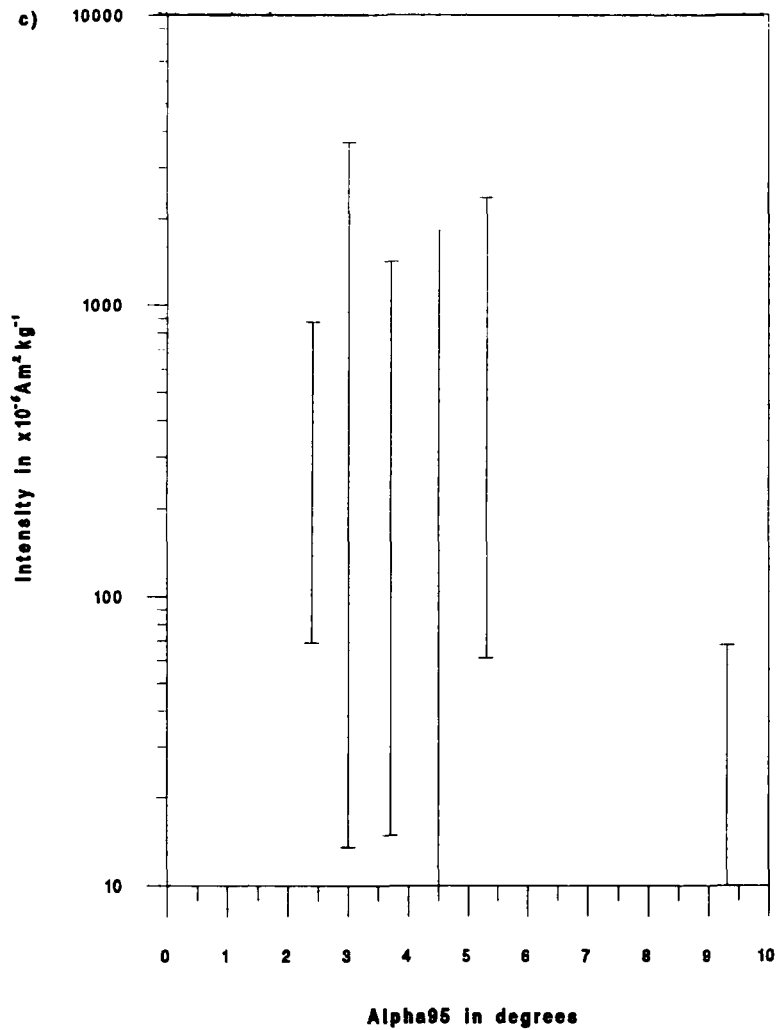


Figure 4.21c: Range of intensity against Alpha95 value for each fired context (Alpha95 could not be determined for sediments)

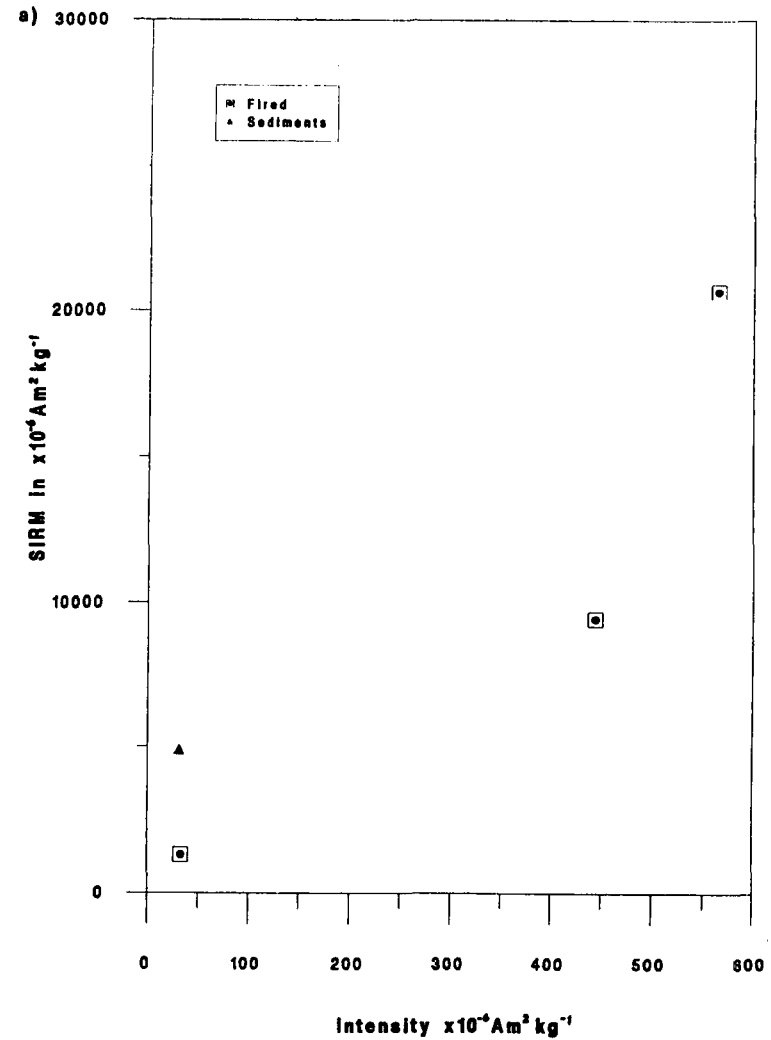


Figure 4.22a: SIRM value against intensity for pilot samples from sediments and fired material.

of their last cooling or deposition and there is clearly enormous scope for further features to be examined.

4.5.4 *Other magnetic measurements*

The primary objective of this study was to investigate remanence properties but a small number of other studies were carried out in order to obtain additional information about the magnetic mineralogy and sedimentary environments. Mineral magnetic studies were used to provide further information about the remanence carriers in both the fired material and sediments. The results of these studies complemented the information available from demagnetisation of pilot samples. Constraints of time meant that only a selection of samples were investigated in this way and so any generalisations from the information obtained are very tentative, particularly in the case of fired materials where there is apparently considerable sample to sample variation, even within material from the same archaeological feature.

The SIRM values gave a broad indication of the concentration of magnetic minerals, their grain size and mineralogy (Section 2.4.1). Any relationship between SIRM and intensity of magnetisation was hard to prove (Fig. 4.22a) because there were so few pilot samples, but as expected, materials with a higher intensity of magnetisation also tended to have a higher SIRM. It is interesting to note that although the sediments and burnt material from Banpo had similar intensities, the sediments had a higher SIRM, possibly indicating a greater concentration of remanence-carrying minerals in the sediment. The very high SIRM values of the Terracotta and Yaozhou samples indicated that these samples contained a high proportion of magnetic minerals.

The remanence ratio S provided a normalised measurement of remanence-carrying minerals which saturated in low fields, in comparison with those saturating in fields above 1T (Section 2.4.1). The most notable feature (Fig. 4.22b) was that the S values of the fired materials were low, in the Yaozhou Yao example as low as 0.49, indicating a high proportion of a hard magnetic mineral, probably haematite. The sediments had a higher S value, suggesting a greater soft magnetic mineral content, probably magnetite. The relatively high S value for the fired Banpo material could be interpreted as being due to a low firing temperature or reducing firing conditions, leading to restricted production of haematite. Such an explanation would also account for the relatively low intensity and stability of the primary magnetisation of this material. There were insufficient pilot studies to relate S value to sample colour, but demagnetisation behaviour did not indicate that samples of a particular colour necessarily contained more haematite than other samples. The coercivity of the SIRM, $(B_0)_{cr}$, for the fired materials

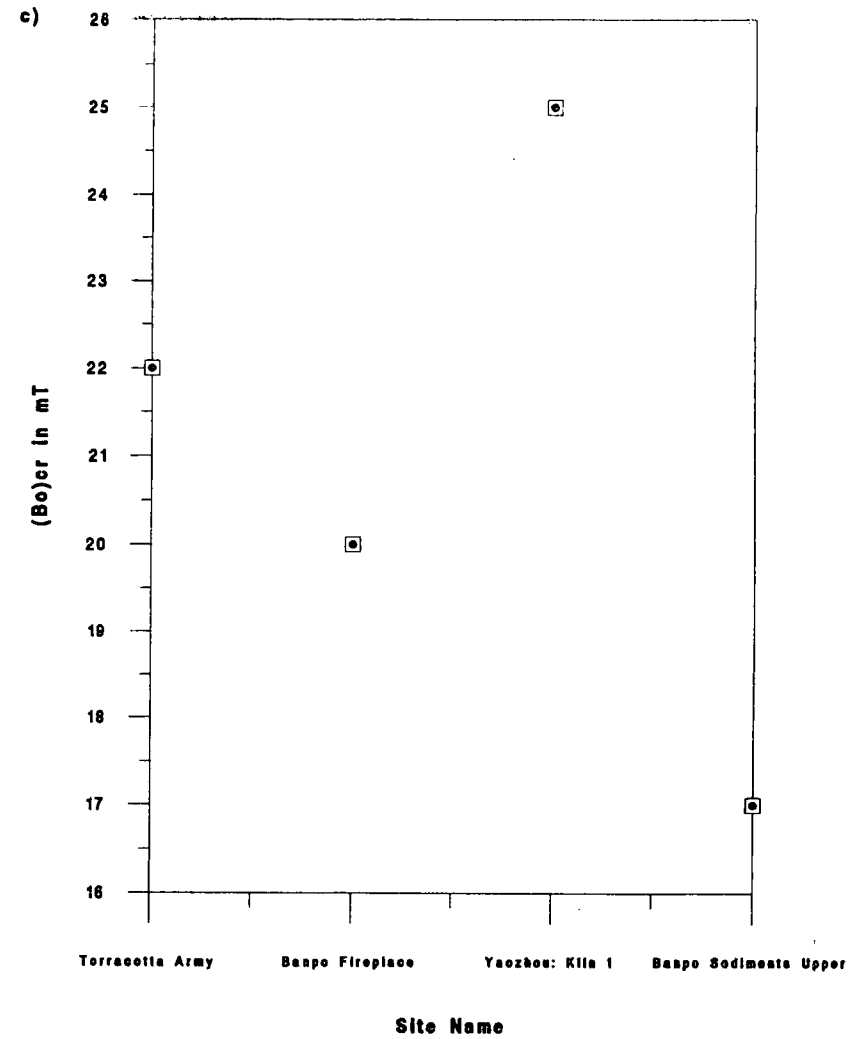
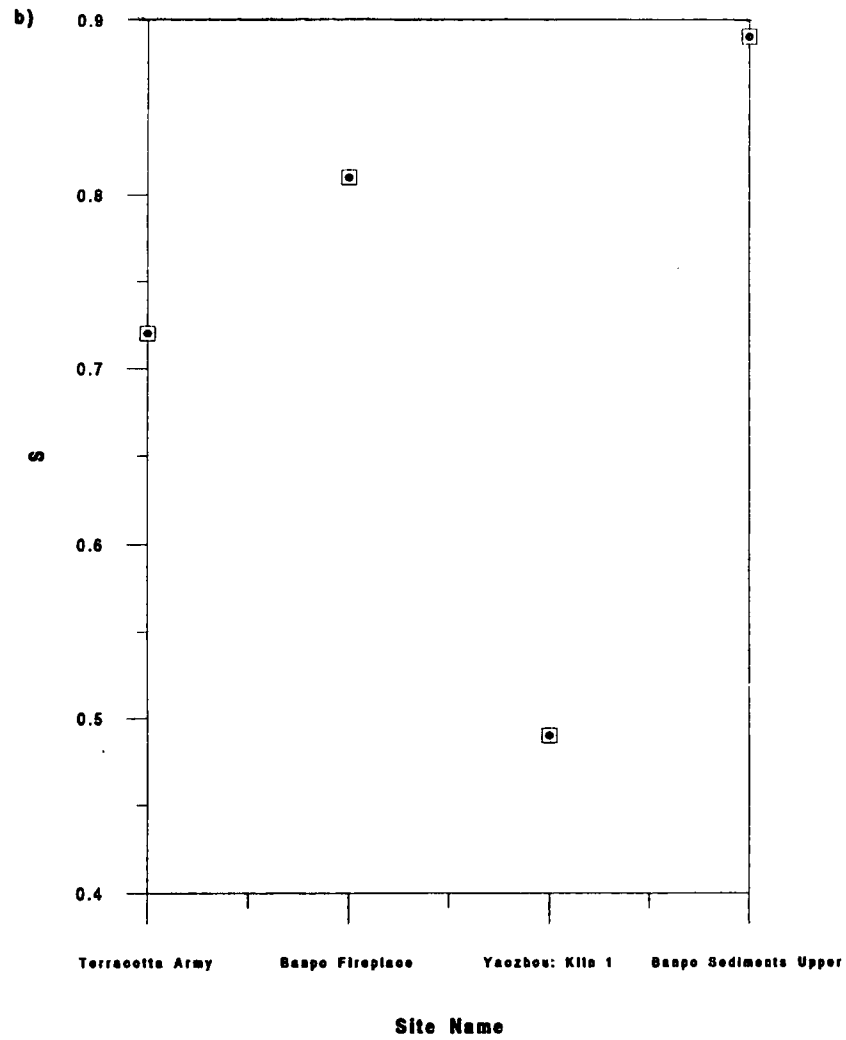


Figure 4.22b: *S* ratio for pilot samples from selected features and c: (Bo)cr for selected features

was also consistent with the presence of haematite, while for the sediments it was characteristic of multidomain magnetite (Fig. 4.22c).

Curie temperature determinations were attempted in order to provide another method of determining the magnetic mineralogy of the fired materials (Section 2.4.2). However, these experiments did not prove to be very successful; in the case of the Banpo samples, the concentration of magnetic minerals was too small for accurate measurements to be made on the equipment available and for the Yaozhou samples the results were inconsistent and difficult to interpret (Section 4.4.3). Where, as in this study, the main question of interest is the ratio of magnetite to haematite, IRM studies are more appropriate and simpler to carry out.

Magnetic fabric measurements were made on the sediment samples (Section 4.4.2) and these showed a primary magnetic fabric with preferential alignment of susceptibility axes suggesting a flow direction, although the susceptibility anisotropy was very low and difficult to measure. There was a linear relationship between intensity and susceptibility for the lower horizon (Fig. 4.23; Table 1D), established using a *t*-test (Section 3.5.4), suggesting a consistent magnetic grain size and mineralogy throughout the horizon. The other two horizons did not show such a relationship suggesting variations in magnetic grain size and mineralogy within and between contexts.

In summary, the additional magnetic measurements of IRM characteristics added considerably to the study, particularly by identifying magnetite/haematite ratios. These allowed conclusions to be drawn about the temperature or conditions of firing in some cases. Curie temperature experiments were shown to be largely unsuitable for the material, but magnetic fabric measurements aided the interpretation of the depositional environment of the moat sediments.

4.5.5 Comparison with previous archaeomagnetic measurements and direct observations of the geomagnetic field

While the small number of results obtained (Fig. 4.24) cannot be extrapolated into a calibration curve, a visual comparison can be made with direct observations and previous archaeomagnetic measurements. In collecting data for building an archaeomagnetic calibration curve, good dating control is of paramount importance. In this respect the sites investigated around Xi'an were ideal, with precise dates being provided by written records or a well-established pottery chronology, avoiding reliance on less precise radiocarbon or thermoluminescence dates.

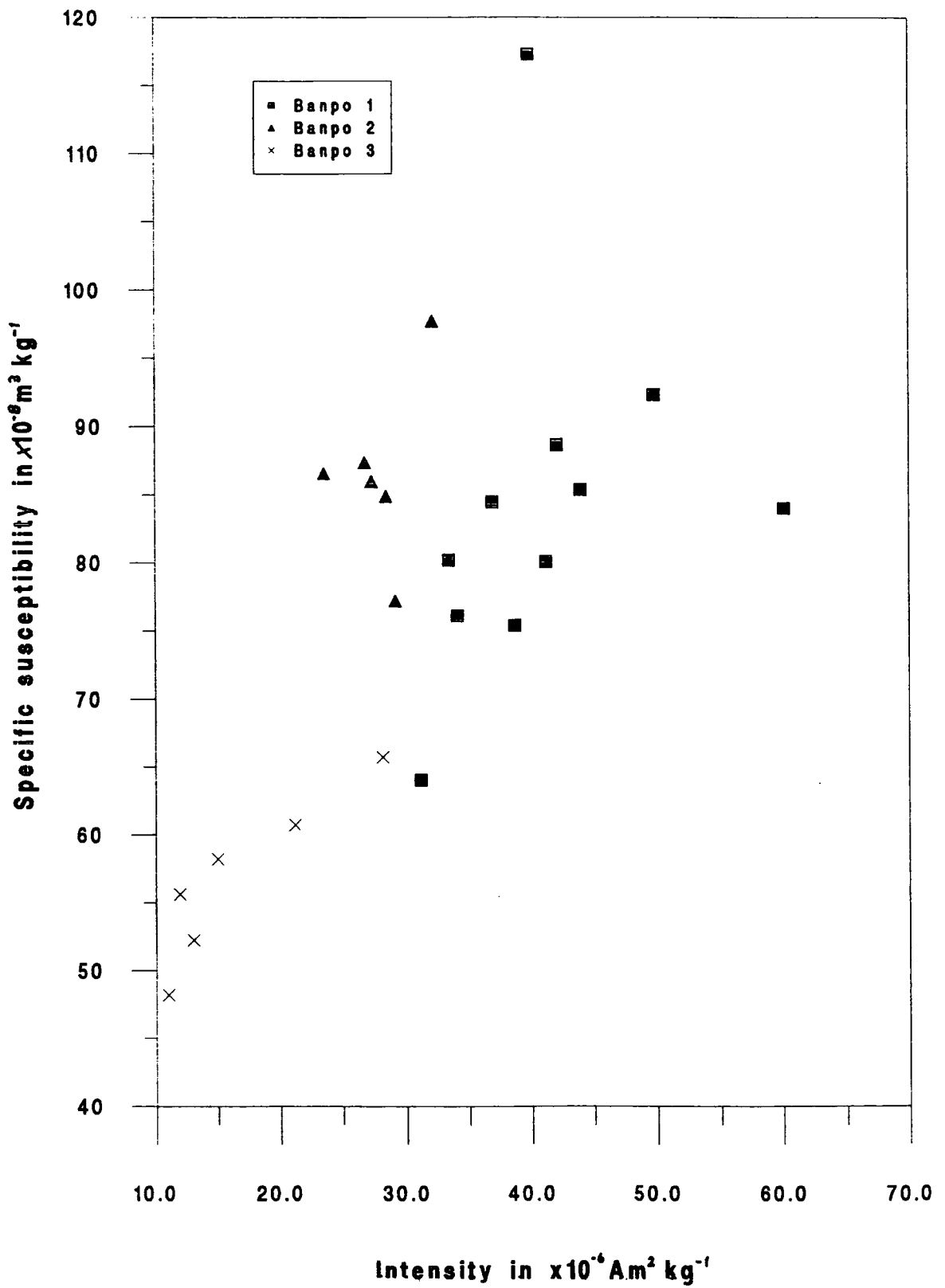


Figure 4.23: Specific susceptibility against intensity for the three Banpo sediment contexts.

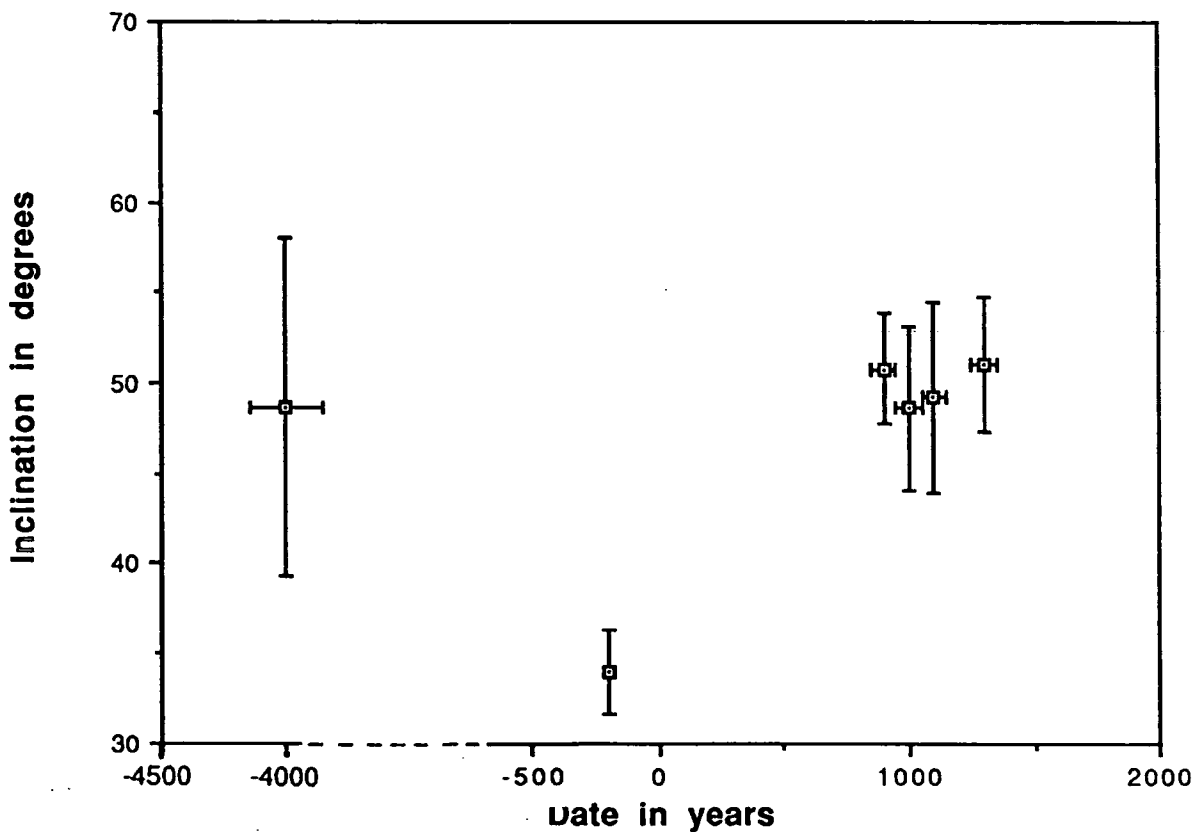
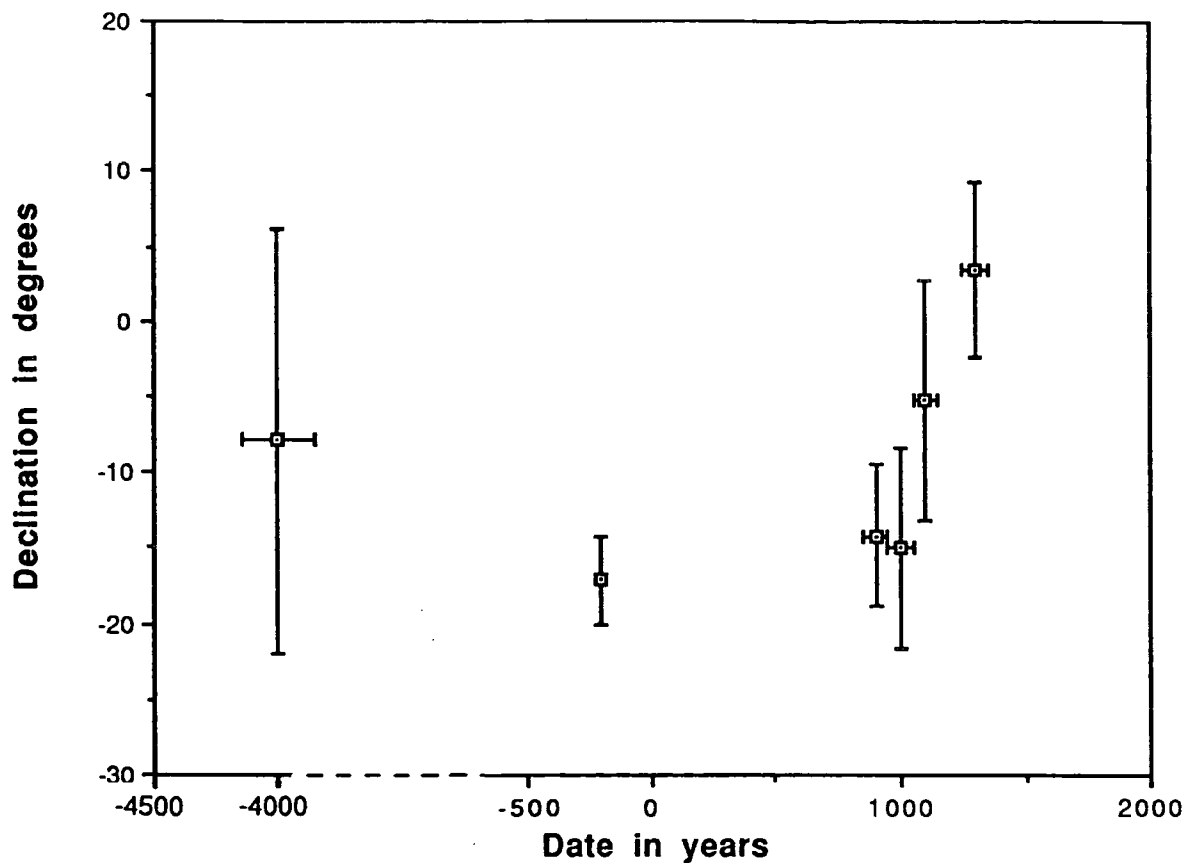


Figure 4.24: Plots of declination vs time and inclination vs time for all results from this study. Magnetic directions are corrected to Xi'an. Errors in declination and inclination are at 95% confidence and the age ranges are provided by archaeological dating as discussed in the text. Note the discontinuous time axes.

A comparison of the secular variation of declination obtained in this study (Fig. 4.24) with the results from Loyang, corrected to Xi'an (Fig. 4.3a; Wei *et al.*, 1981; Section 4.3) was of limited validity as only two of Wei's points fell in the period AD750 to AD1300 covered by the Yaozhou Yao results. Furthermore one of Wei's points had an extremely large measurement uncertainty. However, the agreement between the two datasets in this period seemed acceptable, as the error bars of points from similar dates overlapped. The declination obtained from the Terracotta Army samples was over 17° further west than declination measurements at Loyang from around the same date. Whilst the declination record from Yaozhou Yao and, to a limited extent, that of Loyang showed a trend from about 15°W to 2.5°E over the period AD900 to AD1300, the direct observations of declination showed the opposite trend from 7.5°E to 7.5°W over a similar period. It was hoped that these discrepancies might be resolved by a study of the marine sediment core (Fig. 4.3b; Cong & Wei, 1989), but unfortunately the declination record from the core was too scattered for such detailed comparisons to be made. The core does appear to show an extreme easterly direction at around 200calBC, but this is hard to confirm until further work has been carried out on the assignment of absolute dates to the core and the effect of changing rates of sediment deposition on the secular variation record.

The Loyang inclination record (Fig 4.3a) showed a clear trend from inclinations of about 35° in 200BC, rising to a maximum of 62° in about AD700 and then falling again to about 42° by AD1400. The Yaozhou Yao results from this study all grouped at inclinations around 50° (Fig. 4.24), comparing well with Loyang inclination measurements from the same period. The Terracotta Army Museum inclination value also accorded extremely well with Loyang inclination results for the same date. All the Loyang results were of a slightly higher inclination than the results from this study, consistent with the latitude difference of 3.5° between Loyang and Xi'an. The inclination values from this study seem to correspond well with previous results obtained for Xi'an (Wei *et al.*, 1983) but any comparison can only be tentative as the latter results were given without error indications and the secular variation curve drawn by Wei *et al.* was based on a sparse dataset. The inclination trend from the core samples (Fig. 4.3b; Cong & Wei, 1989) also appeared to show a similar pattern to that of the Loyang results, but again scatter in the data and the lack of error estimates made detailed comparisons difficult.

The magnetic direction obtained from Banpo was in agreement with the direction from Jiangzhai of the same period (Wei *et al.*, 1980), with particularly close agreement between the mean inclination values for the two sites. The directions of magnetisation were separated by 8.1° , but as the error in the direction of the Banpo measurement was so great, the two directions could not be distinguished statistically. The possible trend

seen in the Banpo sediments could not be compared with the changes in direction in the marine core as the latter were extremely scattered, making detailed trends hard to discern.

In conclusion, this study provided an initial indication of the suitability of sites in the Xi'an area for archaeomagnetic study, with a view to compiling a calibration curve for the vicinity. In general, the magnetic results compared well with archaeomagnetic results from other regions of China. The two notable exceptions were the discrepancy between the Loyang and Terracotta Army declination values in the 2nd and 3rd century BC and the difference between the trends in declination in both this and the Loyang study, and the direct observations. Although this study revealed no reason to doubt the magnetic direction from the Terracotta Army samples, the Loyang results for this date included 4 features with similar magnetic directions. Without further data it was impossible to establish whether the difference actually represented a rapid change in the declination of the ancient geomagnetic field between 100-200BC. The difference in declination values in this period can only be resolved by studying more features. Both this study and the limited results from Loyang were at variance with the direct observations between AD850-1350, particularly the three earliest observed measurements. The discrepancy might arise from uncertainty in dating the Medieval texts (Smith & Needham, 1967) or from a misunderstanding of the mechanisms of the early Chinese compass. Both the direct and archaeomagnetic measurements are sparse and a further investigation into both is necessary before their validity can be properly assessed.

4.5.6 Suggestions for future work

Having established the suitability of archaeological remains in the Xi'an area for the construction of an archaeomagnetic calibration curve, it is now necessary to implement an extensive sampling program on well-dated sites. Initially it would be advisable to concentrate on specific periods when dated remains are abundant. For example, the four kilns from Yaozhou Yao already provide an indication of secular variation, which might be used for precise dating of a structure already loosely assigned to that period. The most exciting recent development has been the study of the magnetic direction as recorded in sediments (Cong & Wei, 1989). Although suitable sediments are rare, particularly in the Xi'an area, cores of slowly deposited sediments might give a detailed record of the trends in magnetic direction over time. Such studies would advance Chinese archaeomagnetic studies in the same way as the study of lake cores has done in Britain (Section 5.2). One possibility that has yet to be explored is the construction of a continuous record of secular variation from stalagmites (Section 1.4.3), which are common in southern China. With sufficient archaeomagnetic directions obtained from all these sources, work could begin on the construction of a dated secular

variation curve (Chapter 5), which would prove invaluable in the dating of the fired remains which are so prevalent on Chinese archaeological sites. Additionally, archaeomagnetic and mineral magnetic measurements on Chinese fired material would advance the understanding of the process of magnetisation, the magnetic minerals involved and identify which features, parts of features and materials are most suited to archaeomagnetic study.

Chapter 5

The Archaeomagnetic Calibration Curve

5.1 THE PURPOSE OF THE CALIBRATION CURVE

In order to use archaeomagnetic measurements to give an absolute date, the declination and inclination of the stable magnetisation are conventionally compared visually with a calibration curve, which shows the variation of the direction of the geomagnetic field over time for a particular region (Section 1.2 & 2.5.4). Despite early indications to the contrary (Bauer, 1895 & 1899), variations in the geomagnetic field do not follow a simple cycle. This means that the calibration curve must be compiled from direct measurements of the geomagnetic field or indirect measurements provided by archaeomagnetic studies. In Britain, observations of the geomagnetic field have been carried out since AD1576 (Malin & Bullard, 1981) but previous to this, information must come from archaeomagnetic measurements on features that can be dated by other means, such as documentary sources, pottery typology, coins or radiocarbon dating. Inevitably, finding sufficient well-dated material with a stable remanence direction is difficult; hence the construction of a calibration curve has been slow and laborious.

This chapter examines how the British calibration curve has developed, how it is currently represented and the problems that arise in its presentation and use. The methods employed by archaeomagnetists in other parts of the world are assessed. The establishment of a centralised British archaeomagnetic data base is discussed and an investigation is made into new ways of constructing the British curve. As well as its use in archaeomagnetic dating, the calibration curve is compiled from the most detailed, dated information on the ancient geomagnetic field in Britain. Hence, it is of great interest to geomagnetists in their attempts to construct and constrain models of the behaviour of the geomagnetic field over time.

5.2 THE BRITISH ARCHAEOMAGNETIC CALIBRATION CURVE: ITS CONSTRUCTION AND PROBLEMS THAT ARISE IN ITS USE

Cook and Belshé (1958) were the first to present an archaeomagnetic curve, basing it upon measurements made on material from Roman and later Medieval fired structures. This was then followed by ten years of intensive archaeomagnetic studies at the Research Laboratory for Archaeology in Oxford, which culminated in the presentation of an archaeomagnetic curve covering the periods AD50 to AD350 and AD1000 to AD1600 and also including data from a number of prehistoric hearths (Section 1.5; Aitken, 1970). Subsequent measurements have been incorporated in the calibration curve, filling some of the gaps but producing little change in its overall shape. The current British curve was drawn empirically by A.J. Clark (Clark *et al.*, 1988; Fig. 5.1 a & b), through archaeomagnetic measurements from over 250 features, mainly conducted by the Ancient Monuments Laboratory, Newcastle University, Plymouth Polytechnic and the Clark Consultancy, as well as the early work of Aitken (Section 1.5). In order to assess the British calibration curve, the data from which it was constructed were collated into a data base (Section 5.4). These comprised of all the data used by Clark in drawing the curve. The selection criteria are explained fully in Section 5.4.4.

Of the archaeomagnetic measurements used by Clark and in this study, 96% are from fired material and 4% from sediments, with 237 direct observatory measurements being used to define the curve from AD1723 to the present. The small number of results from sediments incorporated in the calibration curve reflects the fact that this is a relatively new area of research and that a number of problems arise in the archaeomagnetic dating of sediments (Chapter 3). Of the fired material sampled, kilns make up 54% and hearths 33% (Fig. 5.2), due to their suitability for archaeomagnetic studies and the frequency with which they occur on British archaeological sites. The data points are distributed unevenly over time (Fig. 5.3), with many more data available from the Roman and Medieval periods and very few data in the Dark Ages and before AD/BC1. This uneven distribution arises from a combination of factors; in some periods fewer features suitable for archaeomagnetic study may have been constructed, the number of occupation sites may have been less, building methods and hence preservation may have been poor, and the lack of material remains may make the archaeological determination of the date of a feature difficult. Excavation procedures may also be a contributing factor; there may be little interest in a particular historical period, and so excavations are not conducted on remains of that date, or the excavator may not require dates for a particular feature and so would not alert the archaeomagnetist to the sampling opportunity.

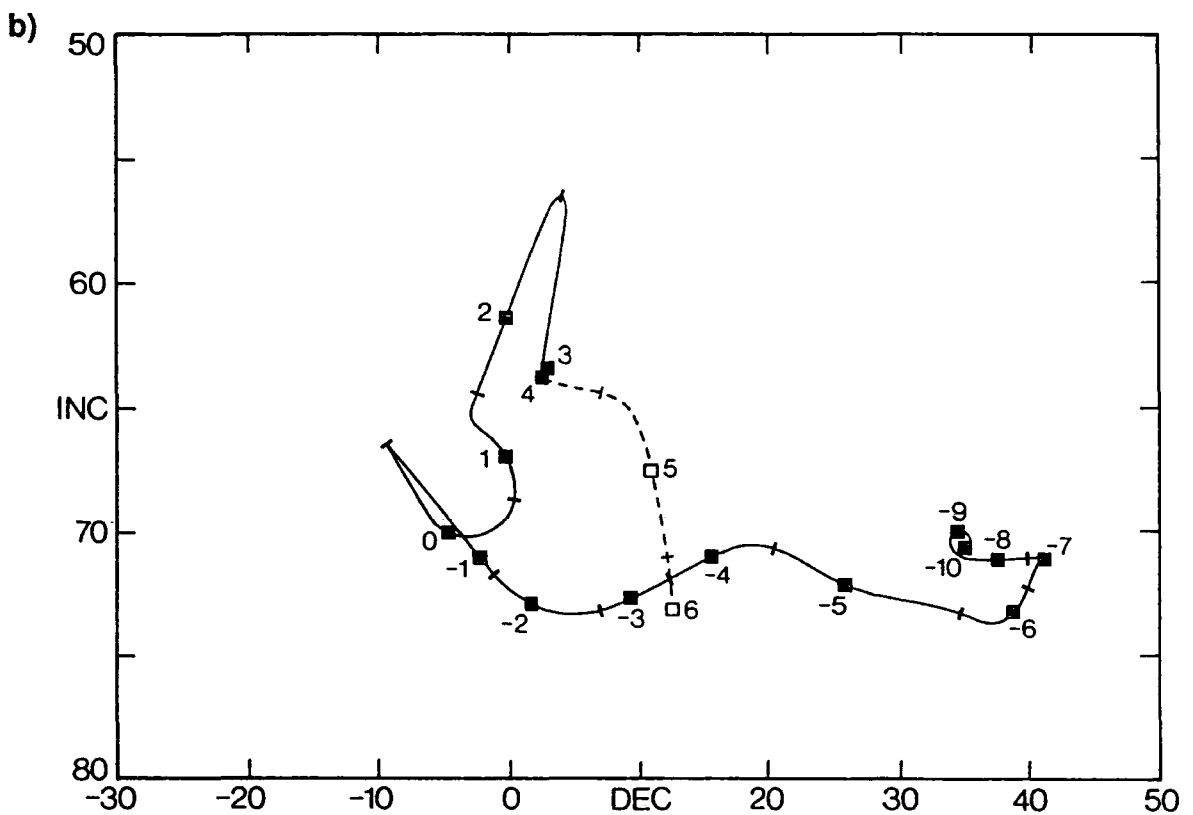
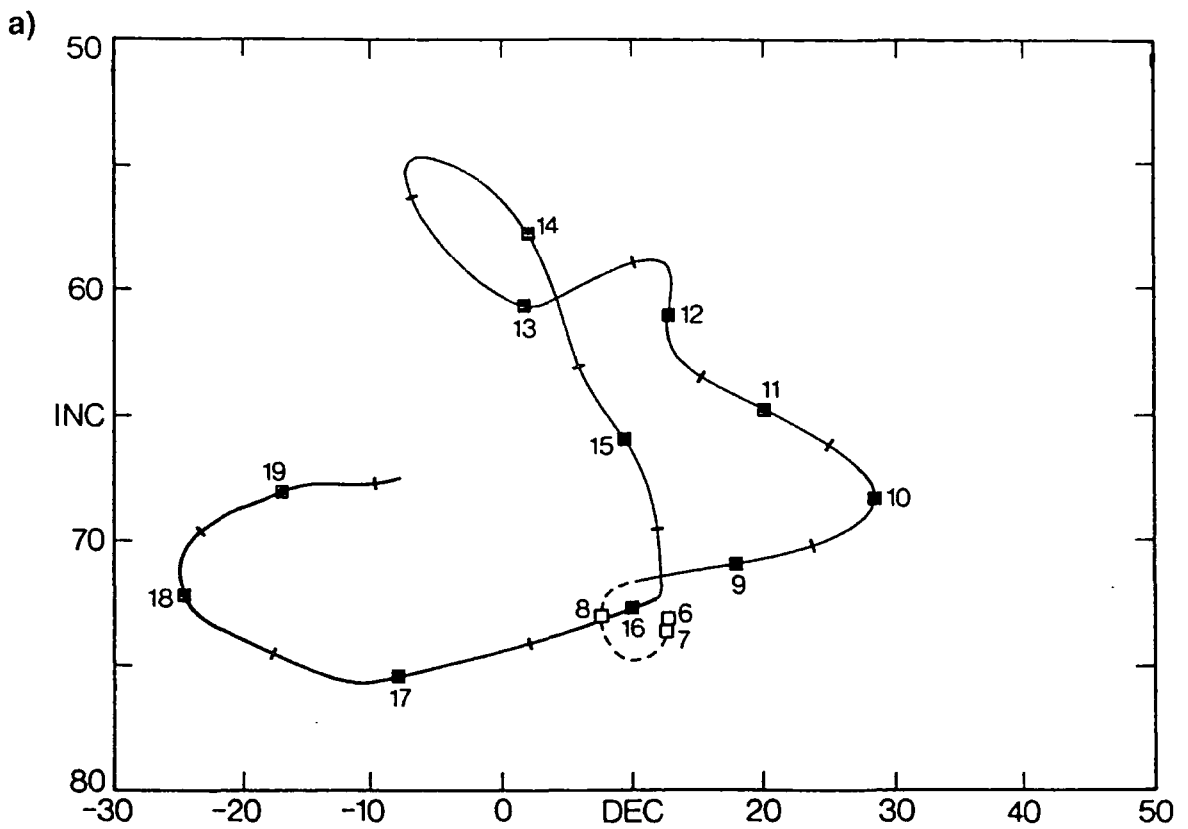


Figure 5.1: The current British archaeomagnetic calibration curve (Clark et al, 1988), normalised to Meriden, showing a) AD600-1975 and b) 1000BC-AD600. Figures are in hundreds of years BC (-) and AD. 0 = BC/AD1. Ticks indicate half-century points. The declination and inclination scales are in degrees.

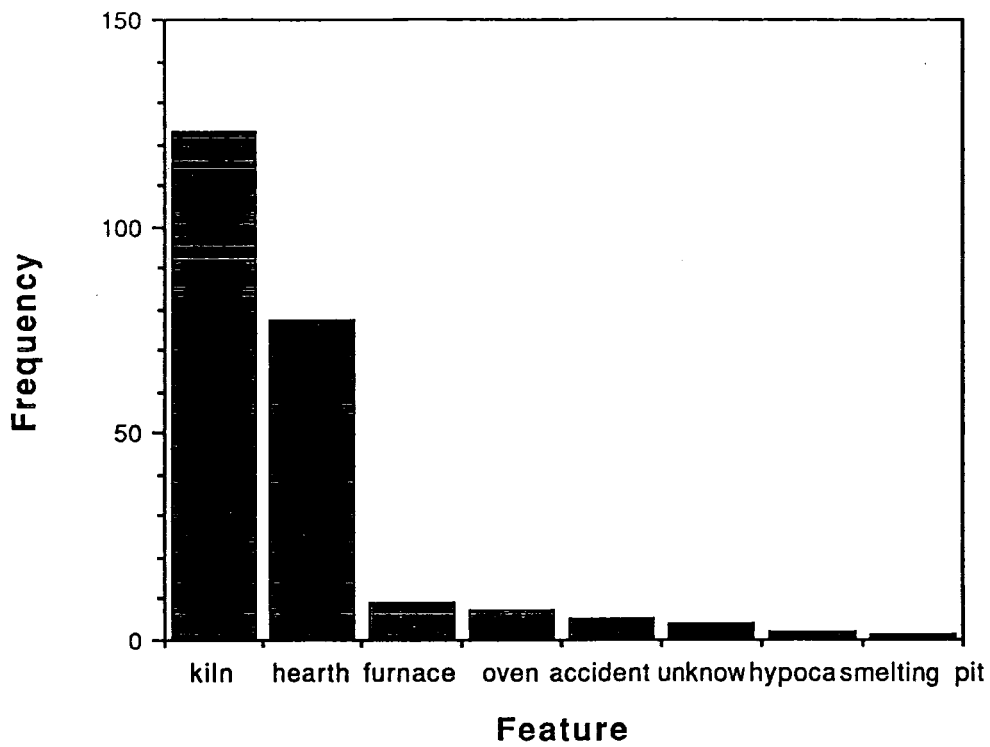


Figure 5.2: Bar chart showing the numbers of different types of fired structures used in the British calibration curve (hypocaust is abbreviated to hypoca).

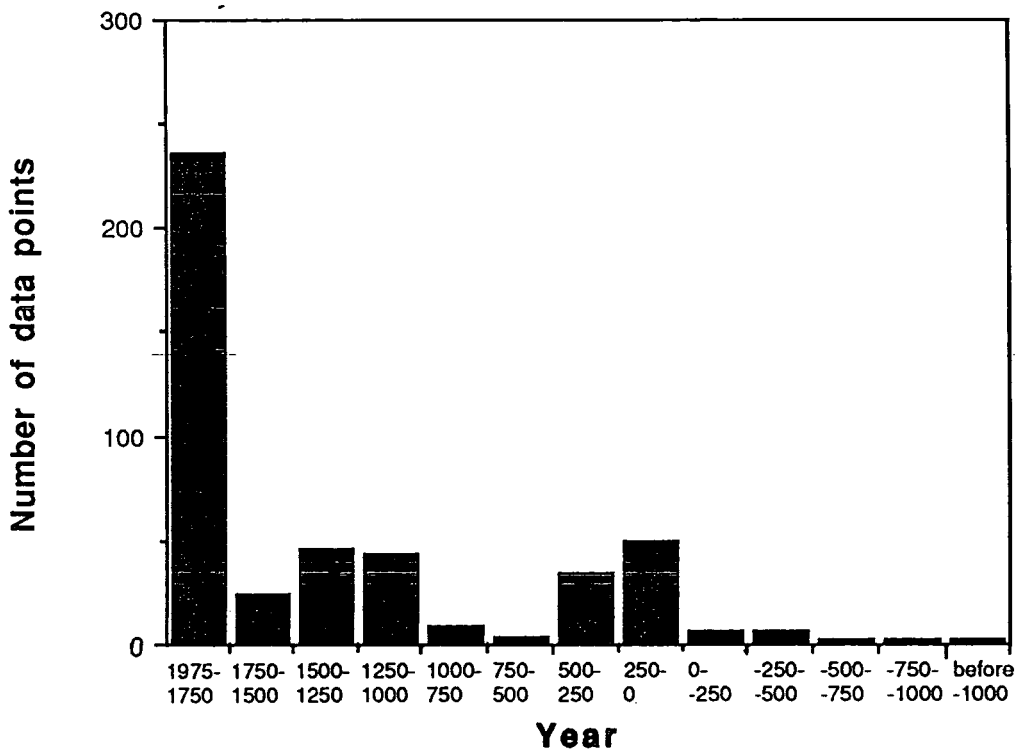


Figure 5.3: Bar chart showing the distribution through time of the archaeological dates of the features used in the British calibration curve. Where the date range covered a wide span, it was assigned to the bar in which the greatest part of its age range fell. - indicates BC

Secular variation records from lake sediments (Section 3.3; Turner & Thompson, 1982) have made a significant contribution to construction of the calibration curve and were not available to earlier workers. The directional measurements themselves cannot be incorporated directly into the calibration curve, as their absolute values of declination are uncertain (Section 3.3). However, they provide a continuous record and have been used by Clark *et al.* (1988) to indicate the general trends of secular variation, particularly in the pre-Roman period.

At present, the British calibration curve is represented as a plot of declination vs. inclination, with time given as marks along the curve (Fig. 5.1). The curve itself consists of a line drawn freehand through the available dated archaeomagnetic points, giving intuitive weight to those deemed to be more reliable. In periods where there are insufficient archaeomagnetic data, such as the Dark Ages, considerable interpolation is required; whereas for other periods, such as that delineated by observatory measurements, the curve virtually 'draws itself'. Dates for a magnetic direction of unknown date are obtained by a visual comparison of the mean magnetic direction, with its error at α_{95} , with the calibration curve (Section 2.5.4), as carried out in Chapter 3 (e.g. Section 3.4.1). No representation is made of errors in the determination of the date or the direction of magnetisation of the points used in the construction of the calibration curve.

Despite its universal use by British archaeomagnetists, there are a number of serious problems with the current representation of the calibration curve:

Lack of error representation. One of the most fundamental problems is that the curve does not include uncertainties in declination, inclination or archaeological date. Drawing the curve as a continuous, thin line of uniform thickness implies, to the uninitiated, considerable precision in the values it represents. For example, it is unclear from studying the curve alone whether the tight loop in the Roman period is really a distinct loop or simply a band of points with overlapping errors.

Lack of representation of individual points. No representation is made of the density of data points used in constructing the curve. For some periods, for example between 0 and AD250 there are over 50 points, whereas between AD500 and AD750 there are only 4, making any interpolation very tentative. The density of points along the curve depends on both the speed of change of the geomagnetic field and the number of sites sampled in a particular archaeological period. The latter may, in turn, depend on the rate of cultural development and the number of excavations of sites of that age, as discussed above.

Fitting of the curve itself by hand. Dr. Clark brings to his drawing of the curve considerable detailed knowledge of individual archaeomagnetic measurements and their archaeological contexts and can use this information to guide his drawing. However, as the available data set increases, it becomes impossible for one person to retain familiarity with information about all the points. Hence, it becomes essential that, if a line is to be fitted to the points at all, this must be done by objective, mathematical and statistical methods which can empirically weight the data according to their reliability and give a reproducible calibration curve.

Self-reinforcement of the existing curve. When the archaeomagnetic curve is presented as such a convincing line, it encourages a tendency to accept as 'correct' all mean archaeomagnetic directions that fall on the curve. Those not falling on the curve are either rejected or an attempt is made to move them onto the curve by postulating slumping or subsidence of the material sampled, even if this was not evident in the field. Hence the calibration curve is reinforced by only accepting and building it from data that fit the existing curve.

Fitting a magnetic direction of unknown date to the curve. At present magnetic directions of unknown date are fitted to the curve by eye, usually using α_{95} as an indication of the error, a problem which is discussed in Section 5.6.4.

It is clear that, with sufficient measurements of the direction of magnetisation from well-dated features, the archaeomagnetic calibration curve will, to some extent, 'draw itself' (Clark, 1980) as it already does in the last 200 years. However, there will always be uncertainty in the direction of magnetisation and the archaeological date; for some periods it may simply not be possible to obtain enough data. Improvements in techniques of isolating the stable component of magnetisation, sample measurement and the refinement of archaeological chronologies will increase the quality of the data in the curve (Tarling, 1983 p154) but uncertainties will inevitably remain. If archaeomagnetism is to retain credibility as a viable dating technique, it must provide a sound scientific and mathematical basis for the dates and error margins it gives the archaeologist and some changes to current practice may be necessary. It is also essential for a general consensus to be reached amongst archaeomagnetists as to the form of the calibration curve; disagreements might lead to different laboratories providing different dates for the same magnetic direction. To be of maximum use to archaeomagnetists and geomagnetists, the curve must be updated with recent measurements, extended back in time, and constructed and presented in a more rigorous manner.

5.3 HOW CALIBRATION CURVES FOR OTHER REGIONS ARE CURRENTLY DRAWN

Archaeomagnetic dating may be the only method with the potential to provide dates for certain periods or in certain parts of the world and so there has been considerable international interest in the technique (Section 1.6). Calibration curves are now being constructed for many geographical regions. In studying the British calibration curve, it is interesting to compare and contrast the various methods of construction and presentation of similar information, adopted by archaeomagnetists in different countries.

The first issue is to decide which quantities should be included in the calibration curve or curves. Kovacheva (1980 & 1991) argues strongly for the measurement of all three geomagnetic parameters; declination, inclination and intensity; and has presented curves covering most of the last 8000 years for the three quantities in Bulgaria. The Egyptian archaeomagnetic curve (Hussain, 1983) is also presented in terms of declination, inclination and intensity against time. However, in most cases directional archaeomagnetic data alone are presented, reflecting the difficulty of making accurate intensity measurements and the specialised equipment required to produce them. When directional data are sparse and distributed over a long period of time, they are most clearly represented as separate plots of declination vs. time and inclination vs. time. This representation has the advantage that uncertainties in both the determination of the magnetic direction and in the archaeological date can be clearly represented, for example in the calibration curve for the last 2000 years for Hungary (Márton, 1991). Another advantage is that data consisting of inclination measurements only, for example from glazed pottery (Section 1.2.2) can be included. However, undated points cannot be used and for this reason declination vs. inclination is often preferred (Clark *et al.*, 1988).

When sufficient archaeomagnetic data points have been collected to define a systematic variation in the geomagnetic field over time, this trend is commonly emphasised by drawing a continuous line through the points. In many cases, the position of this line is decided visually and it is drawn by hand, as with the archaeomagnetic record for Iran covering 2500BC to 2000BC (Kawai *et al.*, 1972) and the record for Egypt for the last 6000 years (Hussain, 1983). In some instances the archaeomagnetic data do not appear to be sufficient to justify the trends derived from them; in the early work in the USSR (Burlatskaya, 1983), China (Wei *et al.*, 1983 and Section 4.3) and Morocco (Kovacheva, 1984) large swings in the secular variation record were defined on a single point and, on some occasions, no error bars were presented. Similar visual curve fitting has been applied to plots of virtual geomagnetic poles (VGPs) (e.g. Barbetti and Hein's VGP curves for Thailand (1989)) but these also rarely included any error estimates or weighting of points. One exception was the VGP plot of archaeomagnetic

results from Italy (Evans & Mareschal, 1989) where pole positions were plotted with α_{63} values and joined by straight lines. Different symbols were used to represent the precision with which a feature was independently dated and, although the plot was not immediately easy to interpret, it did provide a good indication of the scatter of the data without imposing preconceived ideas of the expected trends onto the data.

The most systematic approach to curve drawing in Europe has been taken by Kovacheva who has compiled an archaeomagnetic curve for most of the last 8000 years in Bulgaria (Kovacheva, 1980 & 1986; Kovacheva & Zagniy, 1985). She obtained sufficient data to present the results as values of declination, inclination and intensity, averaged over 100 year intervals, weighting the data according to the number of samples from each site. The information was plotted as averaged declination, inclination and intensity against time. However, this approach did not take into account uncertainties in the independent archaeological dating of the magnetic directions which are particularly prevalent in prehistory, when the archaeomagnetist must rely on radiocarbon dating. Kovacheva acknowledged the need for a mathematical solution to the problem which would incorporate both experimental error and dating uncertainties (Kovacheva, 1986).

Palaeomagnetists are faced with a similar problem when fitting apparent polar wander paths to palaeomagnetic data (Thompson & Clark, 1981). With sparse data sets these had been fitted by hand, as in archaeomagnetism. However, as more data became available, smoothing techniques were employed or the data were broken into time intervals within which a mean direction was computed using Fisher statistics and the means summed over successive or overlapping periods of time. Thompson and Clark (1981) suggested fitting a cubic spline to data weighted by palaeomagnetic precision measurements, to obtain an apparent polar wander path of vector means with 95% confidence limits. Such techniques have been used on archaeomagnetic data (Wolfman, 1990a), but still did not provide a method of accounting for dating uncertainty and tended to emphasise the importance of the sequence of magnetic directions, at the expense of independent dating of features.

The foundations to the most recent approaches to curve drawing through archaeomagnetic data were laid in 1970 by Burlatskaya *et al.* They used two different methods of data treatment on inclination and intensity measurements from the Ukraine, Moscow and the Caucasus in order to allow a curve to be drawn through the dispersed data. The first method calculated a weighted running mean for the data falling in a 100 year interval. Each data point was weighted by the fraction of its archaeological time span falling within the chosen 100 year bracket. The process was repeated every 50 years. The data were also weighted according to the measurement technique by which they were obtained. The second method involved the calculation of a similarly weighted

running mode for each 100 year interval. Curves were then fitted through the weighted points by hand. Both methods gave similar curves, but involved considerable smoothing of the data.

Sternberg (1982) proposed a moving window approach to the averaging of archaeomagnetic data, similar to that of Burlatskaya *et al.* (1970) and Kovacheva (1980). In this approach all the data falling in a window of time were averaged together using Fisher statistics. The window was then moved on through a fixed interval and the average of the data in the new window was computed. The result was an evenly spaced series of discrete points with Fisher estimates of their precision. The method was modified (Sternberg & McGuire, 1990a; Sternberg, 1989b) to account for uncertainties in archaeological date and magnetic direction. This technique has been applied to data from the southwest of the United States from the Dolores program, covering AD620-920 (Section 1.6; Eighmy *et al.*, 1990) and AD700-1450 (Section 1.6; Sternberg & McGuire, 1990b) and is discussed in detail below (Section 5.6.3), in relation to smoothing the British archaeomagnetic dataset.

5.4 THE IMPORTANCE OF AN ARCHAEOMAGNETIC DATA BASE AND ITS SUGGESTED FORM

5.4.1 *The need for an archaeomagnetic data base*

A data base is probably best described by Elbra (1982) as "a collection of interrelated data stored together without harmful or unnecessary redundancy to serve multiple applications. The storage of data is done so as to achieve independence from the programs that use the data, and the structure of the data allows for future application development." The aim of this part of the research was to produce a data base fulfilling these criteria for the British archaeomagnetic dataset.

In order to produce an archaeomagnetic reference curve, large numbers of archaeomagnetic measurements must be compiled and as more of these data become available, the need for systematic storage of them becomes increasingly apparent. This need was acknowledged by the I.A.G.A. (International Association of Geomagnetism and Aeronomy) working groups on Palaeomagnetism and Rock Magnetism who, in Vancouver in August 1987, passed a resolution supporting the compilation of global and regional palaeomagnetic and archaeomagnetic data bases. Subsequently, there has been considerable discussion of the issue in the academic community. This section discusses the advantages of a computerised data base and how the information is best selected and stored. It also describes the data base established during this work, containing British

archaeomagnetic data, which was used in this investigation of the calibration curve (Section 5.6).

There are many advantages to be gained from storage of archaeomagnetic data in a central, computerised data base and these are summarised below.

Availability of information. The primary advantage would be the accessibility of archaeomagnetic data to all workers in the discipline. Many groups working in British archaeomagnetism have constructed data bases of their own but, because they are held in separate institutions and often in incompatible formats, sharing information between them is difficult. If archaeomagnetic data were to be widely available, in a convenient form, critical examination of the data themselves and the calibration curve would be encouraged. The data base would also be of interest those of other disciplines, as mentioned previously (Section 1.3).

Compactness. A central, computerised data base would reduce the need for the voluminous paper files currently used to store information.

Speed. Retrieval of data from a computer is much faster and more accurate than from paper files. This would be particularly useful for *ad hoc* enquiries, enabling them to be performed in a matter of seconds.

Currency. A computerised data base could be regularly updated and the updates would replace outdated information, thus always providing accurate, current information on demand. This property would be particularly useful when revising archaeological dates of features in the light of later excavations, new interpretations of a site or newly available dates from other techniques.

Centralisation of control. This would mean that information was controlled in a systematic way, enabling standards to be enforced on contributions to the data base. Thus, all archaeomagnetic results would follow a standard format, making data exchange simpler and ensuring a uniformly high standard of information. Integrity checks could be made on any additions to the data base and on the data's internal consistency, thus reducing errors. Security restrictions could also be implemented on a centrally controlled data base, so that the information contained could be accessible to all; but those allowed to add or alter data could be restricted, protecting the data themselves from accidental or deliberate tampering.

Data independence. Data could be stored and manipulated completely independently of the applications to which they are put, so that particular views of those collecting the data (for example, whether a particular magnetic direction is anomalous) would not be reflected in the data themselves. Data independence would also enable changes to be made to data organisation or storage, without affecting what the user perceives through the applications programs.

5.4.2 *The requirements of an archaeomagnetic data base*

Having made the case for the establishment of an archaeomagnetic data base, it is important to consider the use that would be made of such a system before investigating the available software and hardware. The primary requirement is for the data to be in a convenient form, preferably using widely available software, so that as many groups of workers as possible can use the information with a minimum of difficulty. There must be a simple procedure for the entering of data, preferably using screen based forms, which reduces to a minimum the entering of duplicate information and allows integrity checks to be made on incoming data. Procedures to question and extract information from the data base must be simple. Output would need to be on screen, paper and as numerical files on all standard formats of disc, so that the data could be directly read into graphical display or mathematical modelling programs. A data base for Britain would need to hold upwards of 3000 records, containing both numeric and alphabetic information and each record must contain sufficient information for most likely applications to be possible without recourse to paper records. It must also be possible to expand the data base to include both new data and new fields of information, as interests in the subject diversify. If the data base is to be extended to cover European or even world-wide information, it would also be necessary to consider the language used, differences in archaeomagnetic procedures and a suitable format for international use.

5.4.3 *The choice of data base software*

Data base management systems were first developed for commercial use in 1960's (Smith D., 1990), primarily as record management systems. Since then the trend has been towards increased abstraction; through more sophisticated record management, including data validation and concurrent access in the 1970's, to set-based interactive structures in the 1980's. These developments have been accompanied by changes in mainframe, mini and micro computing hardware and are comprehensively reviewed in Elbra (1982). A number of data base models have developed, which are distinguished mainly by the forms of data storage they employ. Chiefly, these are the hierarchical, network and relational models (Date, 1986 p20-21). Of these, the relational model is the most recent and has a number of features which recommend it for an archaeomagnetic

data base. Of particular interest was the ease with which *ad hoc* enquiries could be made and the flexibility available for reorganising the data base at a later stage, to meet changes in the requirements of the users without affecting the user interface.

The theory of relational data bases was developed by Codd (1970) and is based on mathematical set theory. The underlying theory can be summarised in two simple principles (Denmead & Irvine, 1990):

- 1) Stored items are perceived by the user as being arranged into tables which resemble conventional files and are 'flat', that is the intersection of a table row and column is a single value, not another table. Tables are known as relations, each record (row) in a relation is called a tuple and the columns of the table are termed attributes.
- 2) Data are manipulated within tables by relational operators which generate new tables from old. The relational operators are those familiar from set theory, such as union or intersection of tables. The concept that the manipulation of a relation or a group of relations is another relation is known as 'relational closure' and is fundamental to this type of data base structure.

Relational data bases have a number of advantages. The design of tables can be simple and economical in the disk space required, aiding a systematic approach to data base design. Because manipulation of data is not dependent on an understanding of the data base organisation, the data base looks simple to the user, encouraging use, and the underlying structures can be changed and expanded to contain new tables without affecting the user's perceptions. Relations between tables are based on matching attributes and so redundancy in data input is kept to a minimum.

The relational data base management system selected for this work was INGRES (INteractive GRaphics and RETreival System) developed by RTI (Relational Technology International). INGRES is one of the three most widely used relational data bases, the others being ORACLE and DB2. INGRES is available in many forms for hardware from mainframe to microcomputer and can run under a number of operating systems. For this application INGRES Version 6.0 was used on a SUN workstation under a UNIX operating system.

The basic structure of INGRES is shown in Fig. 5.4. The user programs instructions into the 'front end' using a forms-based approach or a programming language. INGRES offers a number of modules of set forms to perform tasks such as creation, modification or deletion of tables; the entry of new data and their storage in

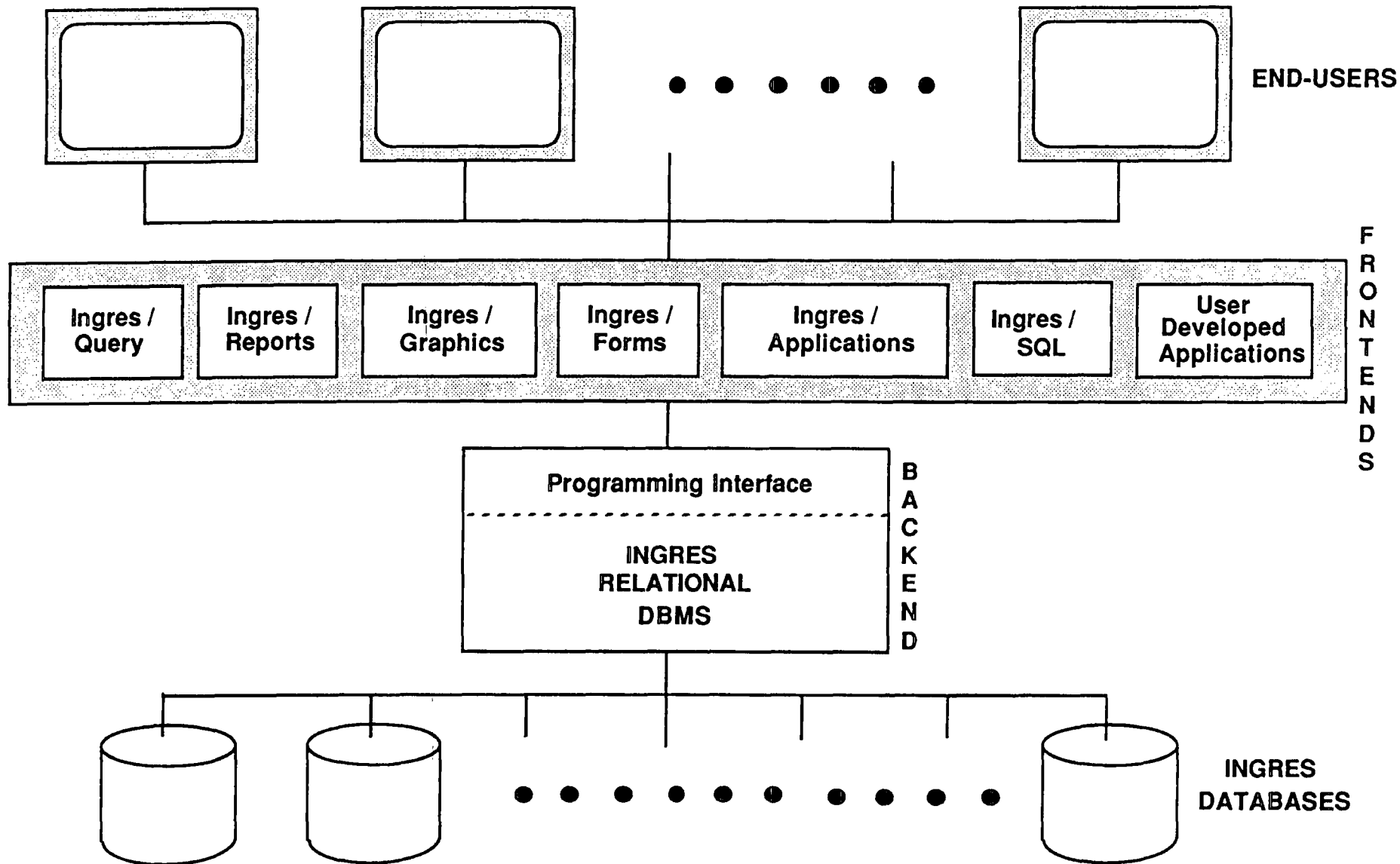


Figure 5.4: The basic structure of the INGRES relational database management system (from Denmead & Irvine, 1990).

data base tables; modification or deletion of existing stored data; and the retrieval of stored data and their display in a variety of formats. It is also possible to perform these and other operations using SQL (Structured Query Language). This formal procedural language was developed by I.B.M. in the mid-1970's and is now accepted as the international standard, supported by most mainframe data base management systems (Date, 1987 p16). SQL is more flexible than simple forms-based approaches, particularly if the data base structure is complex. SQL can be embedded into programs written in conventional programming languages (Date, 1986 p189-206). Experimental implementations have also been made of the use of 'bounded natural language' for making queries (e.g. Wallace, 1984) but this proved verbose and required an extensive dialogue to clarify instructions. A programming interface at the 'back end' translates SQL or forms-based queries into a form appropriate to the physical storage organisation. The data are stored in a much more complex way than the simple user-perceived tables. INGRES also performs a number of 'housekeeping' tasks, such as protecting the data from systems crashes and defining access controls.

The INGRES relational database described above was chosen in this study because it fulfilled the requirements outlined in Section 5.4.2, and was widely used and well supported at Durham University. A number of other software packages, such as dBase or Excel, might also have been capable of performing the same tasks. The crucial requirement was for data to be easily transferable between packages, to enable as wide a use as possible.

5.4.4 The construction of the archaeomagnetic data base and the selection of data

Most users of the archaeomagnetic data base will only be interested in a subset of the data, for example archaeomagnetic results for a particular geographical region or a particular period. However, the more fields of data available, the more diverse the applications possible. A desire to include as many fields of data as possible must be balanced against the time taken to enter large quantities of data which may rarely be used. The object of this part of the research was to construct a data base suitable for British directional archaeomagnetic data, to find the advantages and restrictions of the data base over paper records and to use information from it to investigate the archaeomagnetic calibration curve. It was not intended to collect all the currently available archaeomagnetic data, since this would be an enormous and time consuming task, but rather to collate the data represented in the current archaeomagnetic calibration curve (Clark *et al.*, 1988) and to investigate different ways of representing the same information.

The tables constructed (Fig. 5.5) contained the basic information needed for most archaeomagnetic purposes, but could easily be expanded to include more information. They were designed to give the minimum duplication of input information, for example the site latitude and longitude only needed to be entered once for each site. All the data were recorded in their most basic form, for example declination and inclination values were not corrected to a central location (Section 5.5), so no preconceived ideas were forced upon the data. The problems caused by not following this course of action have previously been illustrated by the publication by early archaeomagnetists (e.g. Aitken *et al.*, 1963; Aitken & Hawley, 1966 & 1967) of inclination values corrected to London using a model of an axial dipole field (Section 5.5). Others wishing to use these data have subsequently had to reverse the calculation. It would be simple to provide users of the data base with routines to perform such tasks as correction to a central location or VGP calculations.

The fields chosen for the tables were as follows:

Main Table

- Sitename:* This linked the table 'main' with table 'site information'.
- Code:* Some archaeomagnetists, for example Clark Consultancy or the Ancient Monuments Laboratory, give a code to each of the features sampled, which could be used in tracing a set of samples, if further information is required.
- Feature:* This field contained information on the type of feature sampled e.g. kiln, hearth. Owing to the variation in terminology, a thesaurus of acceptable terms was provided so that the same word was always used when the same type of structure was referred to.
- Acquisition:* In this field a letter was given which denoted the probable mode of acquisition of the primary remanence (DRM (D), TRM (T), CRM (C), Observatory data (O) or unknown (U)). The data base user might wish to treat different forms of acquisition in different ways, for example to investigate the evidence for systematic shallowing of inclination in detrital remanent magnetisations.
- Declination & Inclination:* The values entered were those considered by the laboratory involved to be the best representation of the ancient field, usually the values after partial demagnetisation. If only one of the quantities was available it could still be entered.
- Alpha95:* As the most widely used measure of precision of mean magnetic direction, α_{95} was considered to be the most useful indication of error in the magnetic vector.

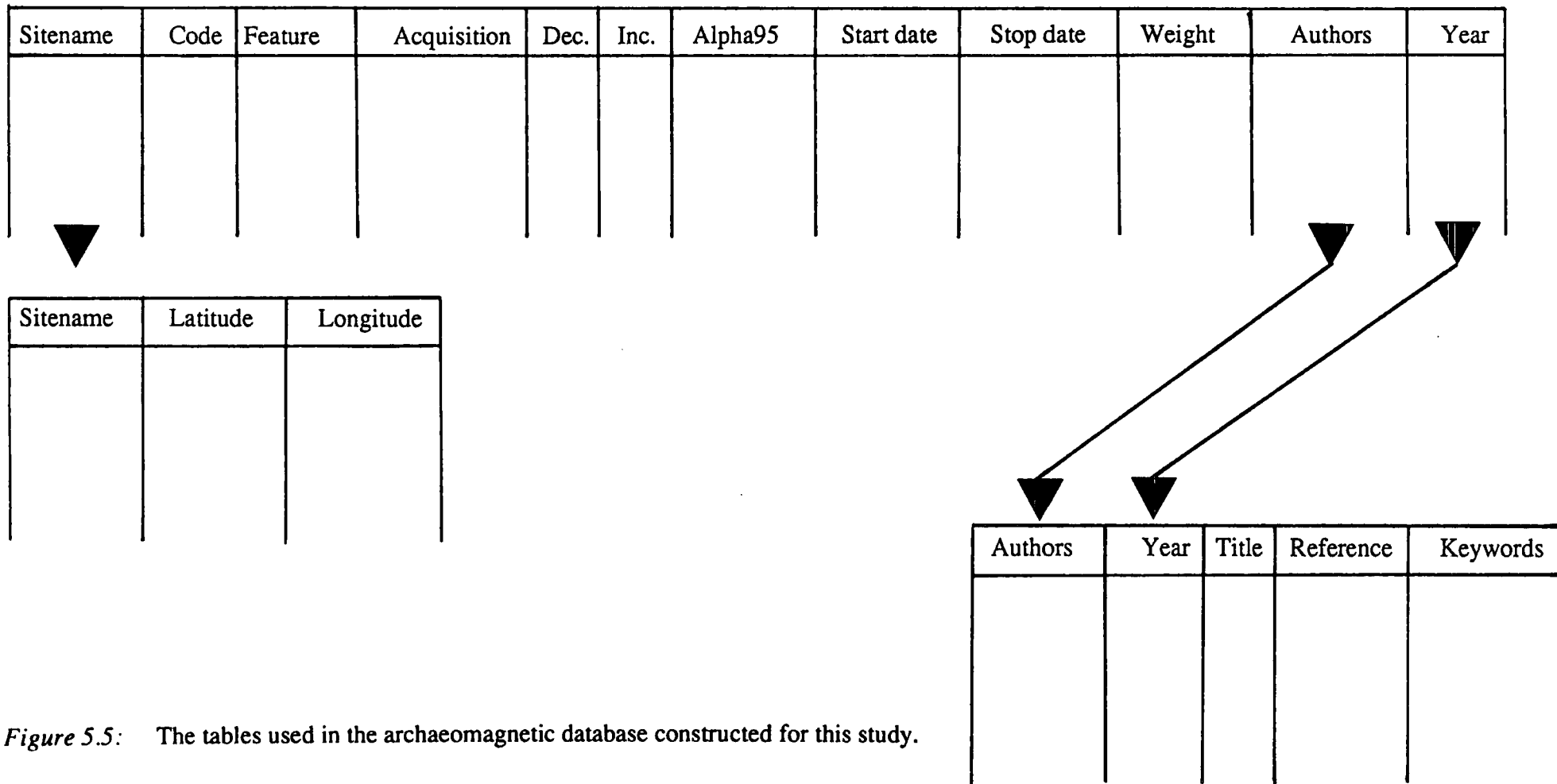


Figure 5.5: The tables used in the archaeomagnetic database constructed for this study.

Start date & Stop date: Representing time in a data base format presents a number of problems (Smith D., 1990). Whilst physical time is perceived as discrete intervals on a linear scale, archaeological time is often imprecise, probabilistic and sometimes only expressible as a range. For example, distinction must be made between "2nd to 3rd Century BC", "late 1st Century AD", "post AD1066", "probably Roman", "possibly Saxon" or "almost certainly Medieval". It would be possible to introduce a coding approach which would map dating expressions onto a numerical date, taking into account the degree of confidence. However, in this trial data base, the date was simply entered as an upper and lower numeric value, interpreted from the archaeological information. If uncertainty existed the time intervals were enlarged to include all possible dates.

Weight: Early archaeomagnetists (e.g. Aitken & Hawley, 1966) assigned a subjective estimate of reliability of a directional result, ranging from A (complete confidence) to F (random). In this data base a numeric scale from 1 (comparable to Aitken's E data) to 5 (comparable to Aitken's A data) was used. Clark *et al.* (1988) assigned 5 to 'good' dating points and 4 to the others. Whilst these weights were not considered to be particularly reliable, they were included in the database for completeness.

Author & Year: The last two categories linked with the table 'Bibliography' to enable the original data and site information to be traced.

Site information

Sitename: Correlated with table 'main'.

Latitude & Longitude: These were included so that corrections to a central location could be performed (Section 5.5) and so that sites in a specific area could be selected.

Bibliography

Authors & Year: Correlated with table 'main', giving the authors of the publication of the archaeomagnetic information, or the laboratory where the work was carried out, and the date of publication.

Title & Reference: Title and reference were included to enable the original publication of data to be traced. If the data were unpublished, the address of the laboratory was given.

Keywords: This attribute included a number of keywords from the publication.

All data entry was made using screen-based forms, with integrity checks included to detect typing errors.

The tables described above formed a basic framework for the data base. They could be easily expanded to include further information of interest; such as number of samples, precision parameter, date sampled, which laboratory carried out the measurements, what instrumentation was used, and NRM and pilot demagnetisation information. There is scope for improving the way that weights are attributed to records and to improving the representation of archaeological date. Palaeointensity or susceptibility measurements could also be included but, since they are not collected as frequently as directional measurements, it would seem sensible to initially restrict the data base to directional information.

The data selected for inclusion in the data base used in this thesis were that used by Clark in the most recent British calibration curve (Clark *et al.*, 1988). These were direct observatory measurements (Malin & Bullard, 1981); lake sediment data (Turner & Thompson, 1981 & 1982); archaeomagnetic measurements made over the last 30 years (Cook and Belshé (1958), Aitken and Harold (1959), Aitken and Weaver (1962), Aitken *et al.* (1963), Aitken and Hawley (1966 & 1967), Clark *et al.* (1988)) and unpublished information provided by A.J. Clark (pers. comm.). There are a great deal more data that could be included; stalagmite magnetic data (Section 1.4.3), directional results from columns of sediment (Section 3.3) and many more recent archaeomagnetic measurements from fired and sedimentary archaeological contexts. Not all data are easily available; some resides in theses (e.g. Noel, 1976; Hammo-Yassi, 1984; Gentles, 1989) and still more in unpublished site reports. Given the widespread use of archaeomagnetism as a dating technique, it might be useful to disseminate information as a date list, as is used in thermoluminescence (Ancient TL from the Luminescence Dating Laboratory at Durham University). For future curve drawing exercises it is important to be able to use as many data as possible and for the data to be selected objectively; points which appear anomalous at present may be interpretable in the future. Hence, there appears to be considerable scope for the expansion of the data base.

Copies of this data base are available from the author.

5.4.5 Suggestions for future development of the data base

The data base established here proved invaluable in providing information from which the calibration curve could be constructed and in answering *ad hoc* enquiries, such as the number of data points from a particular time interval, geographical region or type of deposit. This data base, or one constructed to a similar design, would provide a useful,

if not essential, contribution to archaeomagnetism. The data base would clearly require central administrative control, to decide upon the contents, to ensure that it was kept up-to-date, to publicise the data base and make it widely available to users and to encourage archaeomagnetic laboratories to submit their data for inclusion. A data base administrator would need to establish systems to protect the data base from errors made by the user, to back-up and recover data in the event of system failure and to monitor the data base's performance, adjusting it to changing user requirements. The archaeological dates in the data base should also be checked periodically to enable new interpretations of the archaeology, or dates available from other methods, to be used to refine the chronology.

In the longer term it is possible to envisage a data base into which all British archaeomagnetic measurements are entered. This could output directly into a curve drawing program which would modify the calibration curve in the light of new information. If the data base was extended to include European archaeomagnetism, it would be possible to produce a calibration curve from a dataset unrestricted by national boundaries.

5.5 CORRECTING ARCHAEOMAGNETIC DIRECTIONAL MEASUREMENTS FROM GEOGRAPHICALLY SEPARATED LOCATIONS

The work presented in this section has been published previously (Noel & Batt, 1990).

As discussed in Section 1.3, the geomagnetic field not only varies with time, but also varies spatially. Archaeomagnetic studies generally assume that in a restricted 'archaeomagnetic region' the geomagnetic secular variation is sufficiently coherent that it can be represented by a single master curve assigned to a fixed reference site (e.g. Sternberg & McGuire, 1990b; Kovacheva, 1980; Clark *et al.*, 1988). In this case, it is important to consider from what area samples can be taken for use in the master curve or to be dated using the curve, whilst keeping the errors introduced by the spatial variation comparable to those arising from sampling and measurement. Consideration must also be given to geographic corrections which could reduce the spatial variation error. In some cases (e.g. Kovacheva, 1989) it is assumed that the area from which features are sampled is so small that spatial variation in the geomagnetic field can be ignored. However, two methods for correcting geographically separated remanence directions to a fixed central location have been proposed and are described below. In this section their relative precision and the effect of using no correction at all are compared using a numerical model based on the I.G.R.F.

The inclination correction

Early British archaeomagnetic studies (summarised in Aitken, 1970) used a simple remanence correction based on latitude difference to convert the measured vector to a reference site in London (e.g. Aitken & Hawley, 1966). The correction assumes that the geomagnetic field is axial and dipolar. If λ_s and λ_r are the latitudes of sampling and reference sites respectively, then the new inclination, I_r can be derived from the measured inclination value, I_s using the equation:

$$I_r = I_s + \tan^{-1} (2 \tan \lambda_r) - \tan^{-1} (2 \tan \lambda_s)$$

However, as the inclination correction is based on an axial, geocentric dipole model, no account is made of the measured declination, D_s , which is transferred, unmodified to the reference site.

The conversion via pole (CVP) method

In this method the geomagnetic field is modelled by an inclined, geocentric dipole and the remanence direction is converted to the reference site (latitude λ_r longitude ϕ_r) via a virtual magnetic pole. The dipole orientation is determined by D_s and I_s , the measured declination and inclination, and this approach follows well-established procedures in palaeomagnetism (Irving, 1964 p43-45; Tarling, 1983 p111-113).

First the latitude (λ_p) and longitude (ϕ_p) of the virtual pole (Fig. 5.6) are calculated as described by Irving (1964 p43-44):

$$\psi = \cot^{-1} [(\tan I_s) / 2]$$

Thus,

$$\lambda_p = \sin^{-1} (\sin \lambda_s \cos \psi + \cos \lambda_s \sin \psi \cos D_s)$$

and

$$\phi_p = \phi_s + \beta_1 \quad \text{if } \cos \psi \geq \sin \lambda_p \sin \lambda_s$$

or

$$\phi_p = \phi_s + \pi - \beta_1 \quad \text{if } \cos \psi < \sin \lambda_p \sin \lambda_s$$

$$\text{where } \beta_1 = \sin^{-1} (\sin \psi \sin D_s / \cos \lambda_p) \quad (-\pi/2 \leq \beta_1 \leq \pi/2)$$

The positions of the virtual pole, sampling location and reference site define a spherical triangle (Fig. 5.6) from which the corrected values D_r and I_r can be obtained. First the geomagnetic colatitude (c) of the reference site is needed. This is given by:

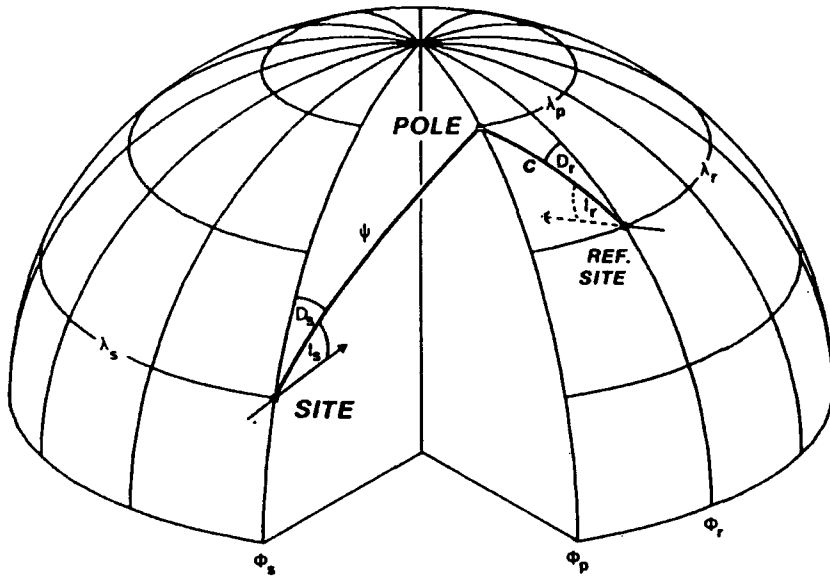


Figure 5.6: The 'Conversion via Pole' method. The geomagnetic field is assumed to arise from an inclined, geocentric dipole with an orientation specified by D_s and I_s . The position of the virtual pole and the coordinates of the sampling and reference sites define a spherical triangle from which the new values, D_r and I_r , can be calculated. λ = latitude, ϕ = longitude. Other symbols are defined in the text.

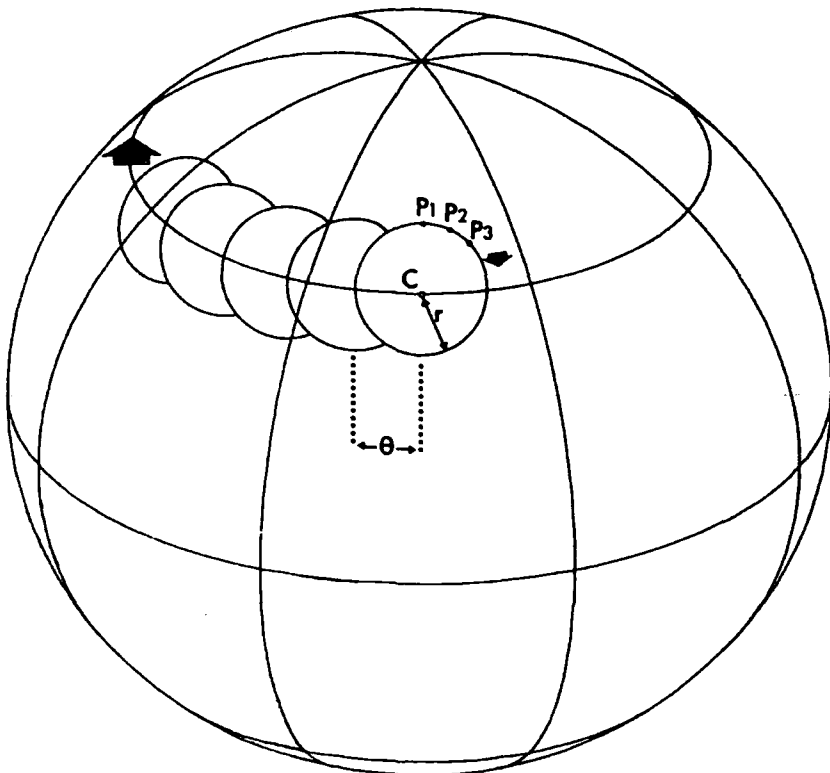


Figure 5.7: Geometry of the numerical method used to evaluate the two methods for relocating remanence directions. P1, P2, P3 etc. are 36 points on the boundary of a circular archaeomagnetic region, radius r , where the direction of the IGRF is calculated and transformed to the centre, C, using the Inclination or CVP correction. A set of angular differences between the IGRF at C and the transformed values are thus obtained and the computation repeated, after longitude shifts of Θ (10°), to yield a mean error.

$$c = \tan^{-1} \{ [\sin \lambda_p \sin \lambda_r + \cos \lambda_p \cos \lambda_r \cos (\phi_p - \phi_r)]^{-2} - 1 \}^{1/2}$$

then

$$I_r = \tan^{-1} (2 / \tan c)$$

and

$$D_r = \sin^{-1} (\sin \beta_2 \cos \lambda_p / \sin c)$$

$$\text{where } \beta_2 = \phi_r - \phi_p + \pi$$

The CVP method was used to normalise the British master curve to Meriden (52.43°N, 1.64°W), the traditional centre of England (Clark *et al.*, 1988).

The effect of no correction, the Inclination and CVP correction schemes were compared using the 1985 IGRF (International Geomagnetic Reference Field) as a convenient working model (Noel & Batt, 1990). Although this representation of the geomagnetic field omits the higher harmonics of the field, in most places these are so small as to change the orientation of the field by less than a few tenths of a degree. An important assumption underlying any conclusions is that the harmonic content of the field has been broadly similar throughout archaeological time.

IGRF vectors were calculated at 36 points around the perimeter of a circular region and relocated to the centre using either the Inclination Correction or the CVP method (the points chosen are shown in Fig. 5.7). The angular differences between the new directions and the IGRF at the central point were then calculated. The area was moved by 10° along the same latitude and the procedure repeated. Finally, the arithmetic mean of all the angular differences from a single latitude was computed. The entire calculation was repeated using areas of increasing radii from 100km to 1400km in 100km steps. Calculating an average over the longitudes reduced the effects of axial asymmetry in the geomagnetic field. As the points considered were at the perimeter of the area, the error would be expected to be at a maximum (unless the area was so large that it completely enclosed anomalies in the geomagnetic field); in the archaeological situation they would be scattered within the area.

Figures 5.8 and 5.9 show the angular errors produced for the Inclination Correction, the CVP correction and no correction at two latitudes; 52.43° N, the latitude of Meriden, and 45° S, where the errors were greatest. In both cases it is clear that the CVP method produced the smallest dispersion of corrected vectors. Taking a region of radius 900km, centred on Meriden (which would encompass the whole of the British Isles), the mean systematic error introduced by the CVP method was 1.2°, similar to typical archaeomagnetic sample orientation and measurement errors (Sections 2.1, 2.2 &

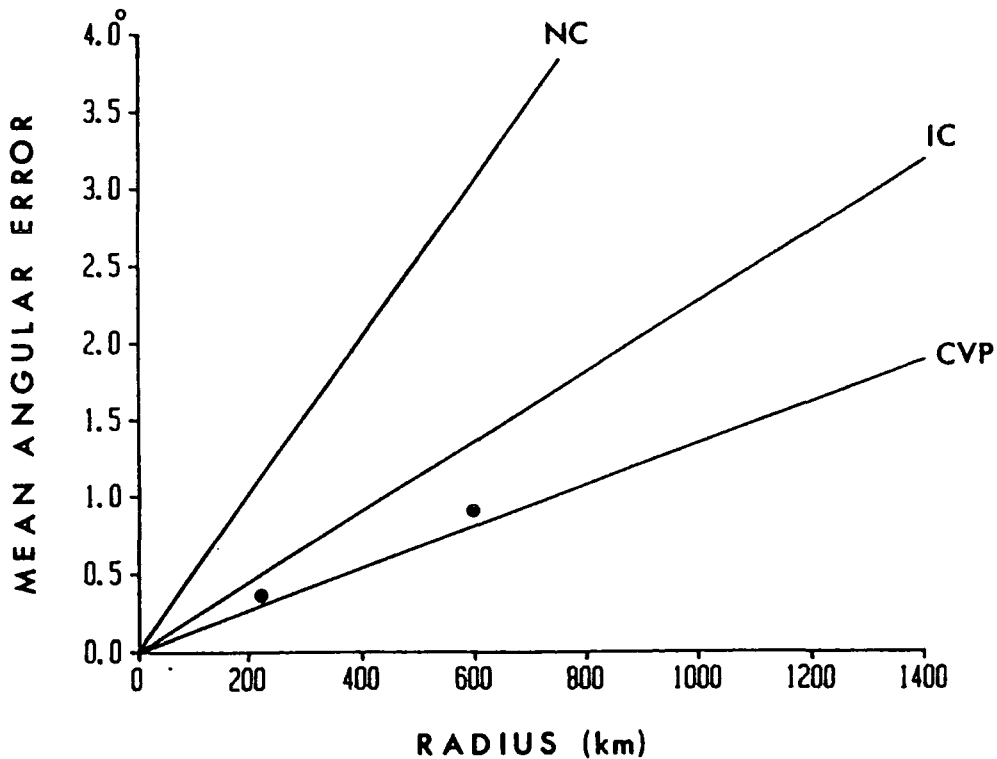


Figure 5.8: Mean angular errors at the centre of an archaeomagnetic region as a function of radius. NC = no correction, IC = inclination correction, CVP = conversion via pole. Calculations are based on IGRF (1985) and circular regions centred on latitude 52.43° . Circles show the results of Tarling (1989 and pers. com.) for two regions centred on Meriden.

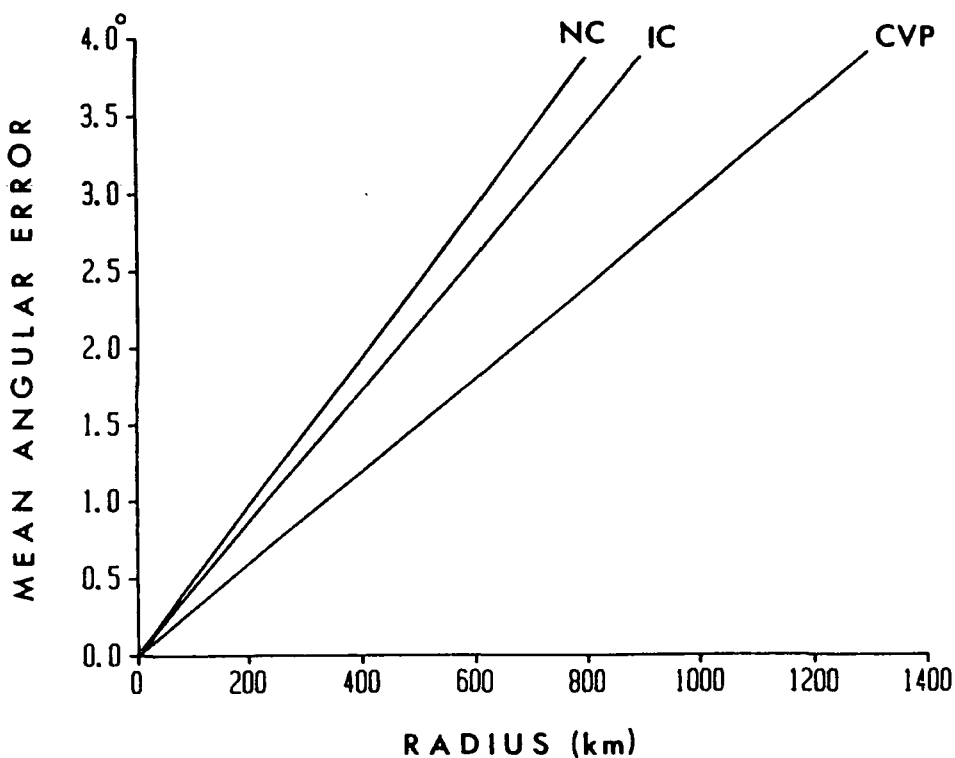


Figure 5.9: As for Fig. 5.8 except these results are for latitude 45°S where the mean errors were found to have their maximum.

2.6). The Inclination Correction method resulted in a mean error of 2.0° and when no correction was applied the error was over 4.5° . These results were similar to a preliminary investigation of the errors in the CVP correction by Tarling (1989), who considered circular areas of radii 220 and 600km, centred on Meriden (Fig. 5.8). Shuey *et al.* (1970) also performed a similar analysis on the CVP and Inclination corrections. They calculated the errors from converting a field direction from one location to another, moving the two sites through different latitude and longitudes, whilst keeping the magnitude and direction of the site separation fixed. They also found CVP to be the most effective conversion method.

This study found that errors in the corrections varied with latitude (Fig 5.10) due to standing asymmetries in the field. The error increased when moving from northerly to southerly latitudes. Low errors were produced near the poles because the circular areas on which the calculation was based overlapped more at very high and low latitudes. However, if the harmonic content of the field has remained broadly similar, it could be anticipated that the maximum error would remain the same in magnitude, even if the anomaly causing it changed in position.

The effectiveness of the CVP correction was clearly demonstrated when it was used to convert the Paris observatory data to London, where it matched the London observatory data extremely well (Fig 5.11). The small jumps in declination and inclination values can be attributed to slight changes of observatory location, within the London and Paris areas, and have not been corrected for.

The results from this study indicated that using the CVP method to convert remanence directions to a reference site will minimise the dispersion of the vectors used in the master curve, thus reducing errors in the archaeomagnetic curve and in the dates derived from it. This study also showed that archaeomagnetic information from throughout the United Kingdom could be corrected to a central location by the CVP method, without introducing a significant error. Hitherto, reference sites have usually been chosen on geographic rather than geophysical criteria (e.g. London, Paris, Meriden). However, such locations are unlikely to correspond to the position of minimum angular dispersion in the relocated vectors, and hence their use may lead to unnecessary errors. It would be possible to use a floating central location, continually repositioned as a national data set is accumulated, to provide an optimum synthesis of the archaeomagnetic curve. If international archaeomagnetic data were contained in a single data base, the data set used to produce the calibration curve could be varied according to the location of the site to be dated, regardless of national boundaries. For example, observatory data from Paris could be used in dating sites in Southern England. The calibration curve could even be located at the sampling site. Ultimately, it may be

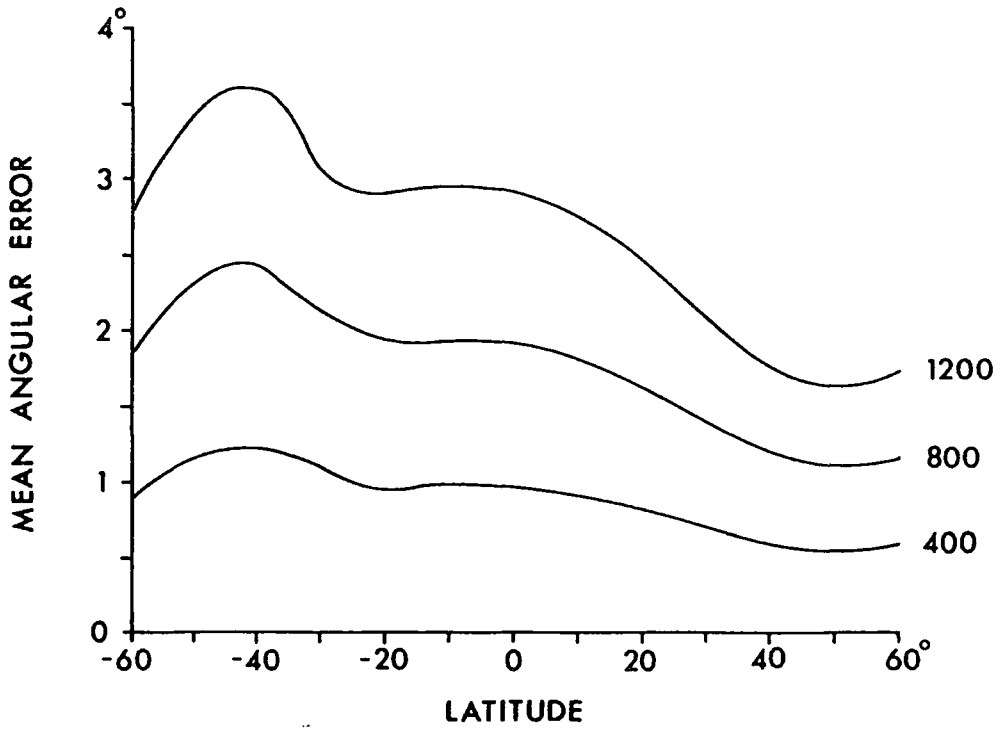


Figure 5.10: Mean angular errors at the centre of archaeomagnetic region as a function of latitude (computed at 10° intervals). These results are for the CVP method using archaeomagnetic areas of radius 400, 800 and 1200km.

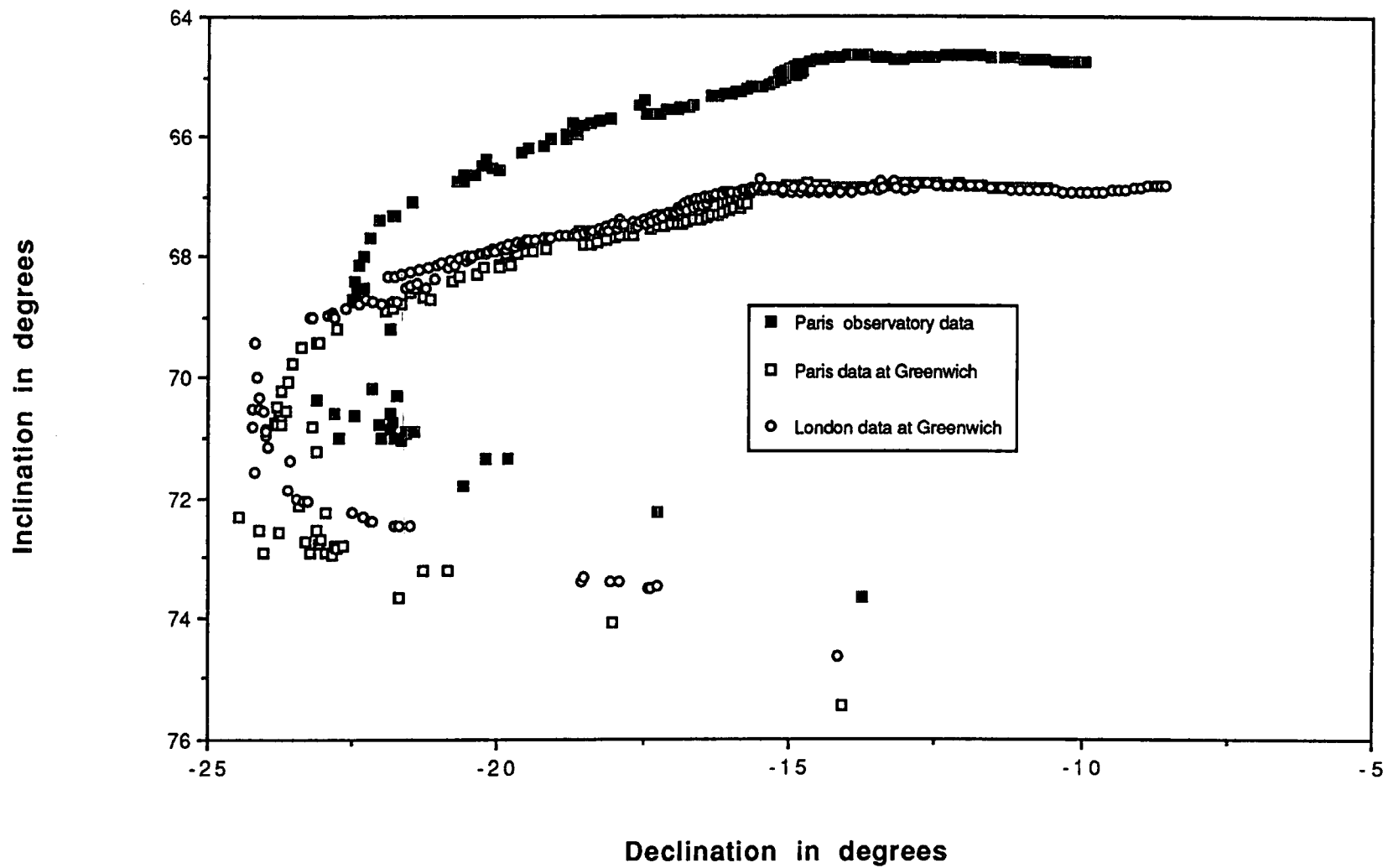


Figure 5.11: Paris observatory data converted using the CVP method to Greenwich and compared with the London observatory data, also corrected to Greenwich by the CVP method.

more convenient to present all archaeomagnetic data as pole positions, rather than correcting to a central location at all, a procedure already followed by Sternberg (1989b), Wolfman (1990a & b) and DuBois (1989). In this approach, instead of representing directions of magnetisation in terms of the directions actually measured, they are presented as the related pole position, assuming that the geomagnetic field is geocentric and dipolar. Such practice would conform to established procedures in palaeomagnetism (Irving, 1964 p69-70).

5.6 REPRESENTING THE BRITISH ARCHAEOMAGNETIC DATA AND DRAWING THE CALIBRATION CURVE

5.6.1 Examination of the raw archaeomagnetic data

Having considered some of the approaches used by archaeomagnetists across the world to represent archaeomagnetic information (Section 5.3) and compiled a data base of British information (Section 5.4), the next stage of development was to explore various ways of deriving a British calibration curve. Section 5.4.4 discussed the criteria for selecting data for inclusion in the data base, but additional strictures were placed upon the data to be used in the calibration curve. Only data from the present to 1000BC were included because, previous to this, archaeomagnetic measurements are sparse and their dating control is poor. In early British archaeomagnetism data were categorised from A (complete confidence) to F (random) (e.g. Aitken & Hawley, 1966) by the archaeomagnetist, as a general indication of the 'reliability' of the result. While all the early measurements were included in the data base for completeness, only A, B and C quality data were considered sufficiently reliable to be used in the calibration curve. The subset of data selected on these criteria all had $\alpha_{95} < 5.5^\circ$. Some workers (e.g. Wolfman, 1990a) reject all data with an α_{95} greater than a certain value. However, imprecise data rejected under this method could be valuable in periods when little other archaeomagnetic information is available.

The first step in this examination of the representation of the British archaeomagnetic data was to plot them in the conventional form used by Clark *et al.* (1988), as declination vs. inclination, corrected to Meriden, without error bars. This information is usually presented as two plots, pre-AD600 and post-AD600. A single plot would be visually confusing; more than two would lead to a deceptively simple representation of secular variation and difficulty in deciding how to assign points with a large age range. AD600 is the best date at which to divide the plots, since there are few data from AD500 to AD700 and division at this date gives a similar number of archaeomagnetic measurements on each plot. The plot of the data obtained (Fig. 5.12a &

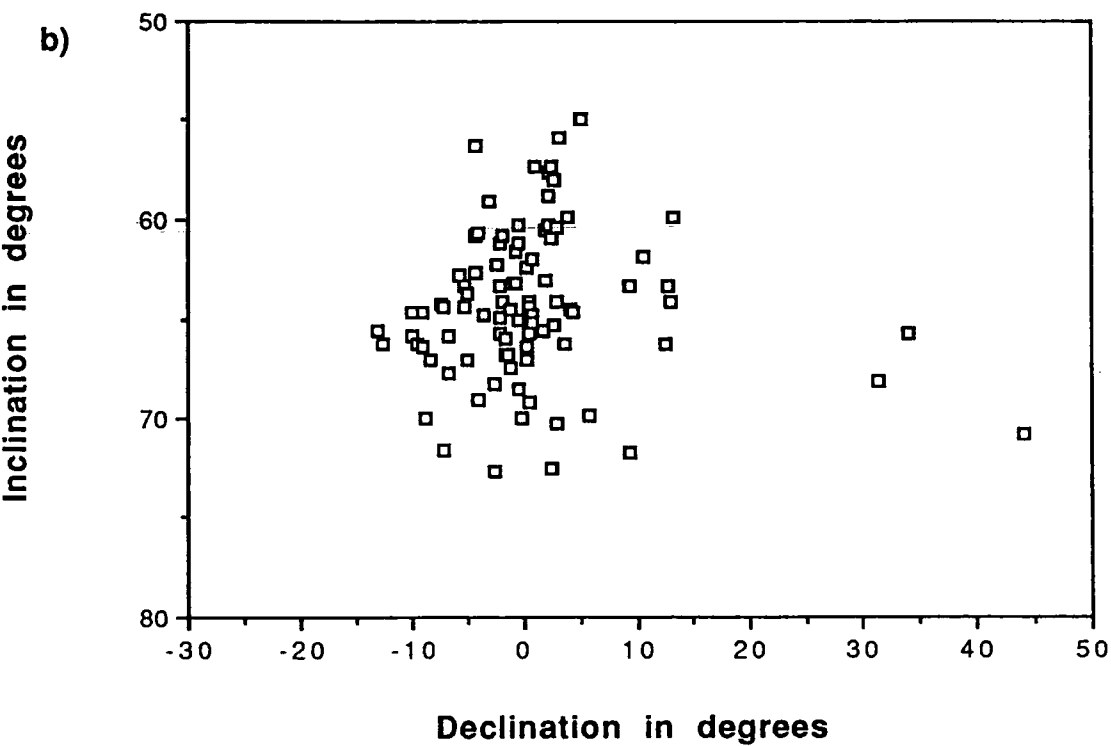
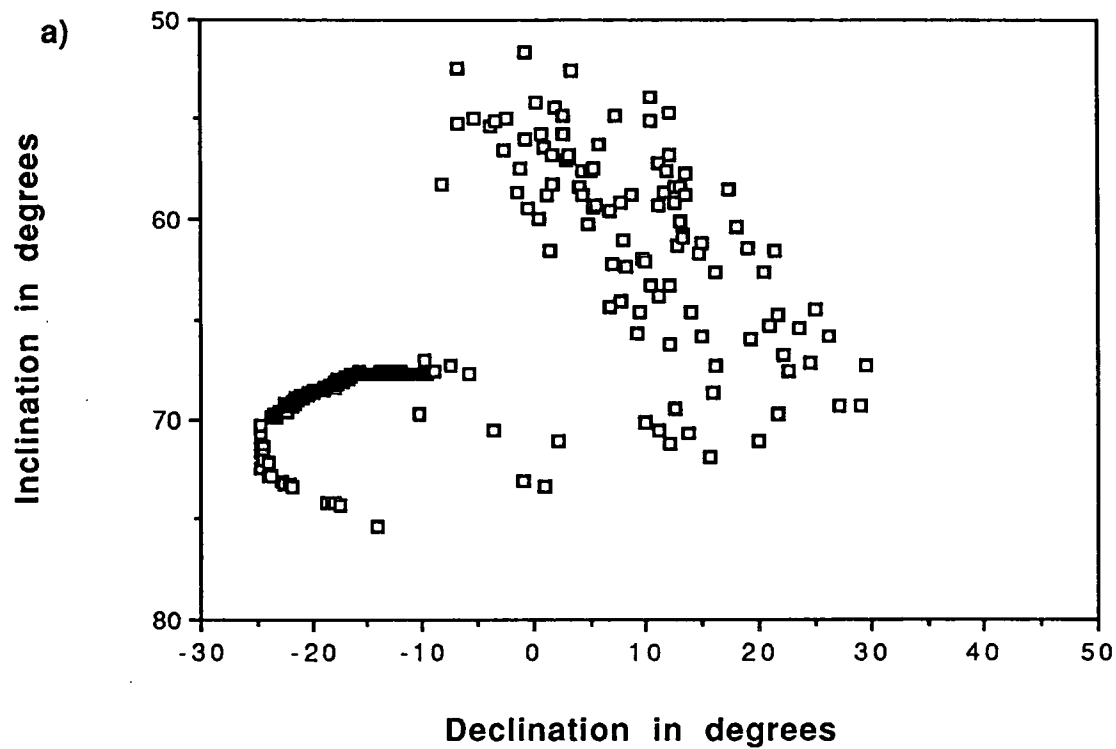


Figure 5.12: The selected British archaeomagnetic data, normalised to Meriden, plotted as declination vs inclination for the period a) AD600-1975 and b) 1000BC-AD600

b) showed similar trends to the accepted calibration curve (Clark *et al.*, 1988). However, information on the dating of points and an indication of the errors in declination and inclination was necessary before a secular variation curve could be constructed. It is interesting to note (Fig 5.12a) the clear movement of the geomagnetic field defined by the numerous direct observatory measurements from 1754, when measurements of declination and inclination at the same time and place commenced. Representing each of the confidence categories with different symbols was considered (as in the study Evans and Mareschal, 1989; Section 5.3), but this approach was visually confusing and gave too much importance to a rather subjective categorisation which has not been widely used in recent years.

Whilst the archaeomagnetic directions plotted without an indication of uncertainties bore some resemblance to the calibration curve currently used, when error bars at α_{95} were added to the plot, the picture became far more confusing (Fig 5.13a & b). Although this confusion was partly due to the fact that, where error bars crossed each other, they appeared to form another point, obtaining secular variation from this plot would clearly be difficult. Visual determination of secular variation from this representation would be impossible, apart from the period covered by observatory measurements, during which the errors were small and the rate of secular variation appeared to have been relatively rapid. This representation could not intuitively lead to the detailed secular variation record derived from the same data by Clark *et al.* (1988). The fact that dating information could not be represented on these plots led to the consideration that plots of declination vs. time and inclination vs. time might be more informative. Such plots are commonly used in archaeomagnetism (e.g. Kovacheva, 1991; Márton, 1991). Although undated points cannot be included, measurements of inclination only (Section 1.2.2) can be used and the data set does not need to be divided at an arbitrary date. A representation in this form of the British data (Fig 5.14a & b) showed more clearly the trends in secular variation over time, but the clustering of data in certain periods suggested that some form of averaging of the data might lead to a more informative representation.

Whilst the α_{95} values of the data used were considered to be small, the errors they indicated were significant when compared with secular variation. Errors in declination were particularly large, owing to the high latitude of Britain when compared with, for example the south-west United States. Uncertainties in the archaeological dating varied enormously, depending upon the information available to the archaeologist and were particularly large in the early measurements, where radiocarbon dates were the only independent dating information available.

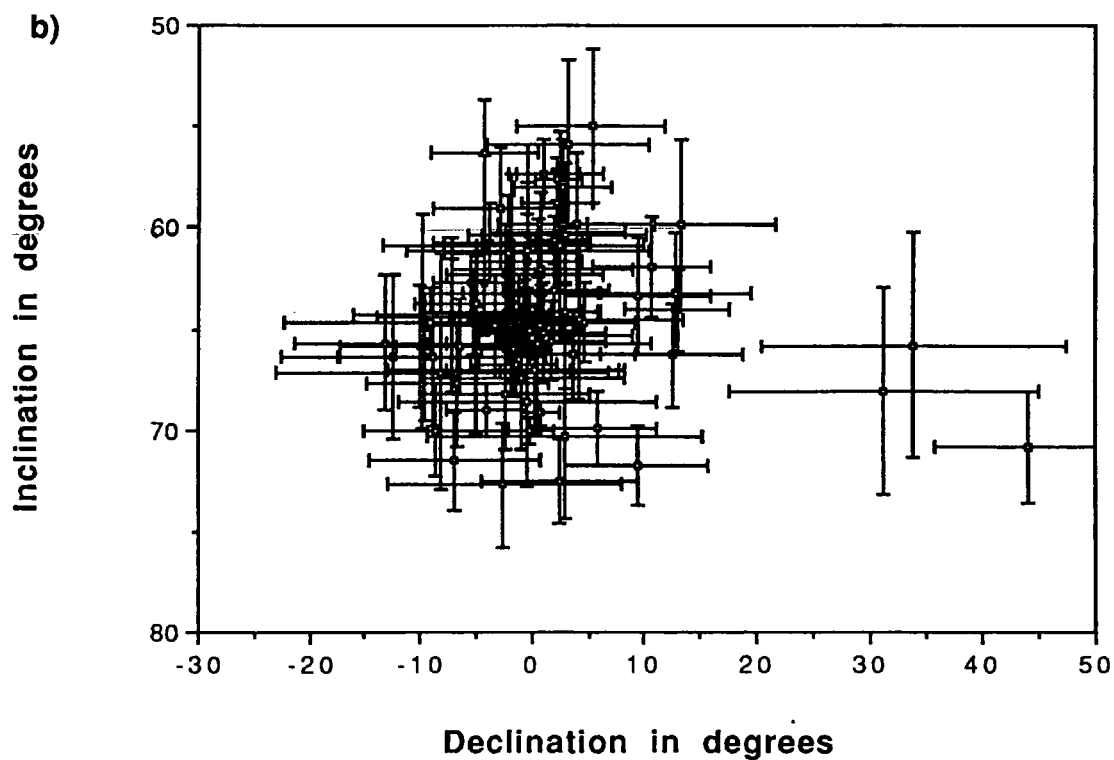
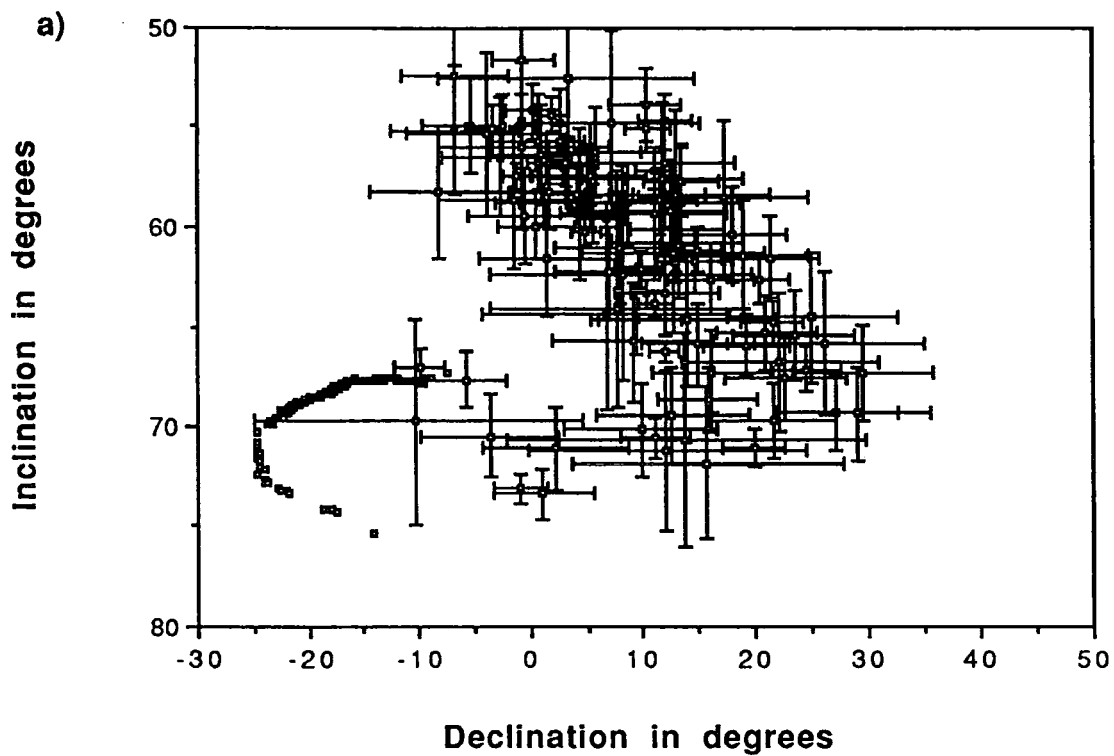


Figure 5.13: As Fig. 5.12, but with each magnetic direction shown with bars representing the error in declination and inclination, at 95% confidence.

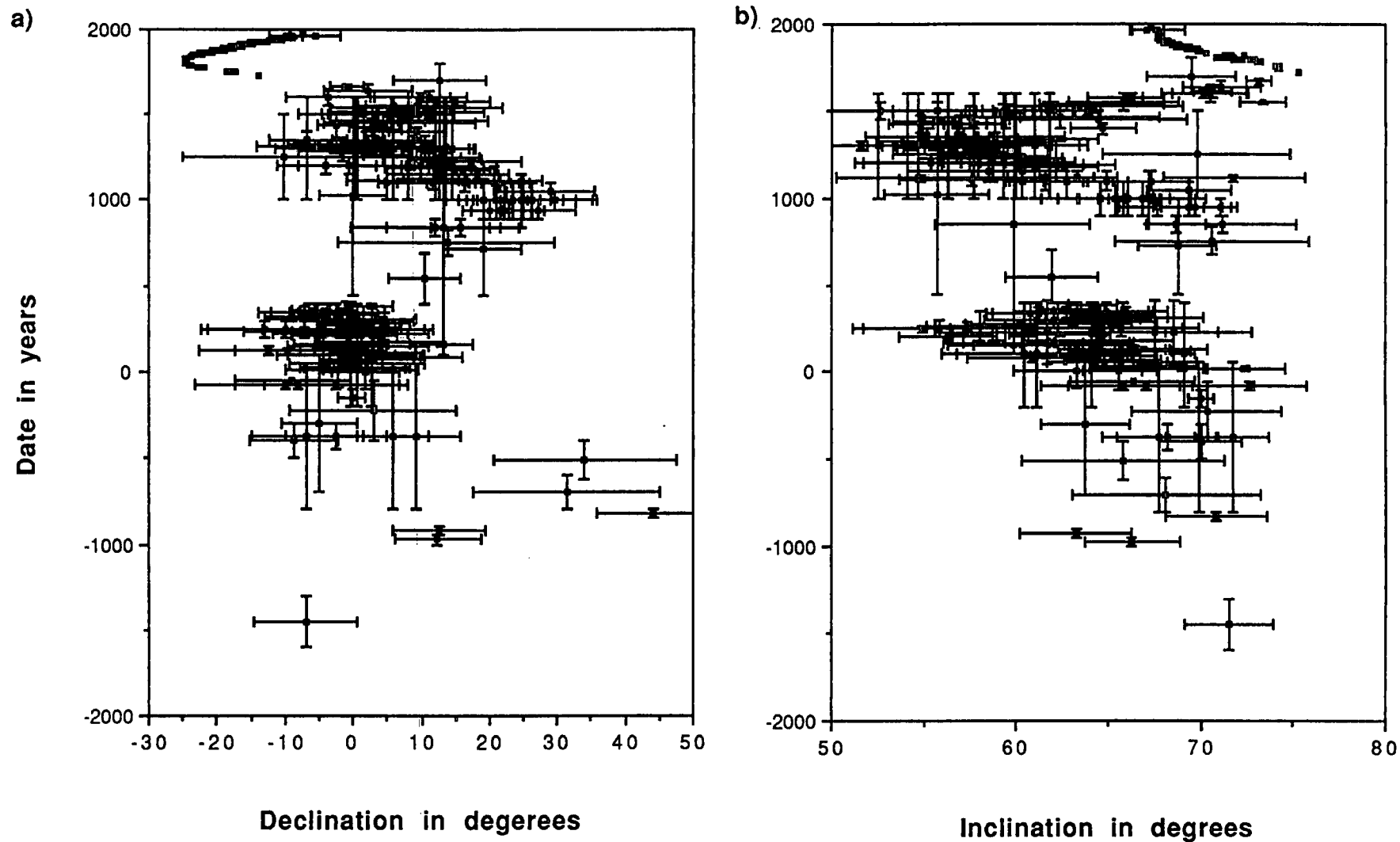


Figure 5.14: The selected British archaeomagnetic data, normalised to Meriden, plotted as *a)* declination vs time and *b)* inclination vs time. Error bars in the magnetic direction are at 95% confidence and error bars in date are equal to the archaeological age range.

A number of other representations of archaeomagnetic measurements were considered but deemed unsuitable. A 3-dimensional plot, with declination and inclination on the x- and y- axes respectively and time on the z-axis might give an interesting insight into secular variation over time and enable the errors in all three quantities to be represented. However, such a plot would be difficult to present on paper and very complicated to use for dating purposes. A grey scale or dot density presentation was also considered. In this, a point would be plotted for each declination and inclination value, the darkness of the point being dependent on the precision of the measurement. However, assigning such a scale would be difficult as errors occur in both magnetic direction and date and a large number of points close together would be deceptive.

5.6.2 Simple averaging of the archaeomagnetic directions

The initial approach to averaging the archaeomagnetic information was simply to combine all the data falling within a fixed interval of 50 years, similar to the method employed by Kovacheva (1980; Section 5.3). The archaeological date for each magnetic direction was taken to be the midpoint of the age range assigned to it. All of the directions with a date falling within a fixed 50-year window were averaged using Fisher's method (Fisher, 1953) to give a mean declination and inclination and an α_{95} estimate of the precision of the mean. Whilst the plots obtained from averaging of the British archaeomagnetic data in this way (Fig. 5.15a & b) gave a clearer indication of secular variation, much information was lost in the averaging process. No account was made for the archaeological date range attributed to an individual magnetic direction or to its individual α_{95} value. The fixed window size meant that some windows contained a large number of magnetic directions, whereas others contained very few. If only one data point fell in a window, no estimation could be made of its precision and so it was represented as a single point. The α_{95} values calculated for windows containing only three or four points were also unlikely to be reliable. Assigning the middle of a date range to each direction caused particular problems; the magnetic direction from a feature given a wide date range was assigned to a specific date and all features designated as, for example, 'Roman' were dated to the same 50 year window. At this stage it became clear that it might be necessary to eliminate precise but anomalous magnetic directions from the analysis as they might lead to large errors on the combined direction, giving a misleading average direction.

5.6.3 The moving window method of producing an archaeomagnetic curve

Combining the British archaeomagnetic data into 50 year averages gave some indications of trends in secular variation. However, the assignation of dates to the midpoint of the date range, the fact that uncertainties in the determination of the

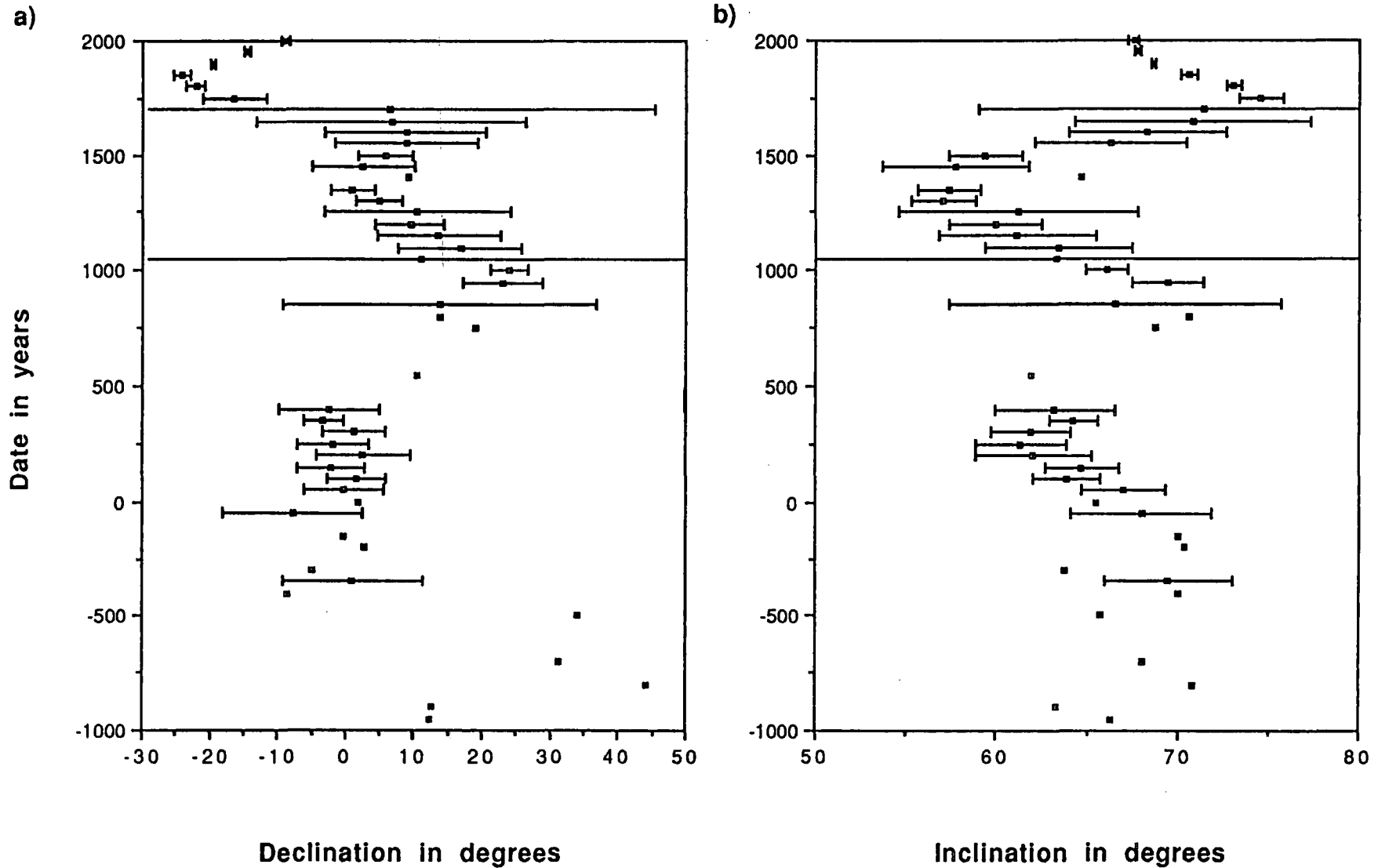


Figure 5.15: As Fig. 5.14 but with data averaged into 50 year spans as described in the text and plotted at the mid-point of the 50 year span. Where there was only one point in the range, no error could be calculated.

magnetic vector and the archaeological date were not incorporated, and the small number of points in some of the windows all caused difficulties. The next step was to perform a similar averaging, but to overcome these problems by weighting the data and using a more flexible windowing system.

A 'moving window' was introduced into the averaging process. In this procedure data falling in a fixed window of time were averaged using Fisher statistics as before. The window was then moved by a set increment and the average of the data falling in the new window was calculated. Directional information was plotted at the midpoint of each window, giving a series of smoothed declination and inclination values, at regular time intervals, describing a smoothly varying curve.

A further advance was to weight the data according to their α_{95} and archaeological date in the manner suggested by Sternberg (1982 & 1989b) and Sternberg and McGuire (1990a). Uncertainty in age was accounted for by weighting individual measurements of magnetic direction according to the overlap of their age range with the given window. If it is assumed that the probability distribution within an age range is uniform, then this weight is simply equal to the fractional overlap of the two time spans; that is the amount of time in the overlap of the window and the age range, divided by the age range. Hence, if the age range of a datum was completely contained within the window, the datum was given a weight of 1; if the age range lay completely outside the window, the datum had a weight of zero. Uncertainty in magnetic direction was accounted for by weighting individual measurements of magnetic direction using either k (the precision parameter; Section 2.5.1) or α_{95} . Although k is the more sensitive parameter, with a wider range, α_{95} was chosen when weighting the British data as it is the parameter most commonly used in British archaeomagnetic studies. Weighting in this manner reduced the influence of less precisely determined magnetic directions, thus eliminating the need for an arbitrary cut off point for 'acceptable' α_{95} values. The total weight for each datum was obtained by multiplying the two weighting factors. This method of producing an archaeomagnetic reference curve was developed by Sternberg (1982) and has been used by archaeomagnetists working in the southwest United States (Sternberg & McGuire, 1990b; Eighmy *et al.*, 1990). The work presented here used a copy of the routine, kindly provided by Dr. Sternberg, to apply this smoothing procedure to information from the British archaeomagnetic data base. A listing of the program is given in Appendix 4.

The effect of the smoothing procedure depended upon the errors in the data, the density and temporal distribution of the data, the window size and the increment between the windows. The window had to be large enough to contain sufficient information to give a meaningful α_{95} value and to filter out noise or very high frequency variations in

the geomagnetic field, but not so large that smoothing was excessive and information lost. The aim was to have at least seven points in each interval so that Fisher statistics could be used with confidence (Sternberg & McGuire, 1990a). Initially, a 50 year window was chosen as it was similar to the average archaeological age range (Fig. 5.16a & b), but the window size was later increased to 100 years in periods where data were sparse (Fig. 5.17a & b). Small increments between windows would have yielded more points and a smoother curve, but would have meant that successive smoothed points were even less independent and would have artificially reduced extreme values in the data. In this study, an increment of half the window width was found to produce smooth curves, without appearing to lose significant information. As no α_{95} value was available for the observatory measurements, a fixed value of 0.5° was assigned to take into account likely instrumentation and measurement errors.

Figure 5.16 (a & b) shows the British archaeomagnetic data after smoothing using the Sternberg method. The resulting curves were smooth, as would be expected to result from the moving window routine. They clearly showed the trends which could be discerned, but which were not obvious, on inspection of the raw data. The error bars at α_{95} gave an excellent representation of the uncertainty of the curve arising from uncertainties in archaeological date and the determination of the magnetic direction. In periods such as the Dark Ages and before 100BC, where archaeomagnetic information is very sparse, large error bars arose, leading to difficulty in defining the calibration curve in these periods. Increasing the window size from 50 years to 100 years in the periods for which data are most sparse, AD450 to AD900 and 100BC to 1000BC (Fig. 5.17a & b), did not greatly change the shape of the curves or the size of the error bars, as there were so few points in these periods, even when 100 year intervals were used. It would be possible to use a window size that varied at each step, according to the density of data in that particular archaeological period.

Sternberg (1982 & 1989b) found that the rejection of outlying mean magnetic directions was an essential part of the smoothing procedure. For each window, the feature overlapping with the window and farthest from the mean direction was determined. After deleting this value, a new mean was calculated for that window. If the feature with the outlying magnetisation had less than a 0.5% probability of being a member of the same population as the other magnetic directions from that window (McFadden, 1980), it was deemed an outlier and deleted. The test was repeated until no further outliers were detected. Examination of the British data base showed that it included very few archaeomagnetic directions that would be classed as outliers on these criteria. Rather than attributing this to the accuracy of British measurements, it seems more likely that apparently anomalous magnetic directions were rejected at an earlier stage by archaeomagnetists, perhaps when compiling data for the calibration curve. Even

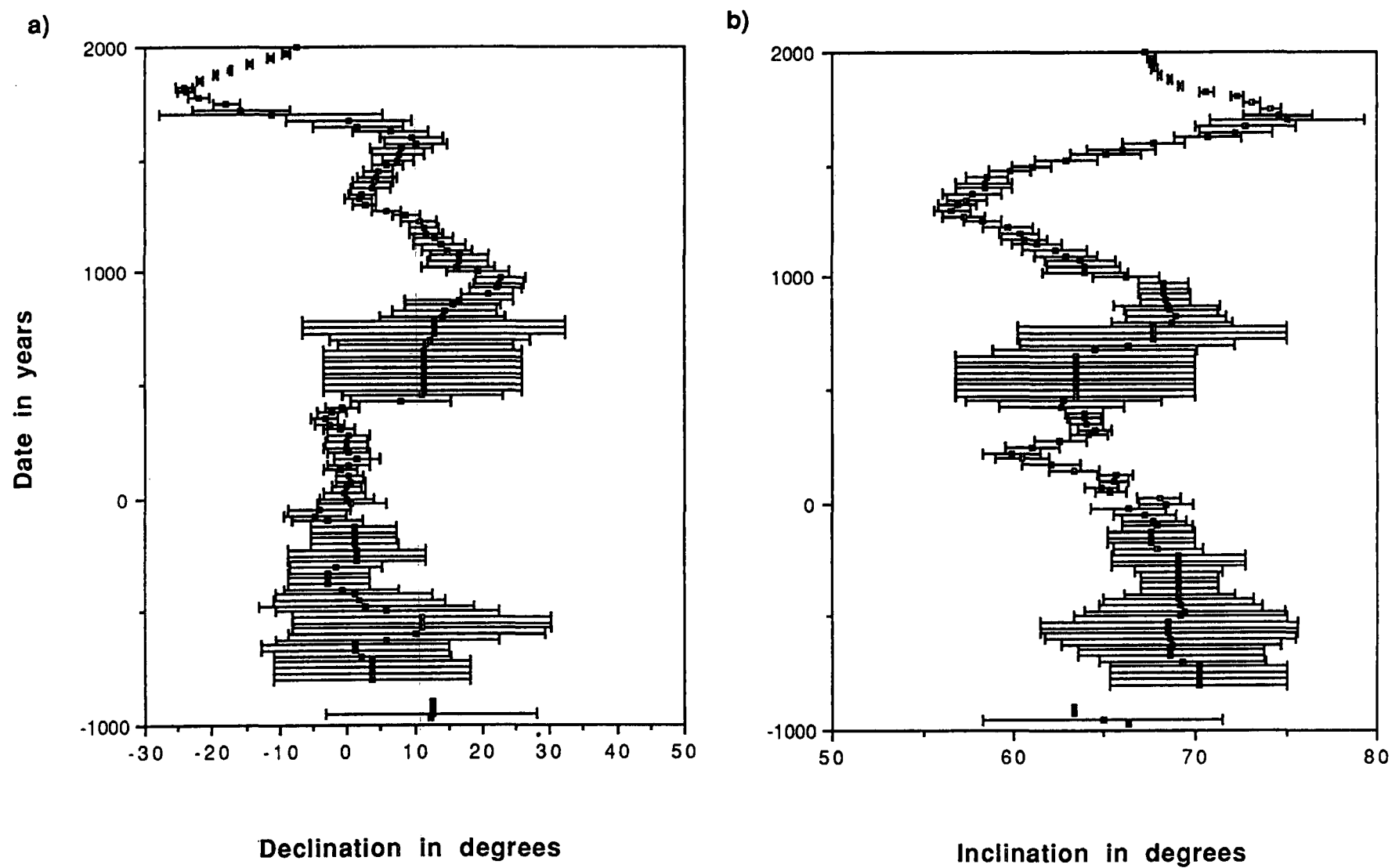


Figure 5.16: The selected British archaeomagnetic data, normalised to Meriden, smoothed using the moving window method (Sternberg & McGuire, 1990a), with a window of 50 years moved by an increment of 25 years. Error bars in magnetic direction are at 95% confidence. *a)* shows declination vs time and *b)* shows inclination vs time

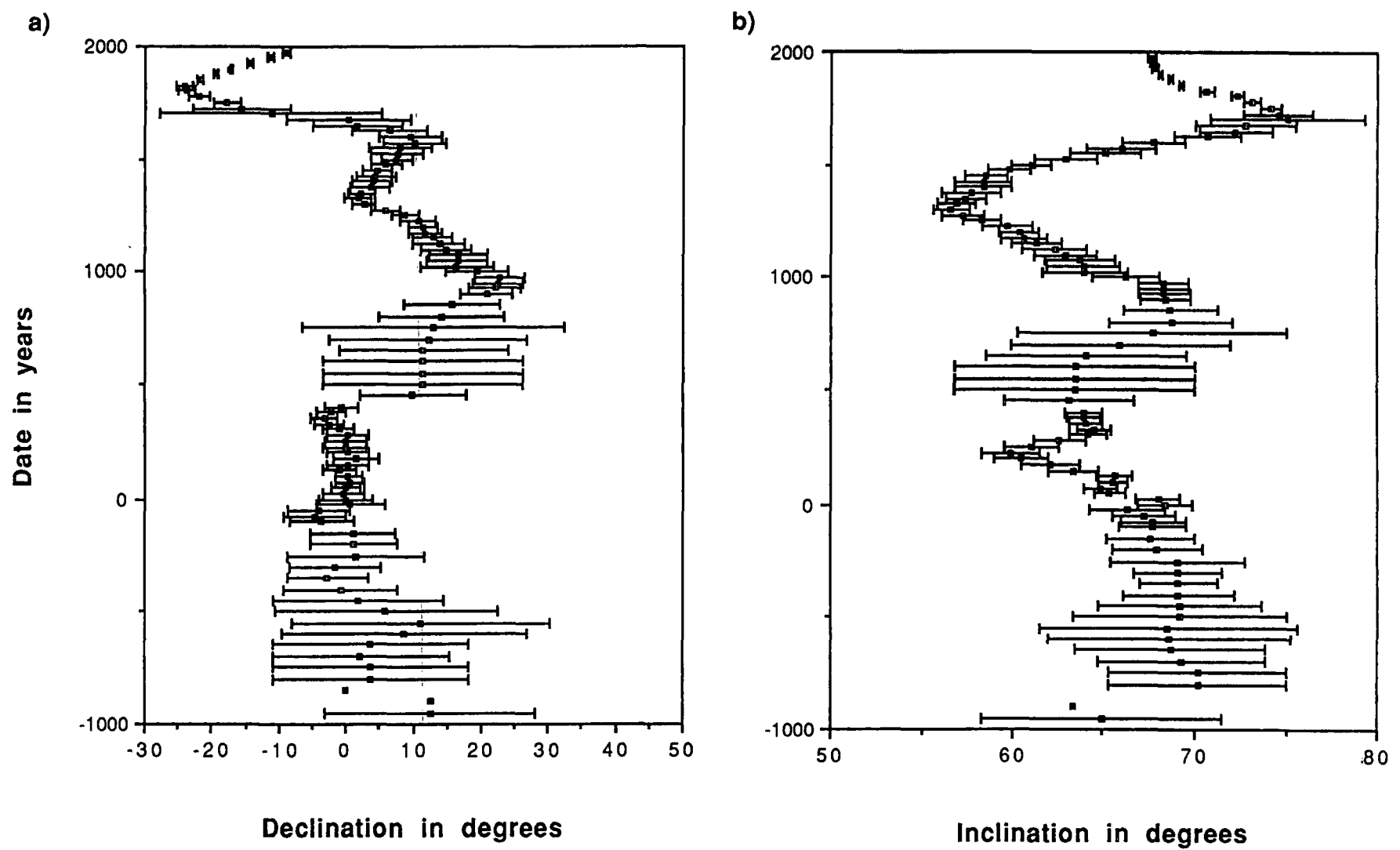


Figure 5.17: As Fig. 5.16 but using a window of 50 years, moved by an increment of 25 years for the periods AD900-AD1975 and AD450-100BC and a window of 100 years, moved by an increment of 50 years for the periods AD450 to AD900 and 100BC to 1000BC.

without outlier rejection, the very large error bars produced by the simple averaging attempt (Fig. 5.15a & b; Section 5.6.2) have disappeared. This suggested that they arose from inappropriately assigning dates to be the mid-point of the date range for individual directions, rather than from anomalous magnetic directions. Further archaeomagnetic measurements, particularly on well-dated features from periods where data are sparse, would reduce the errors in the calibration curve. The best precision attainable would be limited by the accuracy of the archaeomagnetic recorders, the measurement process and the non-dipole components of the field (Section 2.6).

The smoothed archaeomagnetic information was plotted as declination vs. inclination (Fig. 5.18a & b), in order to compare it with the current archaeomagnetic calibration curve (Clark *et al.*, 1988; Fig. 5.1). Correspondence between the two curves from the present to AD900 was fairly good, with a number of interesting features. Whilst the general shape was followed, particularly where the data were dense, the new curve did not show the closed loop between the 14th and 15th centuries. The inclination was steeper in this period, which may be a function of the averaging process. For most of this period, the errors were small and discrepancies between the two curves did not exceed the errors. The period from AD1600 to AD1700 had surprisingly large errors as, although observatory measurements from this period exist, they are either declination or inclination and so cannot be used on a D vs. I plot. From AD900 to AD600 there was a swing towards shallow inclinations, completely at variance with the tight loop featured in the Clark curve. However, both curves should be considered to be extremely tenuous in this period, where measurements are so sparse. The curve from AD600 to 1000BC was much more difficult to interpret. Whilst the general path described by the mean directions was similar to the Clark curve, variations in declination were so slight that secular variation was hard to discern. A rapid shallowing in inclination in the Roman period was evident but the familiar 'Roman hairpin' could not be distinguished within the error bounds. The disappearance of the eastwards swing from 300BC to 1000BC illustrates a breakdown in the Sternberg method; so few points exist in this period that the mean direction was distorted towards the body of the curve, resulting in a misleading representation of the curve and large errors. If the lake sediment data could also be incorporated in the curve this particular problem might be alleviated, but the deceptive smoothing caused when data is sparse would remain a factor that must be considered.

This treatment of the British archaeomagnetic data seems to have much to offer; it presents an objective method of obtaining the calibration curve and gives a clear indication of the uncertainty of the curve at different periods. As with any method which involves averaging, the extreme values are reduced, particularly if they are only based on a small number of points. The Sternberg method has been criticised by Wolfman (1990c) because of its supposed over-dependence on archaeological dates. However, Wolfman's

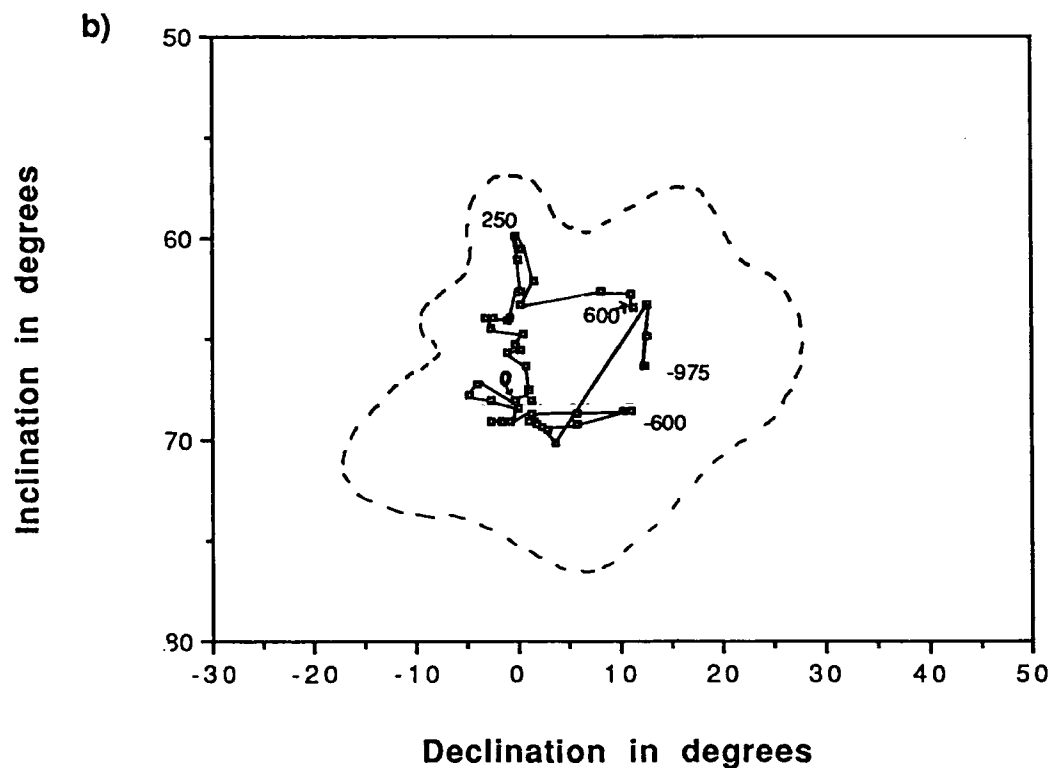
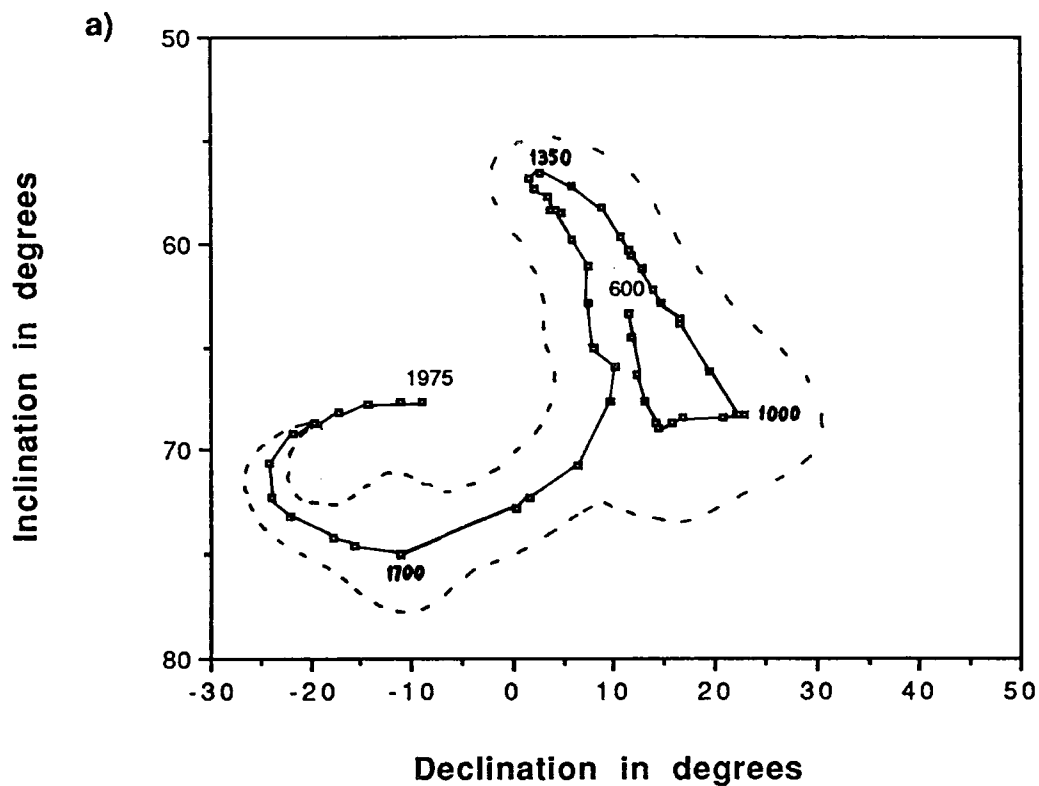


Figure 5.18: The British archaeomagnetic calibration curve obtained from variable, moving window smoothing of selected data (Section 5.6.3), normalised to Meriden *a)* AD600-1975 and *b)* 1000BC-AD600. Figures are in years BC (-) and AD. The dotted line represents the error at 95% confidence. The data represented here are the same data as shown in Fig. 5.17. Note that some mean magnetic directions are coincident.

preferred emphasis on relative rather than absolute dating is impractical, as such sequences rarely arise on the sites for which most British archaeomagnetic dates are required. Secular variation of a period equal to or less than the window length cannot be resolved, but the window size cannot be decreased, whilst still maintaining sufficient points in each interval, until more data are collected.

5.6.4 Obtaining archaeomagnetic dates and reconsidering previous dates

The way in which a magnetic vector is dated is not always explicitly stated in archaeomagnetic publications. In most cases a graphical approach is used, but more recently a statistical approach has been suggested (Sternberg & McGuire, 1990a).

The graphical approach

The graphical approach is commonly used (Section 2.5.4) and involves plotting the mean direction and its error (normally at α_{95}) onto the Clark calibration curve (e.g. Meng & Noel, 1989). The date is then estimated visually as being the point on the curve closest to the mean direction, with its error being the dates where the direction's error bars cut the curve. Dates usually have to be estimated by interpolating between the 50 or 100 year markers along the curve. The date range obtained may be asymmetric about its mean, depending on the velocity of secular variation. Such a procedure is simple if the mean magnetic direction lies on, or very close to, the curve (e.g. Stakis Hotel, Section 3.4.2). However, if the mean magnetic direction lies slightly off the curve, its error bars will intersect with less of the curve, giving a smaller error, whereas a larger one would be expected intuitively. A mean direction and its error might lie completely separate from the curve, in which case no date can be given. The graphical approach does not consider the errors in the calibration curve itself, which will vary along its length, and does not provide a way of treating points which do not obviously fit the calibration curve. Wolfman (1990a) adds 10 years to the age range obtained by this method to account for errors in the curve, but this rather arbitrary approach is unsatisfactory.

If the archaeomagnetic calibration curve is presented as separate plots of declination, inclination and intensity over time; the date can be determined from the overlap of possible date ranges obtained from each of the three plots (Kovacheva, 1991), taking into consideration the errors in the curves. Whilst this method has been used in Bulgaria, it is likely to be less successful in Britain as intensity of magnetisation is not commonly measured.

The statistical approach

To complement the statistical approach to curve drawing, it is suggested that the next step should be the development of a statistical approach to obtaining dates for magnetic directions from the calibration curve. Sternberg (1982) has developed a repeatable and objective method of determining dates, which also takes into account the uncertainties in the secular variation record. This method seems the most promising way forward. The procedure is based on common tests for comparing two palaeomagnetic mean directions and their standard errors, and uses the curve produced by the moving window method. A point-by-point comparison is made of the magnetic direction to be dated with each point in the secular variation, checking that their precisions are not significantly different at a 5% level using the F-test (Watson, 1956). Then, if the precisions are not significantly different, the F-test of McFadden and Lowes (1981) is used to compare directions. The date is taken to be those points where the data in the curve and the magnetic direction to be dated cannot be said statistically to be from different populations. The archaeomagnetic date is the total age range (or age ranges) for such adjacent points.

Using this statistical method the most precise date possible would be the length of a single window interval, ± 25 years in the case of the revised British curve. This is higher than the normally accepted best attainable error estimate of less than 20 years (Tarling, 1983 p151; Clark *et al.*, 1988). However, it is more realistic as it is based not only on the α_{95} value for the magnetic direction to be dated, but also on the errors in the secular variation curve, arising from uncertainties in archaeological date and uncertainties in the determinations of the magnetic directions used in the calibration curve. It is important that any changes in the method of determining errors in magnetic dates is widely agreed upon, or some laboratories will give deceptively precise results, simply by ignoring important error considerations.

Obtaining archaeomagnetic dates in practice

Given the problems with conventional methods of obtaining archaeomagnetic dates, highlighted in this chapter, and the presentation of a revised calibration curve, an attempt was made reconsider the dating of the magnetic directions obtained in the study of sediments (Chapter 3), using the new British curve, and to compare them with the dates obtained using the Clark calibration curve. The dating was carried out by a visual comparison of those magnetic directions which appeared datable using the Clark curve, and their errors at 95% confidence, with the calibration curve obtained from the moving window method with varying window size (Fig. 5.17). Because of the increased errors in this curve, over the Clark curve, it was necessary to use the archaeological evidence to constrain the part of the curve which was used.

The declination of the Stakis Hotel magnetic direction (Section 3.4.2) was consistent with any date before AD750 (Fig. 5.19), but the inclination record was more distinctive, dating the sediment to before AD50. This date corresponded to the date obtained using the Clark curve, but was slightly earlier than the date obtained from the archaeological evidence. It could not be defined any more clearly than 'before AD50' because of the wide error bands of magnetic directions before 0AD/BC. Both declination and inclination values of the West Heslerton magnetic direction (Section 3.4.9) enclosed every date before AD1750, with the exception of AD850-AD1000, within their error bounds (Fig. 5.20). The large age range arose in part from the increased uncertainty in the new curve, but mainly from the large error in the magnetic measurement. Re-examination of the magnetic direction for ABC context 2307 (Fig. 5.21; Section 3.4.1) showed that the declination record, as with the Stakis declination, did not constrain the date a great deal. The inclination record was more useful and the combination of the two dated the sediment to before AD150, a date which agreed well with the archaeological evidence and the previous archaeomagnetic date of AD50-150. However, context 2311 (Fig. 5.22) from the same site, which had a very similar mean direction of magnetisation but a larger α_{95} (1.3° larger) could only be said to be before AD800. Context 2313, also from ABC Cinema, had a small α_{95} (1.5°) and could be dated to before AD50 (Fig. 5.23). The date was in agreement with the archaeological evidence, the previous archaeomagnetic date and its stratigraphic relationship to context 2307. The magnetic direction from Farnley (Section 3.4.6) was extreme both in declination and inclination and, despite a large dispersion, only intersected with the calibration curve at around 600BC (Fig. 5.24). The intersection was so slight that it seems probable that the Farnley direction dated to a period before the calibration curve commences, as suggested by the comparison of the magnetic direction with the lake sediment curve in Section 3.4.6. The magnetic direction from the ditch silt at Wood Hall (context 805; Section 3.4.10) was very well defined and comparison with the curves gave possible dates of between AD750 and AD200 (Fig. 5.25). These dates were considerably earlier than those previously obtained and do not correspond to the archaeological evidence; an investigation into current effects would be necessary before this date could be confirmed.

Clearly, a visual comparison of this nature leaves a great deal to be desired. However, it does allow both errors in the direction to be dated and the calibration curve to be considered, and gives some indication of the effects of using the new calibration curve. The main effect of note is that the errors in dates increase and in some cases the date ranges given are extremely wide. It is clear that less precise magnetic directions, such as the West Heslerton direction ($\alpha_{95}=5.8^\circ$) are undatable unless the mean directions are particularly extreme and that a slight increase in α_{95} can cause a very large increase in possible date, as shown by ABC contexts 2307 and 2311. It can also be seen that, because of the large error bars on the calibration curve before BC/AD0, it is unlikely that

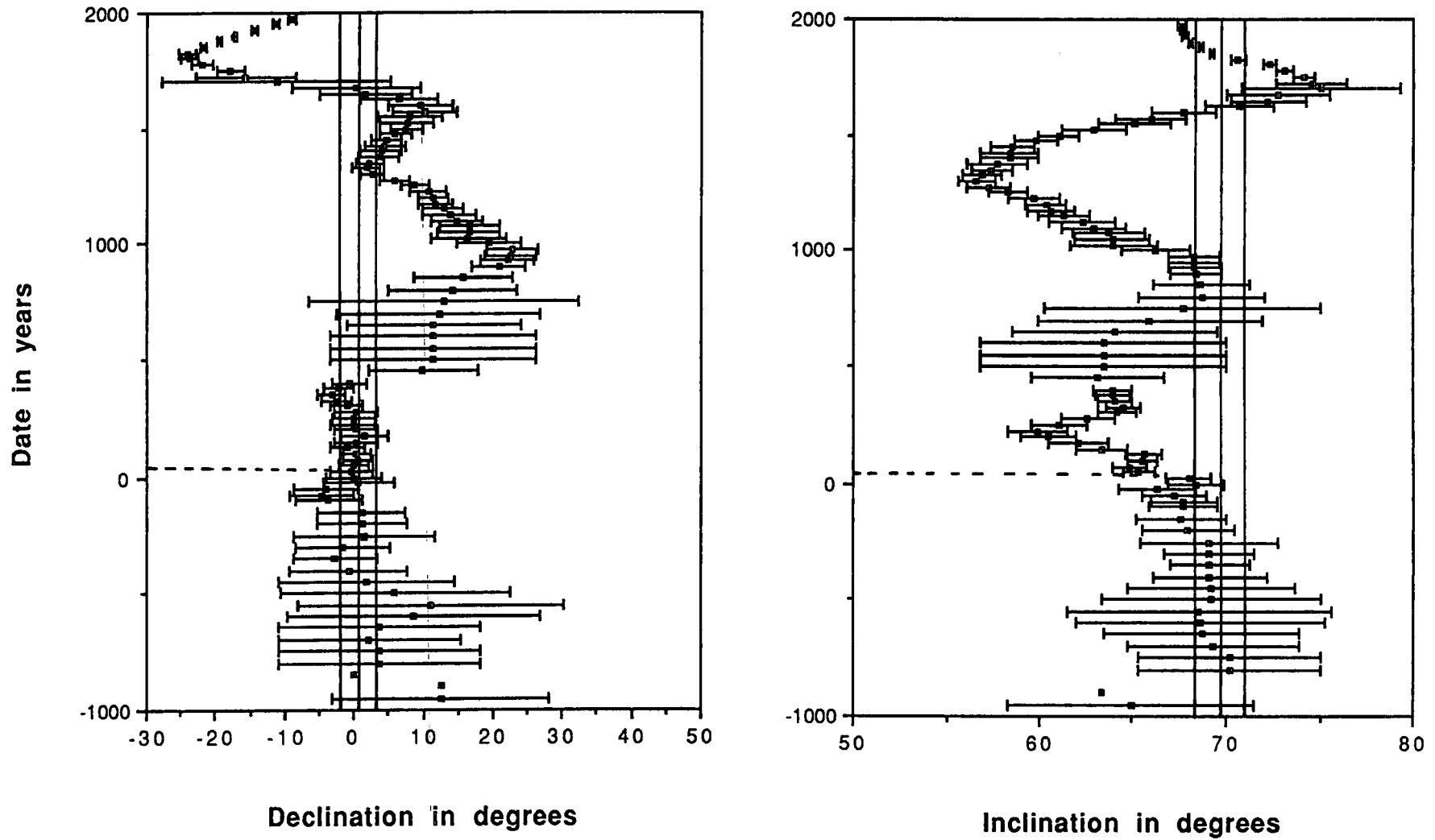


Fig. 5.19: The Stakis Hotel archaeomagnetic direction with errors at 95% confidence (Section 3.4.2), compared to the smoothed curve obtained by the moving window method using a varying window size, as shown in Fig. 5.17.

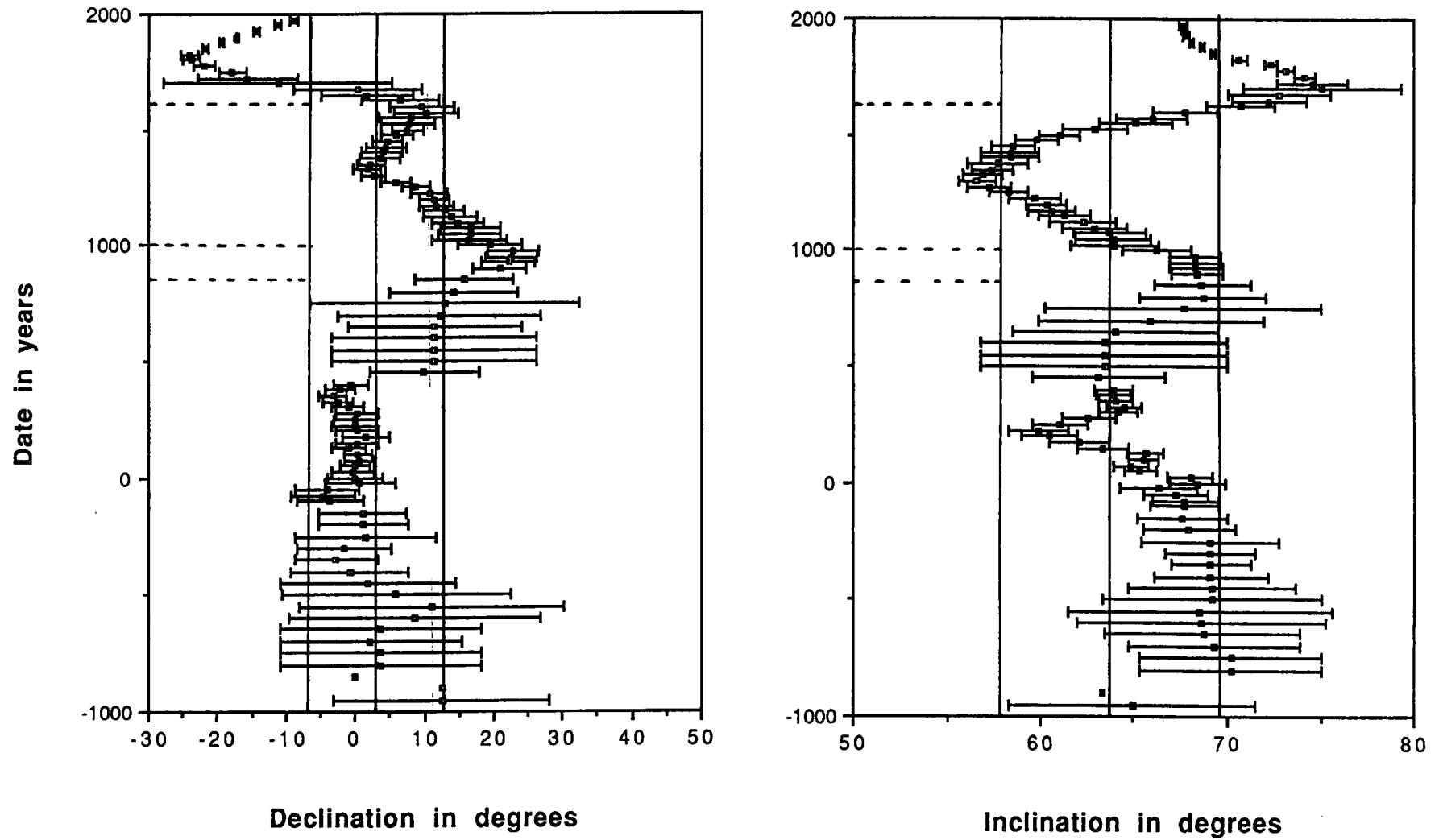


Fig. 5.20: The West Heslerton archaeomagnetic direction with errors at 95% confidence (Section 3.4.9), compared to the smoothed curve obtained by the moving window method using a varying window size, as shown in Fig. 5.17.

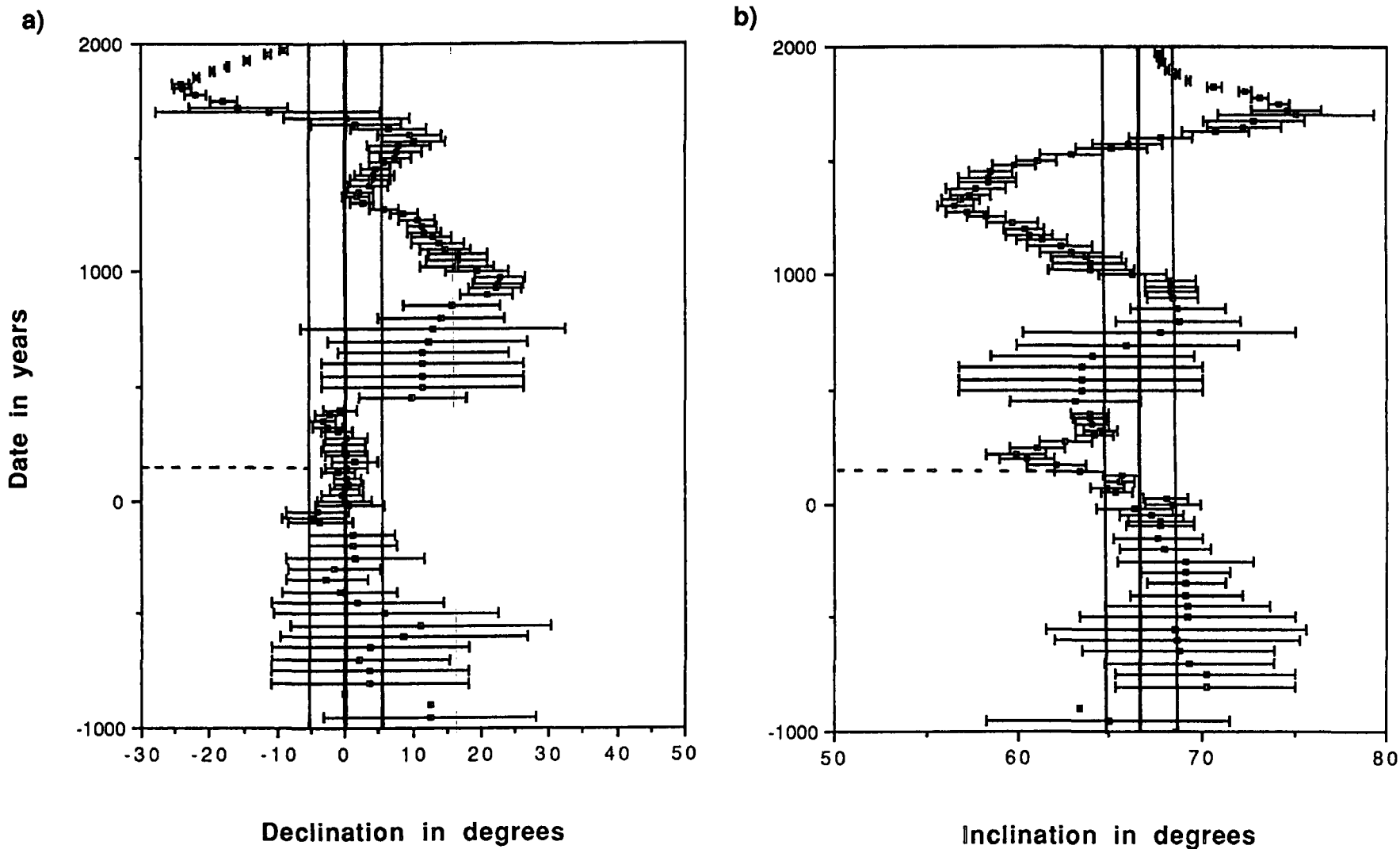


Fig 5.21: The archaeomagnetic direction from ABC Cinema, context 2307 with errors at 95% confidence (Section 3.4.1), compared to the smoothed curve obtained by the moving window method using varying window size, as shown in Fig. 5.17.

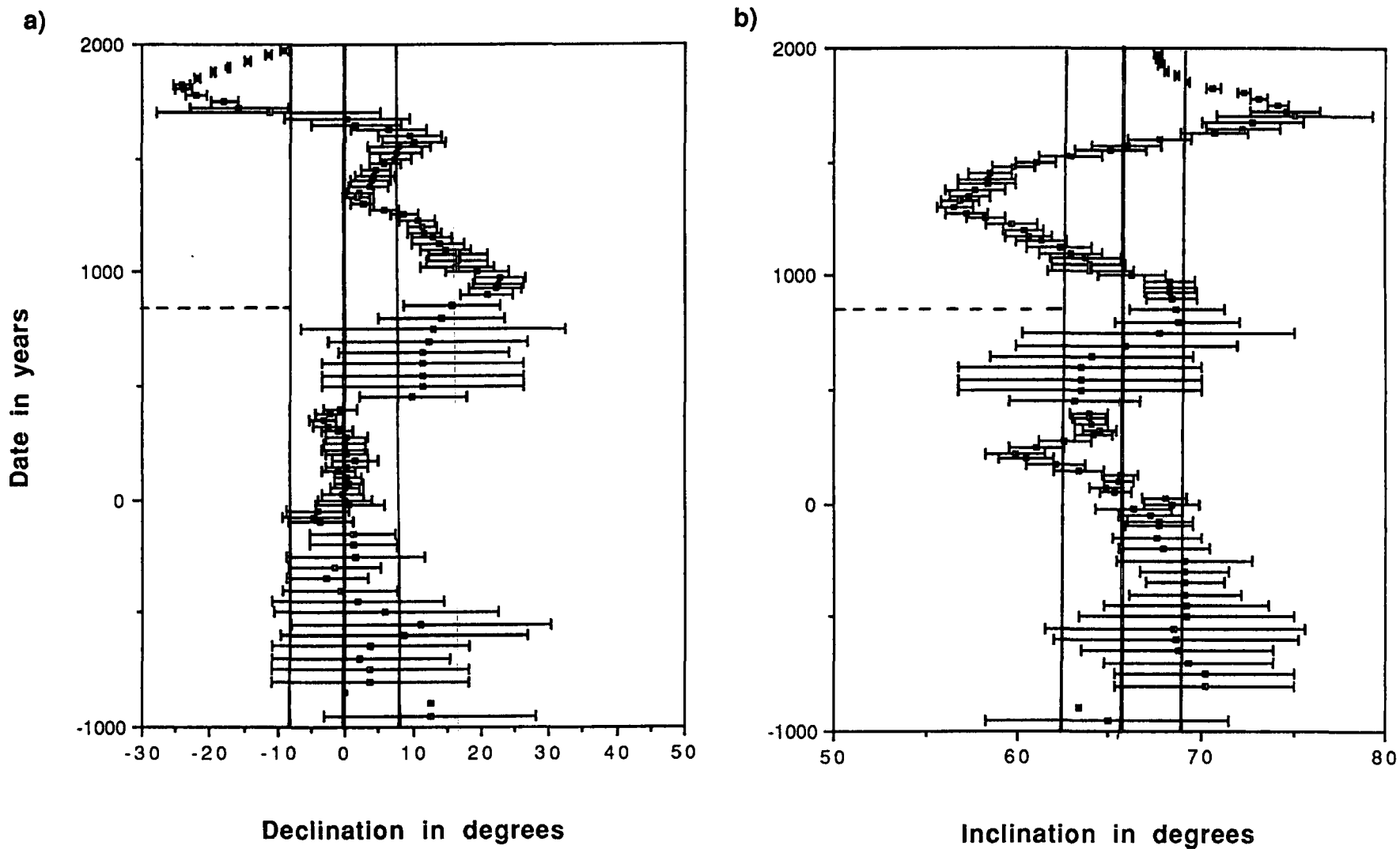


Fig 5.22: The archaeomagnetic direction from ABC Cinema, context 2311 with errors at 95% confidence (Section 3.4.1), compared to the smoothed curve obtained by the moving window method using varying window size, as shown in Fig. 5.17.

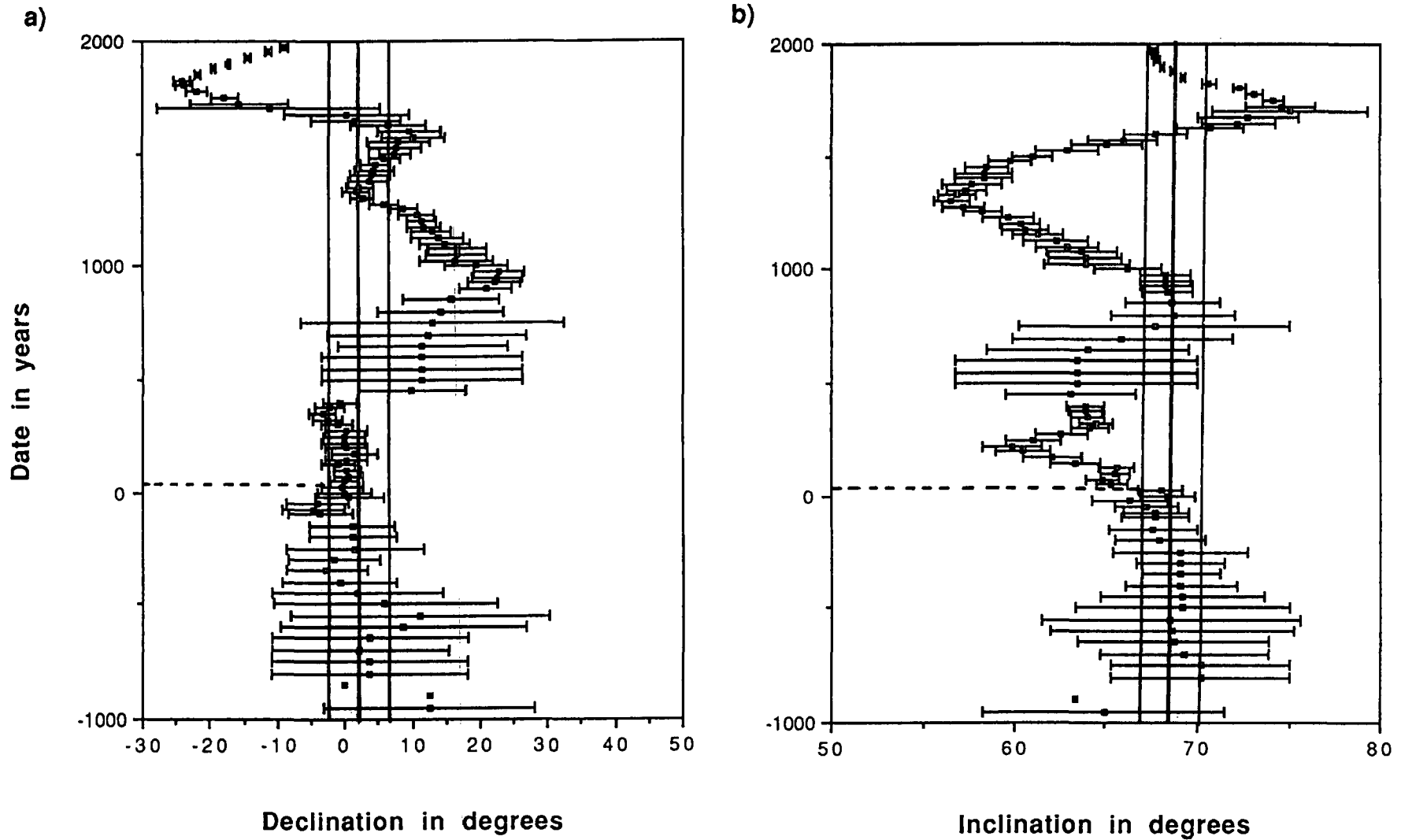


Fig 5.23: The archaeomagnetic direction from ABC Cinema, context 2313 with errors at 95% confidence (Section 3.4.1), compared to the smoothed curve obtained by the moving window method using varying window size, as shown in Fig. 5.17.

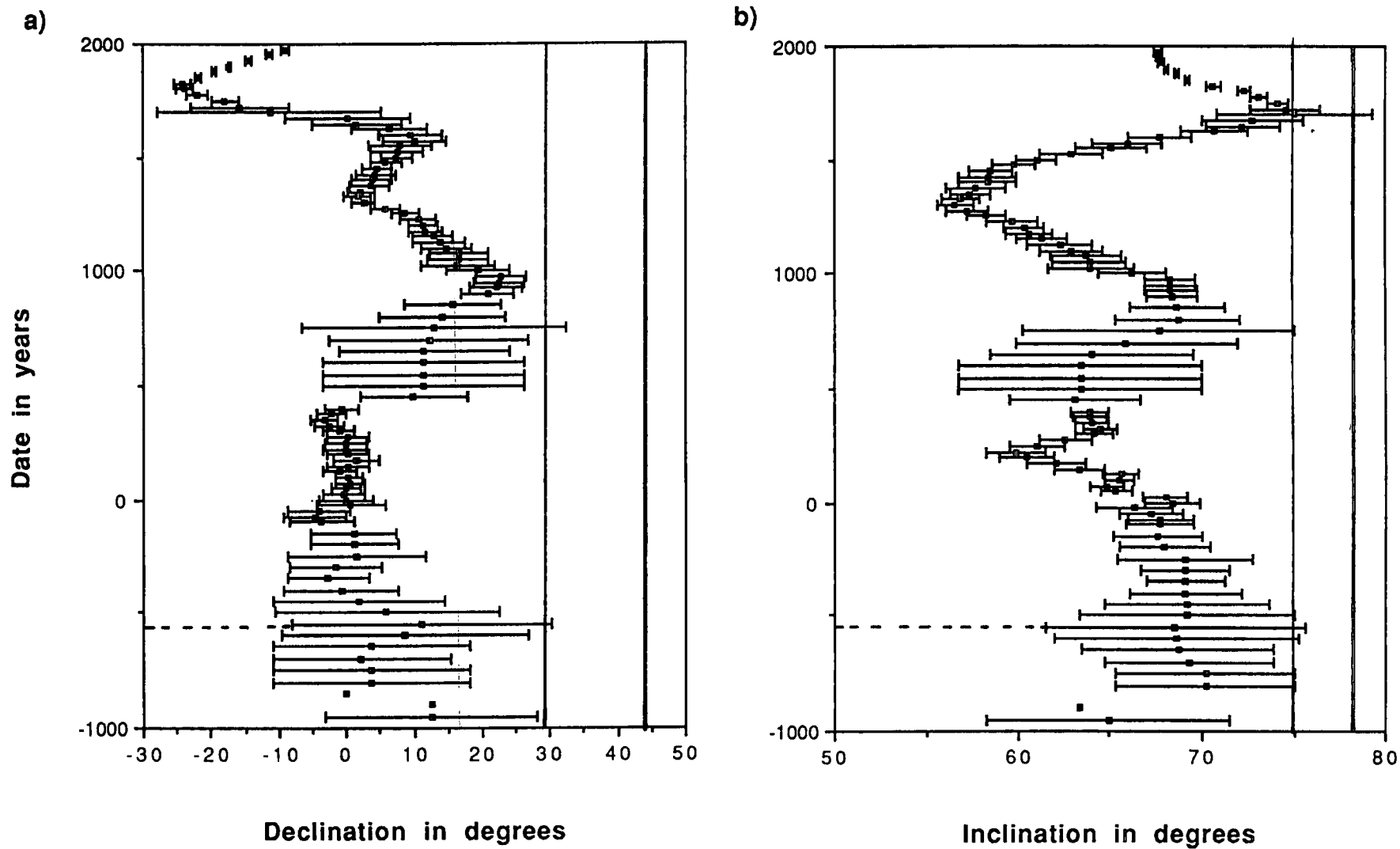


Fig 5.24: The archaeomagnetic direction from Farnley with errors at 95% confidence (Section 3.4.6), compared to the smoothed curve obtained by the moving window method using varying window size, as shown in Fig. 5.17.

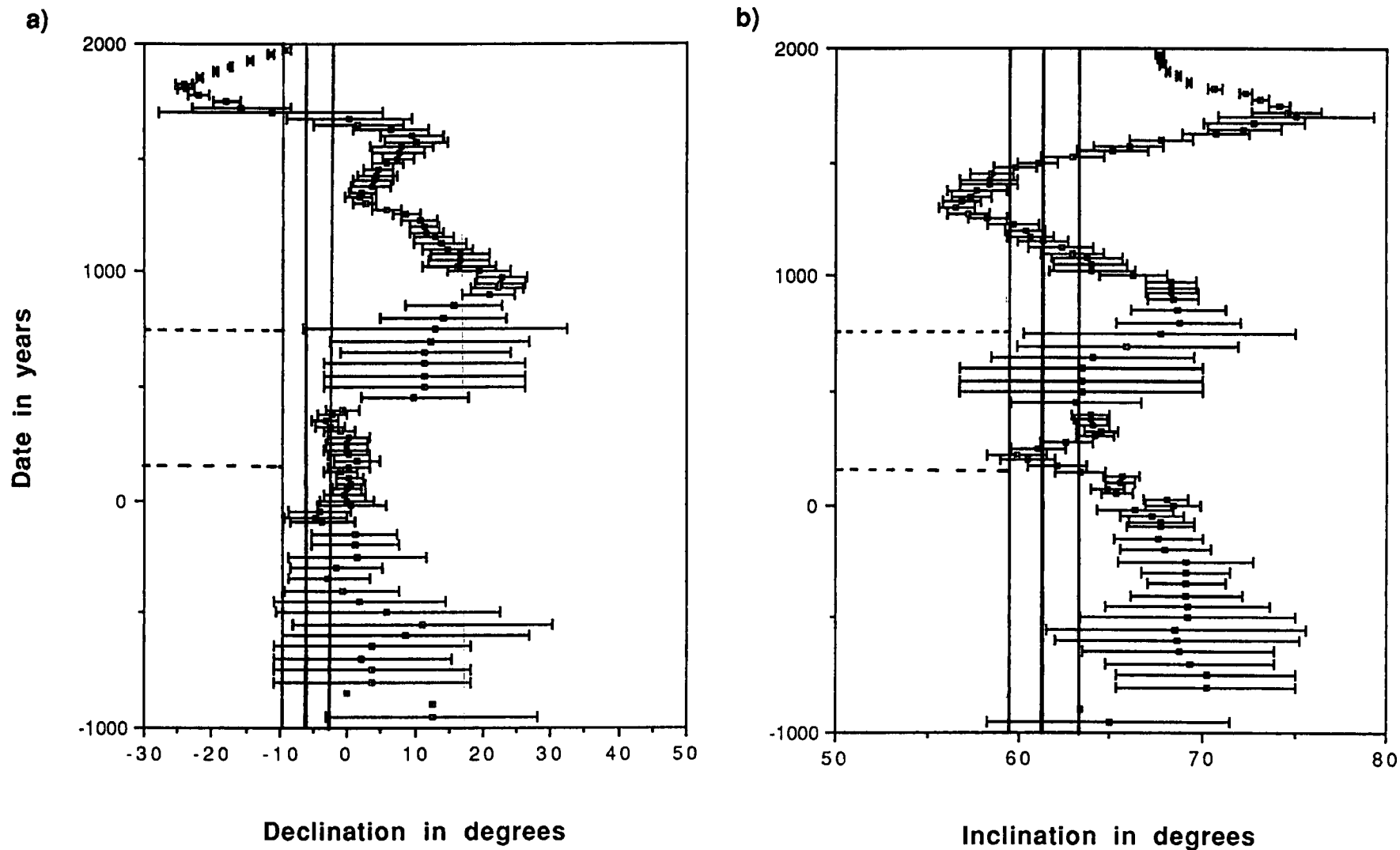


Fig 5.25: The archaeomagnetic direction from Wood Hall context 805 with errors at 95% confidence (Section 3.4.10), compared to the smoothed curve obtained by the moving window method using varying window size, as shown in Fig. 5.17.

magnetic directions before that time can be dated. There is also considerable reliance on the archaeological evidence to indicate the appropriate part of the curve. Whilst these observations might appear to be very negative, it must be remembered that the dates obtained now have a more rigorous basis and improvements to the new calibration curve by adding new data and developing statistical methods of obtaining a date may improve the precision available.

5.7 DISCUSSION OF THE RESULTS

5.7.1 Introduction

Attempts to date British sediments by archaeomagnetism (Chapter 3) and to examine the possibilities of drawing a calibration curve for the Xi'an region of China (Chapter 4), have made clear the importance of the construction and use of archaeomagnetic calibration curves. The detailed attempts to understand the processes of the acquisition of magnetisation, to identify stable components of primary magnetisation and to quantify the dispersion of magnetic vectors must be matched by an equally rigorous method of dating the magnetic direction. The hand-drawn curves of Clark (Clark *et al.*, 1988) and previously Aitken (Aitken, 1970) have been very carefully constructed and have played a vital role in archaeomagnetic dating in Britain in the last 20 years. However, as more data have become available, it is possible to proceed to an objective examination of the method of data presentation and curve fitting. If archaeomagnetism is to retain credibility as a scientific dating technique, it is essential that the methods of construction of the British calibration curve are scrutinised and, where possible, improvements made.

5.7.2 Assessment of the current position

Although the current calibration curve (Clark *et al.*, 1988) has been used extensively and exclusively in British archaeomagnetic dating, it has a number of failings. With the availability of new archaeomagnetic data and methods of data presentation some of these problems can be addressed. The main difficulties with current methods are discussed in detail in Section 5.2 and centre on the representation of the calibration curve by a line drawn freehand through dated magnetic directions. Such a presentation does not allow for the representation of errors or individual data points, leading to a false impression of the precision of the curve, particularly in periods where data are sparse. The curve fitting itself is intuitive and therefore open to errors, as is the process of obtaining dates by comparing an archaeomagnetic direction of unknown date with the curve by eye.

5.7.3 *The archaeomagnetic data base*

For investigations into curve-building to be fruitful, it is essential that all the available archaeomagnetic data are made easily accessible, probably by collecting them into a computerised data base. This thesis (Section 5.4) has demonstrated that such a data base could be established using commercial software, such as INGRES. Suggestions were made as to the categories of information that might be included in the data base. Even the limited range of categories used in this pilot data base provided sufficient information for an examination of the data used in the Clark calibration curve. Extension of the categories would permit the investigation of more diverse areas, such as the relationship between number of samples and dispersion of magnetic directions. There is clearly also great potential for expanding the data base with information from more recent measurements and other data not incorporated in the Clark curve. The limited data base established here proved invaluable for investigating the raw archaeomagnetic data and for providing data for curve building exercises.

A limitation of this study was the assumption that the α_{95} value recorded for each context reflects the total error in the determination of the magnetic direction. This does not take into account such factors as the reliability of a particular material as a magnetic recorder and non-random errors such as tilting. For these factors to be assessed it would be necessary to consider each feature individually and the factors specific to each type of features. This issue is discussed further in Section 6.4.

5.7.4 *Representation of the British data*

Having collected the data to be used in the calibration curve and corrected it to a central location by the 'Conversion via Pole' method (Section 5.5), the next step was to examine ways of presenting the data. A number of alternatives have been explored by archaeomagnetists in different regions (Section 5.3) and this study investigated a number of methods of increasing complexity. It commenced with an examination of the raw data, then displayed the data with error bars, presented both as declination vs. inclination, and declination and inclination vs. time. The investigation then moved to a simple averaging method and a moving window method of averaging, such as that suggested by Sternberg (Sternberg, 1982; Sternberg & McGuire, 1990a). Of particular importance was the ability of an objective method to take into account the uncertainties in both the magnetic direction, and in its archaeological age range. Moving-window smoothing of the British data showed that, in periods where data were abundant, the method appeared to produce a credible secular variation curve. However, where data were sparse, the curve produced was deceptive and had large error margins. With the present state of knowledge, it would seem that there may be valid arguments for the interpolation of the curve by hand

through such periods, but a concerted attempt to sample dated structures within these under-represented periods is the best long term solution to this problem. The great advantage of a treatment of archaeomagnetic data, similar to the weighted moving window smoothing, is that it leads to a secular variation curve with an associated error bound which takes account of errors in the archaeological dating and the dispersion of magnetic directions from a single context. Hence, when archaeomagnetic dates are produced the uncertainties in the curve can be taken into account, as well as the uncertainties in the magnetic direction to be dated. This will inevitably lead to larger error margins on archaeomagnetic dates than have previously been common, as can be seen from the reconsideration of magnetic directions from sediments previously dated using the Clark curve (Section 5.6.4). However, the estimated error is more realistic, being both quantitative and repeatable.

5.7.5 Suggestions for future work

In conclusion, there are serious shortcomings with current procedures for dating archaeomagnetic directions. British archaeomagnetism is now at a stage where it would be possible to collect sufficient archaeomagnetic measurements into a data base and to apply more rigorous methods to curve fitting to the data for at least parts of the last three millennia. This would firmly establish the mathematical basis for producing dates and their errors, laying the foundations for widespread and successful use of archaeomagnetic dating in the future. The first steps should be the creation of a suitable data base and gathering of as many data as possible, particularly from before 1000BC and in periods where data are sparse or the geomagnetic field is changing quickly. This should include samples already measured and a concerted attempt should be made to carry out archaeomagnetic measurements on newly excavated features, of both fired material and sediments. Such sampling should not depend solely on the archaeologist's interest in an archaeomagnetic date but should be a routine part of excavation. In principle, as more samples are collected, the α_{95} value associated with the curve should decrease until it is comparable with the α_{95} of individual features (Sternberg & McGuire, 1990a). In the longer term, it is possible to envisage an integrated system where every archaeomagnetic measurement is entered into the data base and those of high enough precision are added to the curve-drawing routine which constantly redraws the curve in the light of new information. The quantitative curve should be accompanied by quantitative methods of obtaining a date, particularly addressing the problems of dating a sequence of magnetic directions and providing realistic error determinations for dated magnetic directions.

Chapter 6

Conclusions, Discussion and Future Prospects

6.1 INTRODUCTION

6.1.1 *Summary of the aims of the thesis*

The broad aims of this thesis were to advance the study of archaeomagnetic dating by investigating new, and improving old, techniques in its execution and by its application to a number of materials which have not previously been studied rigorously. These objectives were approached by a number of related investigations.

The central experimental investigation was into the dating of waterlain sediments by archaeomagnetism. The aim was to establish which of the wide range of such materials would be most suitable for routine study by archaeomagnetic methods, and to identify the potential and pitfalls of such a study. In addition to extending the range of datable materials to include waterlain sediments, the study aimed to provide information on the environment of deposition and the magnetic mineralogy, using measurement techniques not commonly employed in archaeomagnetic studies. These investigations involved the measurement of magnetic fabric (Section 2.3) and IRM determinations (Section 2.4).

Continuing the theme of the investigation of new materials, a number of sediments and fired materials from the Xi'an area of China were investigated. The sediments provided a comparison with British sedimentary material. Although fired materials have generally been much more widely studied than sediments, results from these structures were valuable because they provided a comparison between sediments and fired material from the same site and between a range of fired materials in China and a range of sedimentary contexts in Britain. The Chinese material also presented a unique opportunity to study extremely important, well dated features and to incorporate the results into the data set needed for the compilation of a calibration curve for the Xi'an region.

Archaeomagnetic dating, whether in Britain or elsewhere, is reliant upon the use of a calibration curve. Hence any investigation of the dating technique must include an examination of the calibration process. The objective of this part of the study was to carry out a detailed assessment of the current calibration process, both in Britain and elsewhere, and to suggest improvements. The calibration of archaeomagnetic directions underpins all archaeomagnetic dates and it was considered critical that new techniques are developed to improve this procedure.

6.1.2 Summary of the work carried out

The stated aims of the project (Section 6.1.1) were pursued by a number of detailed investigations which included fieldwork, laboratory experimental work, computing and critical examination of the results from this, and other, studies.

Chapter 3 describes the experimental investigation of the archaeomagnetism of waterlain sediments. A wide variety of waterlain deposits were examined, concentrating on those which occur most commonly in British archaeological sites, in order to identify which might be most suitable for routine archaeomagnetic investigations. Such a study is particularly important because of the frequency with which these deposits are encountered during excavation and the wealth of archaeological information that is preserved within them. 31 different contexts from 10 sites in England and Wales were studied, including riverlain, dumped, estuarine, ditch, well and moat deposits from archaeological sites and modern riverlain deposits. The majority of deposits studied, 70%, were riverlain, reflecting the frequency with which these occur in British archaeological sites.

Intrinsic to the investigation was a detailed study of the archaeological context of both the site in general and, more specifically, the particular deposit; including a discussion of the results of previous and current excavations. Such information was crucial as it was used to compare the archaeological interpretation of the date and origin of the deposit, with the inferences made on the basis of the archaeomagnetic study.

Adaptations were made to previous sampling and orientation methods (Section 2.1) in order to provide an appropriate method for sampling the types of sediments encountered. A number of measurement techniques were considered (Sections 2.2, 2.3 & 2.4). Those selected were a compromise between the desire to extract the maximum amount of information from the deposit and the time restriction imposed by carrying out the same measurements on all groups of samples to enable valid comparisons to be made. The selected methods provided information about remanent magnetisation, magnetic

fabric and magnetic mineralogy. For all groups of samples measurements were made of natural remanent magnetisation (Section 2.2.1); pilot demagnetisation of representative samples (Section 2.2.2); bulk demagnetisation of all samples (Section 2.2.2); specific susceptibility (Section 2.3.1); susceptibility anisotropy, including $h\%$ and q (Section 2.3.2); and the IRM acquisition of representative samples, characterised by SIRM, % of remanence acquired in 1T, $(B_o)_{cr}$ and the S ratio. The implications of these results for each context were then discussed and compared with the archaeological interpretation and any cases of discrepancy investigated. Where appropriate, an attempt was made to date the context by comparison of its remanent magnetisation with the archaeomagnetic calibration curve or the lake sediment secular variation curve. Whilst a small number of studies of this nature had been carried out previously (Section 3.3), this investigation was significant because it incorporated a wider variety of contexts, some previously unstudied; included modern deposits for comparison; adopted a more systematic approach to sampling and measurement; and applied new measurement techniques.

Chapter 4 discusses the study of 6 fired structures and a sequence of sediments from the Xi'an region of China. A detailed evaluation was made of the archaeological setting of the features examined, particularly any evidence of date which might allow the results to be used in an archaeomagnetic calibration curve. The experimental measurements included natural remanent magnetisation; pilot demagnetisation of representative samples; bulk demagnetisation of all samples; the IRM acquisition of representative samples, characterised by SIRM, % of remanence acquired in 1T, $(B_o)_{cr}$ and the S ratio; and, in some cases, Curie temperature determination. The specific susceptibility and susceptibility anisotropy of the sediments was also measured. The magnetic directions were compared with historical observations of the ancient geomagnetic field and the results of previous archaeomagnetic studies in the vicinity, and the prospects of compiling a calibration curve for the region were evaluated.

Given the aim of improving the techniques by which archaeomagnetic dating is carried out, Chapter 5 forms a vital part of the study. An investigation of the present calibration curve, the data from which it is compiled and its current use were presented (Section 5.2). The limitations of this method were explored and an examination made of the procedures used in producing calibration curves in other regions, to see how other archaeomagnetists have tackled similar problems (Section 5.3). A number of ways of improving the representation of the British curve were suggested and the need for a central data base of archaeomagnetic information was established and a suitable form suggested (Section 5.4). These suggestions were put into practice by the compilation of a data base which was then used to examine a series of ways of representing the calibration curve (Section 5.6). A mathematical investigation of the efficiency of different methods of correction of archaeomagnetic vectors to a central location was also made

(Section 5.5). There was a brief discussion of the ways of obtaining dates from a calibration curve (Section 5.6.4) and a reappraisal of the dates obtained in Chapter 3 using the Clark calibration curve.

6.2 CONCLUSIONS FROM THE SEDIMENT WORK

The study of waterlain archaeological sediments, described in Chapter 3, encompassed a wide range of sedimentary environments and magnetic measurements, with the objective of identifying which sediments are most suitable for routine study and which measurement techniques are the most informative. It is possible to draw a number of broad conclusions which answer, at least in part, these questions. A detailed discussion of the conclusions can be found in Section 3.5.

Sampling with 2.5cm diameter plastic tubes was found to be satisfactory. The small holders offer a number of advantages over the larger holders conventionally used; they enable very thin deposits to be sampled, are quick to insert, create minimal sediment disturbance and allow obstructions to be avoided; yet generally have an easily measurable intensity of magnetisation. With suitable positioning of samples it is possible to obtain a detailed record of secular variation down a vertical section and to assess the dispersion of magnetic directions within a single horizon. The orientation methods available were less than satisfactory and, although the use of a magnetic compass was generally acceptable, it is suggested that this aspect of sampling would benefit from further development (Section 3.5.2).

Measurements of remanent magnetisation and demagnetisation provided the information necessary for dating and identified which sediments were most likely to be datable (Section 3.5.3). Caution must be exercised when drawing general conclusions from what is inevitably a limited data set, but a number of observations can be made. Whilst most sediments have an intensity of magnetisation that is easily measurable with a spinner magnetometer, the finer grained deposits of clay, silty clay and silt have the highest intensities and would thus it would be more likely for small samples to have a measurable magnetisation. Sediments with high organic contents are characterised by low intensities of magnetisation and low stability indices, as are sandy deposits. These factors suggest that if these latter types of sediments did record a stable remanence, it would be less likely to be measurable. Other sediment types show a variety of stability indices, suggesting that factors other than grain size, such as mineralogy, influence stability of magnetisation. Sediments with smaller grain sizes (clay, silty clay, silt) also have the lowest α_{95} values. Attempts were made to date all contexts with $\alpha_{95} < 6^\circ$; in

most cases these gave dates by conventional archaeomagnetic methods which were in agreement with the archaeological evidence.

The broad conclusion is that sediments with a high intensity of magnetisation, measurable stable primary directions of magnetisation and a small enough dispersion of magnetic directions to be datable tend to be smaller grained deposits of clay, silty clay and silt. These come from a variety of contexts, including river floods, estuarine, silted river/streams, and static depositional environments. Material with a high organic content, visibly bioturbated or otherwise disturbed, or with a large grain size, is characterised by low intensities of magnetisation, and hence low stabilities and α_{95} values that were too large to allow dating. Modern analogue environments prove to have very different properties from their archaeological equivalents; an observation which needs further investigation. These conclusions confirm and supplement the list of contexts previously dated in this way (Section 3.3), suggesting that archaeomagnetic dates can be obtained for waterlain sediments, if they are from a particular range of types of sediment and particular depositional environments.

Magnetic fabric measurements have rarely been used in archaeomagnetic studies, but it was hoped that these would provide useful information concerning the environment of deposition (Section 2.3). These studies show that the distribution of minimum and maximum axes of susceptibility are similar to those found previously to originate from specific depositional conditions in natural sediments and laboratory experiments. The axes indicate directions of current flow consistent with the archaeological evidence. Further information is provided by $h\%$ and q , but in both cases the results are at variance with those from earlier laboratory experiments. In particular, q is shown to be of limited use in identifying primary depositional fabrics. Thus, whilst indications of palaeoflow directions may be available to the archaeologist, further work is required before the principles of magnetic fabric analysis can fulfil their potential in the study of archaeological material.

Mineral magnetic studies were carried out in order to identify the remanence carriers and characterise their behaviour, thus leading to a better understanding of the nature of the magnetisation of the sediments. These tests proved particularly useful in identifying magnetic minerals, using their hardness to magnetic fields as the criteria. The ratio of magnetite to haematite/goethite is provided by S , whilst $(B_o)_{cr}$ gives an indication of grain size. In most cases the magnetisation appears to be carried by magnetite in a variety of grain sizes, as suggested by the demagnetisation behaviour. There is clearly much potential for mineral magnetic studies to play a greater part in archaeomagnetic investigations to indicate the source of a sediment and the origin of its

magnetisation. Such studies would be applicable to all types of sediment, regardless of depositional environment.

In summary, a number of complementary techniques, when applied to the appropriate waterlain sediments, are found to reveal information on environment of deposition and magnetic mineralogy, in addition to dating evidence. There is, however, clearly further work to be done in establishing the validity and accuracy of such dates.

6.3 CONCLUSIONS FROM THE STUDY OF CHINESE MATERIAL AND COMPARISON WITH SEDIMENT RESULTS

The study of fired material and sediments from the Xi'an region of Shaanxi Province, China, described in Chapter 4, is valuable for a number of reasons. It shows that certain types of archaeological remains from this area are suitable for archaeomagnetic studies, adds information to the data set necessary for constructing the archaeomagnetic calibration curve for the region, and enables earlier archaeomagnetic and direct measurements of the geomagnetic field to be tested. A detailed discussion these aspects can be found in Section 4.5. Study of this material also allows comparison to be made between the magnetic properties of sediments and fired materials. Such a comparison is extremely important in the assessment of the relative merits of the materials for archaeomagnetic study. Although the data available, especially pertaining to fired materials, are limited, the following section examines the conclusions drawn from the Chinese study in the light of the conclusions from British sediments (Section 6.2).

Fired material was sampled by the button method (Section 2.1.2), which is satisfactory for all but the most friable materials. Whilst sources of errors in sampling are difficult to assess (Section 2.6), it is clear that fired material, being more robust, is less disturbed by sampling than sediments. Although orientation with a magnetic compass is the most common method for both types of material, sediments are frequently more inaccessible and therefore subject to increased errors of orientation. There is a greater choice of sample location for sediments, as the small sample holders enable obstructions to be avoided, whereas fired materials are frequently partially destroyed and reconstructed, restricting sample sites. Aesthetic considerations are also important factors in sampling. For fired remains, particularly those of the importance of these Chinese features, the number of samples and their locations are often severely restricted to preserve the feature. In contrast, sediments are rarely considered to be of great archaeological value and the number of samples is restricted only by the size of the deposit. Disturbance of a sediment is often clearly visible from an examination of sedimentary structures; however cracking, subsidence and differential movement of fired

remains is much more difficult to detect. Despite the problems outlined, some sediments and fired materials had an α_{95} value of $<2.5^\circ$ (Sections 3.5 & 4.5), suggesting that careful sampling could keep the random errors incurred to an acceptably low value. It was observed that sediments were subject to loss of remanence if allowed to dry during storage (Section 3.4.10), a problem that did not occur with fired materials. The fact that a sediment is deposited over a period of time made it capable of recording secular variation of the geomagnetic field, rather than the single magnetic direction available from a fired deposit. In summary, whilst fired materials are more robust and retain their magnetisation during storage; sediments have the advantages of showing disturbances more clearly, sampling being less constrained on aesthetic criteria and occurring more frequently on archaeological sites.

When dating a material, or incorporating its magnetic direction in a calibration curve, the strength and stability of the primary component of magnetisation are very important. The Chinese fired material had much wider ranges of intensity of magnetisation than was common for sediments, reflecting the inhomogeneity of fired materials. The highest values of intensity of magnetisation of fired materials are in excess of $3.5 \times 10^{-3} \text{Am}^2\text{kg}^{-1}$, much greater than the highest values for sediments ($< 4.5 \times 10^{-4} \text{Am}^2\text{kg}^{-1}$) as would be expected from material whose magnetisation has been enhanced by firing. On the other hand, some fired materials, for example Banpo (Section 4.4.2), have an intensity of magnetisation which is below that of many sediments. Hence, as intensity of magnetisation is dependent upon magnetic grain size, mineralogy and concentration, it would be incorrect to assume that all fired materials have an intensity of magnetisation that is in excess of the intensity of magnetisation of sediments, although this is generally the case. For example, sediments from a silty clay deposited under slow moving water conditions (Section 3.4.2) had a greater magnetisation than poorly fired material (Section 4.4.2).

Stability indices of fired materials are generally high, 6 - 60. Whilst none of the sediment samples reached the same maximum values, 62% were in excess of 4, suggesting that sediments from certain environments record a primary magnetisation that is at least as stable as that of fired material. Bioturbated sediments or those with large grain sizes have lower stability indices, relating to their depositional conditions or post-depositional disturbance. The absence of stability indices under 6 for fired materials, reflects the generally greater stability of their magnetisation.

When considering the dispersion of the direction of primary magnetisation, it can be seen that the fired materials all have α_{95} values in the range 2.4° - 9.3° , whereas for some sediments the α_{95} values are very high, over 30° in some cases. However, for fine grained deposits from static or slow-moving water conditions α_{95} values are less than 4° ,

as small as, and sometimes smaller than, fired materials. This suggests that certain sediments are at least as reliable recorders of the geomagnetic field as fired materials, and in some circumstances are more reliable. There appears to be no difficulty in identifying a stable component of primary magnetisation in most fired materials, so the limiting factor on the α_{95} value must be imperfect recording of the geomagnetic field by the remanence carrying minerals; variations in the local geomagnetic field; cracking or movement of the structure itself; the effects of weathering, sample inhomogeneity and anisotropy; and the poorly understood phenomenon of magnetic refraction (Section 1.4.1). Sediments are also subject to problems of imperfect recording, variations in the local field, movement of the sediment and sample anisotropy; in addition to which there are problems of bioturbation and current disturbance (Section 1.4.2). However, sediments are not affected by magnetic refraction, sample inhomogeneity is less common and weathering is reduced as deposits are frequently covered by further material. The relative magnitudes of the α_{95} values for fired material and sediments suggest that, unless a deposit has been extensively bioturbated or has a large grain size, the random errors are of similar magnitude. The magnitude of non-random errors, such as inclination and bedding errors or current rotation in sediments (Section 1.4.2) or tilting of a fired feature (Section 1.4.1), is extremely difficult to assess, as such an assessment requires knowledge of the date of the material, thus determining the expected magnetic direction from the calibration curve, and comparing this value with the measured value of direction. Such a determination was impossible with the Chinese material, as the calibration curve does not exist, and unrealistic with the British calibration curve, as it does not provide the required level of precision (Section 1.4.2). However, magnetic fabric measurements of sediments provide an insight into the effects of depositional conditions, whereas factors such as magnetic refraction and tilting of a fired structure have to be assessed using archaeological observations and depend upon samples being taken from certain parts of the structure. The success in dating fine grained sediments suggests that they are at least as suitable for archaeomagnetic studies as fired material, particularly in cases where material is poorly fired or subjected to extensive cracking. There is the added benefit of the information available from magnetic fabric studies.

However, there is a further, very significant, issue to consider. It has been well established (Section 1.4.1) that in most cases the geomagnetic field recorded by a fired material, such as that sampled in China, is the field in which the material last cooled. In contrast, debate continues about the time when a sediment acquires its magnetisation (Section 1.4.2). Evidence from this study, particularly the modern analogue deposit (Section 3.4.3) and the apparent lack of inclination errors in any of the sediments, supports the view that the magnetisation is acquired post-depositionally. If this is the case, the date of the magnetisation is likely to be related to the compaction and water content of the sediment, and not necessarily to the archaeological event of deposition.

Determining exactly what event is being dated is crucial to the use of archaeomagnetic dates from sediments. Such a determination would require a more detailed examination of the magnetisation of modern analogue sediments, and even then the process might vary under different depositional conditions, and with variations in bulk sediment grain size and magnetic mineral grain size. The fact that bioturbation may both disturb a DRM and aid the formation of a PDRM (Section 1.4.2) has yet to be considered in relation to archaeological deposits and much work also remains in the understanding of the formation of CRM, particularly in organic deposits.

Magnetic mineral studies of the Chinese fired materials revealed them to have considerably higher SIRM values than sediments, as would be expected after firing. In fired materials there is often a much higher haematite content, while the magnetic mineral of sediments is almost entirely magnetite.

In conclusion, both fired material and sediments are shown to retain a stable record of primary directions of magnetisation and therefore possibly to be suitable for archaeomagnetic dating. Fired materials have the advantage of being robust, generally with a higher intensity of magnetisation and usually recording a known archaeological event. Whilst sediments are more prone to disturbance on sampling and storage, and their intensity of magnetisation is usually lower, their magnetisation appears to be of comparable stability and the dispersion of magnetic vectors of similar magnitude to that of fired materials. Sediments have the advantages of occurring more frequently in archaeological sites, their sampling is less restricted and magnetic fabric measurements provide some indication of non-random errors. This study shows that fine grained sediments from static or slow moving water conditions should be as much part of routine archaeomagnetic investigations as fired materials. The Chinese study and the sediment work share a common problem in the construction and use of an archaeomagnetic calibration curve. This issue underpins the whole procedure of archaeomagnetic dating, be it for fired materials or sediments, and hence is of the greatest importance in the application of the technique. Chapter 5 outlines the problems encountered and discusses some solutions to them.

6.4 CONCLUSIONS FROM THE CALIBRATION CURVE STUDY

The work carried out in Chapter 5 to investigate archaeomagnetic calibration curves represents perhaps the most significant contribution of the thesis to current archaeomagnetic practice. Instead of demonstrating ways in which archaeomagnetic techniques might be applied to new materials or used to give new types of information, this chapter exposes some of the serious problems with current archaeomagnetic

procedures. It then examines ways in which these procedures might be improved. The implications of this study affect not only current and future archaeomagnetic practice, but also suggest that dates obtained previously by conventional archaeomagnetic methods should be reappraised. A detailed discussion of the conclusions of this work is to be found in Section 5.7.

The chapter focuses on the data used by Clark in the compilation of the current British archaeomagnetic calibration curve (Clark *et al.*, 1988). Initially the limitations of the current data set and its method of presentation are demonstrated (Section 5.2). Possible improvements are then outlined, concentrating particularly on the need for the establishment of an archaeomagnetic data base. Whilst there are a number of ways in which archaeomagnetic data can be presented in a calibration curve (Section 5.5.3), detailed examination focuses on the moving window averaging approach becoming common in the United States (Sternberg, 1982; Sternberg & McGuire, 1990a). The limitations of this method are acknowledged, but the improvements over current British practice are clear. The investigation does not continue to examine in detail methods of dating an unknown magnetic direction, but a number of suggestions are made and it is shown by visual examination that the more rigorous approach to the calibration curve leads to larger, but more realistic, errors in the dates obtained.

The calibration curve investigation of Chapter 5 only includes the data used by Clark in his calibration curve (Clark *et al.*, 1988) in order to demonstrate how the same data could be used to give different calibration curves by using different procedures and presentations. Obviously there is a great deal of information from other archaeomagnetic studies which could be incorporated in a future curve (Section 5.4.4). A valid criticism of the approach here is that it assumes that the data reflects accurately the ancient geomagnetic field. It is clear that any treatment of archaeomagnetic data must not be limited to mathematical considerations, but must also include an awareness of the archaeological situation and its limitations. For example, it is simply not acceptable to take the empirical approach of adding 2.4° to the inclination of floor samples of fired structures (Clark *et al.*, 1988) in an attempt to account for the effects of magnetic refraction, without an understanding of the sources of the error. The study in Chapter 4 of Chinese fired materials demonstrates how archaeomagnetic directions obtained in this study conflict with those of previous studies for no readily apparent reason and Chapter 3 highlights the problem of identifying the archaeological event that a DRM represents. For these reasons there needs to be an increased understanding of the processes of magnetisation and all data, even those accepted by Clark, must be subjected to detailed scrutiny before acceptance into the data base. The data should at least be accompanied by a measure of their potential uncertainty. Once incorrect data are accepted they will make a permanent, but erroneous, contribution to the calibration curve.

It is also assumed that α_{95} values provide a valid indication of the precision of measurements of magnetic direction. However, as Chapters 3 and 4 have explored, there are sources of consistent errors which will not contribute to the α_{95} value but will still lead the value of magnetic direction not being a true record of the geomagnetic field. Whilst the studies in this thesis indicate that inclination and bedding error and current flow effects do not appear to occur in archaeological sediments in the conditions examined, it is important that magnetic fabric measurements continue to be used to assess their contribution. Factors such as tilting of fired structures may also be significant and must be carefully searched for.

Much of Chapters 3 and 4 concentrate on reducing the errors in sampling, orientation and isolation of the primary component of magnetisation, with the aim of reducing the dispersion of magnetic directions of samples from a context of a single date. Such measures are extremely important, particularly if data are to be incorporated into the calibration curve; the more precisely defined the magnetic vector, the more it constrains the movement of the curve. However, the examination of both fired materials and sediments indicates that, even with very careful sampling of material with an easily identifiable, stable direction of magnetisation, the smallest α_{95} value attainable is around 1.5° (Section 3.4.2). It seems likely that dispersion of this magnitude reflects inhomogeneity in the material and inadequacies in its abilities as a magnetic recorder, which are not reducible by improved sampling and measurement techniques. This lower limit on values of α_{95} means that it may not be possible to clearly define the movement of the curve through some periods where changes in declination or inclination are small, such as the 'Roman hairpin' between AD150-AD400. It is not possible to identify an α_{95} value which is too large to be of value in building the calibration curve, because this would depend on the rate and magnitude of changes in secular variation and the amount of other data available in that period. For example, a magnetic direction with an α_{95} value of say 8° dating to 700 BC would be important because of the apparently extreme values of magnetic direction in that period and the scarcity of other data. However, if the magnetic direction was dated to 200AD it would add little to the interpretation of the curve, because of its large error in a period where secular variation appears to be slow and there are more precise data available.

As demonstrated in Section 5.2, almost all of the magnetic directions used in the British calibration curve are taken from fired materials, and the investigations of such materials in Chapter 4 demonstrates the suitability of fired materials in curve building, because of the precision with which their magnetic directions can be determined and the excellent archaeological dating control. However, Chapter 3 shows that some sediments also have small α_{95} values and stable magnetic directions, indicating that they could make a significant contribution to a calibration curve. Sequences of magnetic directions

from sediment sections have the potential of making a particularly important contribution, if they record secular variation over a period of time. Unfortunately this study has demonstrated the rarity of material preserving a record of this sort. There are also a number of problems associated with the incorporation of sediment data into the calibration curve data set; in particular there is continued debate over the exact archaeological event being dated and varying rates of deposition make sequences of magnetic directions hard to interpret (Section 2.5.3). These problems must be addressed before this potentially valuable source of archaeomagnetic data can be used in the calibration curve.

The results from the Chinese study (Chapter 4) reveal the large number of well dated magnetic directions that are necessary before any deductions can be made about the shape of the calibration curve. Studies in this region are only just entering the slow and laborious process of data collection. However, by the time sufficient data are collected there should be a well-established, rigorous and objective method of combining it into a calibration curve, an advantage which was not available to those compiling the early versions of the British calibration curve.

6.5 THE ACHIEVEMENTS OF THIS STUDY

6.5.1 In the context of archaeomagnetic studies

At the time when this thesis commenced, archaeomagnetic dating was commonly used both in Britain and elsewhere (Section 1.6) as a method of dating archaeological remains. It was largely applied to fired materials, although some studies (Section 3.3) had begun to demonstrate the potential of waterlain sediments. Archaeomagnetic investigations were mainly regarded as a method of dating and little work had used the analyses of magnetic fabric and magnetic mineralogy of archaeological material to provide additional information. Whilst, in some regions of the world, archaeomagnetism was widely used as a dating technique, the procedure for obtaining dates was increasingly criticised for its lack of rigour. In other parts of the world, for example China, work to collect archaeomagnetic data to form a calibration curve was in its early stages. Against this background this study proceeded to investigate a number of aspects of new materials and techniques in archaeomagnetic dating.

As shown in the detailed conclusions above, a number of contributions were made to archaeomagnetic studies by investigating new materials and exploring new techniques. The range of datable materials was extended to include waterlain sediments from certain archaeological environments and fired materials from key sites in China.

Suitable sampling methods were developed and tested; and the potential of magnetic fabric and mineralogy studies for providing information on depositional conditions and origin of magnetisation was established, giving an insight into the process of acquisition of magnetisation in both fired and waterlain materials. Finally, ways in which current dating practices could be improved by revising the calibration curve were demonstrated, suggesting new techniques by which to advance studies.

6.5.2 In the context of scientific dating in general

Archaeomagnetic dating is one of a suite of scientific dating techniques available to the archaeologist (Aitken, 1990), each applicable to a particular material or group of materials, possibly from a specific environment and often only within a certain archaeological period. The advances made in archaeomagnetic studies contained in this thesis mean that the technique can be more widely applied on archaeological sites and there can be increased confidence in the dates obtained from it.

Archaeomagnetic dating has a number of advantages over other dating techniques. It has been shown in this study to require only very small samples and to be cheap and quick, making it possible to carry out archaeomagnetic investigations interactively with excavation. One achievement of this study has been to show that certain archaeological sediments are capable of retaining a record of the ancient magnetic field. Thus the range of materials that it is possible to date by archaeomagnetism is extended from fired materials to include waterlain sediments. This is a significant development as sediments occur frequently on archaeological sites, their conservation is usually not required so sampling can be extensive and they are often directly related to other archaeological events, for example a flood deposit covering an occupation layer.

There are, of course, a number of ways in which waterlain sediments can be dated; organic material in the matrix can be dated by radiocarbon, ceramics by thermoluminescence or typology, and artefacts by their historical associations, for example coins. Biological evidence can give a broad indication of date and dendrochronology can provide a very precise date (Section 3.1). However, all these methods only date inclusions within the sediment and not the event of deposition itself. Hence, problems may arise finding such material or relating the date obtained to the archaeological environment. The techniques currently available for dating the sediment itself are archaeomagnetism and luminescence (Section 3.1). However, uncertainties in identifying the residual signal that remains unbleached in sunlight means that sediments more recent than 5000 years old cannot yet be dated by thermoluminescence (Aitken, 1990). Whilst use of optically stimulated luminescence rather than thermoluminescence may irradiate this problem, at the present time archaeomagnetic dating seems the most

appropriate to cover the last 3000 years, the period encompassing most British archaeological investigations. As this study has discussed, a number of problems still remain with respect to the use of sediment dating by archaeomagnetism, particularly identifying the event being dated and the use of the calibration curve. However, archaeomagnetic studies have also been shown to give additional information about depositional environments and magnetic mineralogy which are not available from other dating techniques, and may, in some circumstances, be of more interest to the archaeologist than a simple date.

In some parts of the world, such as in China, where there are a wealth of well dated fired remains, archaeomagnetic dating is ideal, providing a cheap and quick method of dating materials. There remains the drawback of the large number of measurements required to build a calibration curve, making the method initially laborious and time consuming.

The biggest problem with archaeomagnetic dating is that the method is dependent upon other methods to provide the absolute dates for the calibration curve; that is it transfers a chronology rather than establishing one. Although this problem has been widely recognised, until now there have been few attempts to consider this factor in the archaeomagnetic dates provided. Justifiable criticism of the lack of rigour in the production of archaeomagnetic dates has led to other techniques being preferred where possible. This study has shown that these problems are not insurmountable, but acknowledgement of them will inevitably lead to an apparent decrease in the precision of the dates provided. However, these dates will be more realistic and scientifically justifiable. With further data collection and improvements of calibration data quality (Section 5.7), precision can be improved. However, in this study the precision of dates has been shown to be currently a minimum of ± 25 years and considerably larger where there are fewer calibration data, slower secular variation, poor dating control or greater uncertainty in the magnetic direction to be dated. Although larger than the error previously quoted for archaeomagnetism (Section 5.6.4), this figure still compares favourably with other methods. The best precision attainable by radiocarbon is ± 20 years (Bowman, 1990) by high precision dating, but this method is expensive and such levels of precision difficult to attain. Errors in thermoluminescence dating are at least $\pm 5\%$ (at a 68% level of confidence) but are very dependent upon the conditions of burial and material to be dated (Aitken, 1990). Other dating techniques such as potassium argon, uranium series, fission track or obsidian hydration are applied to periods or materials not usually studied in British archaeology.

In conclusion, this study has served to increase the diversity of applications of archaeomagnetism and to address existing problems which hinder its use as a dating technique. However, until the solutions suggested here or similar ones, are adopted to address the attendant problems, it could be argued that archaeomagnetic dating might be best regarded as a research topic rather than a service dating technique.

6.6 SUGGESTIONS FOR FURTHER WORK AND FUTURE PROSPECTS

Inevitably in an investigation of this nature, a number of questions will remain unanswered and new questions will have arisen during the course of the study, making the identification of priorities for further work extremely difficult. On the one hand, it is essential to the credibility of archaeomagnetism as a dating technique that a more rigorous approach to the calibration curve is developed; on the other, an understanding of the data being used in the calibration curve is also vital. The key to successful future developments must be to proceed with a number of complementary investigations.

The first step that is necessary is to reassess the provision of archaeomagnetic dating as a service in Britain, and at least to qualify dates with cautionary notes, until the problems of the calibration have been addressed and a solution agreed by the archaeomagnetic community. Dates obtained by current procedures have been shown to give a false impression of the precision of the method and may be totally erroneous. If archaeomagnetism is to be treated as a viable scientific dating technique, some of the problems with its use in dating must be addressed immediately. In order to produce a more realistic calibration curve, it is necessary to collect together as many reliable data as possible. This could be achieved with comparatively little effort using the data base established here, but would require considerable organisation and co-operation between archaeomagnetic laboratories. All published data would need to be included, and standard forms developed for the submission of new or unpublished data. These forms should contain details of such matters as measurement processes, sample stability and number of samples, to facilitate quality control of the data base. Even when this information has been collected the data base would not be a fixed record; every new archaeomagnetic measurement would be added to it as a matter of course and the archaeological dates would be changed as more archaeological evidence became available, such as a site being reinterpreted or dates from another method becoming available. This body of information could then be used as the basis on which to commence constructing a calibration curve.

The calibration curve could be produced by the method suggested here or one based on similar principles, the criteria being that it produces a curve with an error bound

which is related to the uncertainty in archaeological date and determination of magnetic direction. A statistical method of deriving a date and its associated error for a magnetic direction would then be required.

Clearly the more data available, the easier it is to construct the calibration curve and the more likely it is to be an accurate reflection of the geomagnetic field. It might be suggested that efforts to sample features should be concentrated on periods where secular variation is fast or there are few existing data. However, the strong recommendation from this work is that archaeomagnetic samples should be taken from all fired structures and suitable sediments as a matter of routine. There are two main reasons for this. Firstly, there are no periods for which there are sufficient archaeomagnetic data and every suitable feature offers new information for the calibration process. Secondly, archaeological excavation is usually a destructive process, once a feature has been excavated that archaeomagnetic information is lost for ever; taking samples allows for some future study of the feature's magnetic properties. The latter reason is particularly relevant if archaeomagnetic research interests change, leading to an archive of material for future investigations. Having advocated such an extensive sampling programme it must be noted that this will require considerable additional financing; in the climate of developer-funded archaeology it is unlikely that existing funding will be able to encompass what is likely to be regarded as a research project.

In order to maximise the information attained by archaeomagnetic investigations, it is necessary to improve orientation methods, thus decreasing the scatter of magnetic directions and making the data more useful in the calibration curve. The development of a system for taking oriented cores would greatly increase the number of sedimentary contexts that could be sampled. A better understanding of the processes of magnetisation acquisition is necessary if data are to be used in a calibration curve. This might be provided by an increased use of magnetic fabric and mineralogy studies or integrated studies involving environmental and geological information, particularly from sedimentary contexts. The existence and effects of magnetic refraction needs to be established by extensive sampling of fired structures and attempts must be made to determine the event recorded in sediments and the relationship between DRM and PDRM processes. The latter needs to be attempted by the study of modern analogue deposits and how their magnetisation changes with time, rather than laboratory reconstructions.

Work in China should proceed with the sampling of both fired structures and sediments as opportunities arise, possibly concentrating on a particular time period with good dating control, unless a feature is under threat when it should be sampled as a matter of course. A large number of measurements are required for a calibration curve

and so extensive sampling is necessary. However, it must be stressed that the required number of samples from a feature must be taken and the feature consolidated if necessary, or the results obtained may be unreliable. A further examination should be made of the historical observations of the geomagnetic field to establish their validity.

In conclusion, if the opportunity to reformulate the procedures of British archaeomagnetic dating on a more rigorous basis is seized, at this stage, a basis can be established for the use of the technique as a valuable scientific dating method. This will set a pattern to be followed by areas which are just developing the study, such as China. Without such advances, archaeomagnetic dating runs the risk of coming to be regarded as a simplistic treatment of a complex physical phenomenon, which is no longer acceptable to the scientific community within archaeology.

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APPENDIX 1

Table 1A	Results of measurements on groups of sediment samples
Table 1B	Results of measurements of pilot samples
Table 1C	Summary of information for datable sediment contexts
Table 1D	Results of liner regression through intensity and susceptibility data

Table 1A: Results of the measurements on the groups of sediment samples in this study, described in Chapter 3. Magnetic directions have not been corrected to Meriden.

Site details	Sample code	No. of samples	Natural Remanent Magnetisation				After demagnetisation				Magnetic Fabric			
			Int. $\times 10^{-6} \text{Am}^2 \text{kg}^{-1}$	Dec. deg.	Inc. deg.	α_{95} deg.	Demag field mT	Dec. deg.	Inc. deg.	α_{95} deg.	Specific susceptibility $\times 10^{-8} \text{m}^3 \text{kg}^{-1}$	h%	q	% in range
ABC Cinema														
Context 2307	ABC 45-56	12	35.7-48.1	2.3	70.9	8.6	7.5	359.9	67.7	2.0	39.7-55.8	1.0-4.3	0.12-0.84	92
Context 2311	ABC 57-70	14	3.9-8.1	4.2	67.1	3.6	7.5	359.9	66.6	3.3	10.8-17.6	1.7-4.7	0.14-1.02	72
Context 2313	ABC 71-79	9	74.0-125.8	3.9	70.3	1.2	7.5	2.3	69.6	1.5	16.2-35.4	0.5-3.1	0.18-1.83	44
Context 4006	ABC 19-27	9	1.0-10.8	32.1	64.8	9.0	15	36.1	67.9	11.7	3.8-31.4	3.0-23.1	0.05-1.4	74
Stakis Hotel														
Context 4159	SK 1-33	33	4.1-43.5	357.2	70.4	1.5	7.5	1.0	70.6	1.3	6.5-44.5	0.8-3.0	0.03-0.81	76
Bluebridge Lane														
Context 1	YMA 1-9	9	0.9-6.9	113.3	54.3	59.5	N.A.	N.A.	N.A.	N.A.	7.7-8.8	2.3-6.8	0.17-0.73	78
Context 2	YMA 11-21	10	0.9-522.6	332.8	43.6	48.3	N.A.	N.A.	N.A.	N.A.	8.7-27.8	2.5-16.9	0.08-0.88	60

Table 1A (cont.)

Site details	Sample code	No. of samples	Natural Remanent Magnetisation				After demagnetisation				Magnetic Fabric			% in range
			Int. $\times 10^{-6} \text{Am}^2 \text{kg}^{-1}$	Dec. deg.	Inc. deg.	α_{95} deg.	Demag field mT	Dec. deg.	Inc. deg.	α_{95} deg.	Specific susceptibility $\times 10^{-8} \text{m}^3 \text{kg}^{-1}$	h%	q	
Caldicot														
Context 174	CAL 1-28	28	2.1-22.0	N.A.	N.A.	N.A.	10	N.A.	N.A.	N.A.	5.6-19.5	1.7-7.8	0.01-1.74	86
Context 173	CAL 30-63	33	2.4-17.5	N.A.	N.A.	N.A.	10	N.A.	N.A.	N.A.	5.2-18.3	1.6-10.0	0.05-1.51	55
Prudhoe														
	PRU 1-8	8	1.7-2.4	62.3	81.7	6.5	5	342.0	75.7	9.3	14.0-17.5	2.7-4.7	0.2-1.8	88
	PRU 9-16	8	1.1-1.7	126.2	72.7	13.3	5	87.0	77.4	17.1	11.8-12.5	1.4-3.4	0.1-1.0	75
	PRU 17-24	8	0.8-1.3	148.6	48.0	18.6	5	142.4	54.2	28.0	10.0-13.7	2.3-4.5	0.4-0.9	38
	PRU 25-32	8	1.0-1.6	171.1	71.2	15.9	5	188.5	75.5	23.7	12.8-13.9	2.2-5.7	0.1-1.1	86
	PRU 33-40	7	0.7-1.4	101.5	58.2	19.7	5	91.0	59.5	28.8	10.4-12.9	2.3-4.2	0.3-1.1	57
	PRU 41-48	8	0.6-1.7	153.8	82.2	47.4	5	85.7	87.4	90.0	10.4-15.1	2.0-4.8	0.2-0.9	57
	PRU 49-56	8	1.2-1.6	113.9	74.3	8.6	5	24.9	82.1	13.6	11.2-13.2	2.4-3.8	0.2-1.2	57
	PRU 57-64	8	0.9-1.8	123.6	77.6	13.0	5	89.5	86.2	14.9	11.1-12.8	1.9-3.6	0.1-1.4	63

Table 1A (cont.)

Site details	Sample code	No. of samples	Natural Remanent Magnetisation				After demagnetisation				Magnetic Fabric			% in range
			Int. $\times 10^{-6} \text{Am}^2 \text{kg}^{-1}$	Dec. deg.	Inc. deg.	α_{95} deg.	Demag field mT	Dec. deg.	Inc. deg.	α_{95} deg.	Specific susceptibility $\times 10^{-8} \text{m}^3 \text{kg}^{-1}$	h%	q	
Farnley														
	FAR 50-56	7	2.0-2.4	74.2	77.0	4.6	5	55.1	76.5	4.0	11.6-12.6	1.1-3.7	0.1-0.8	71
	FAR 57-64	8	1.7-2.7	17.1	80.0	6.1	5	43.8	79.1	6.7	10.9-12.9	1.1-4.5	0.5-1.5	63
	FAR 65-72	8	1.8-2.3	43.4	79.1	5.6	5	45.1	80.8	6.3	10.2-11.5	0.6-2.2	0.3-0.9	75
	FAR 73-79	6	1.1-2.0	101.7	83.8	13.7	5	107.3	53.8	36.9	9.4-11.2	1.4-2.4	0.4-1.0	50
Stanwick														
Context 1388	STAN 1-9	9	7.5-56.7	21.5	58.6	17.1	10	11.5	54.7	22.4	22.2-73.0	4.1-11.3	0.07-0.98	86
Context 1387	STAN 10-17	8	6.7-18.9	13.1	65.8	2.3	10	10.3	58.5	11.4	8.7-11.5	1.5-3.4	0.23-1.22	63
Context 1387	STAN 18-36	19	3.9-20.6	N.A.	N.A.	N.A.	10	N.A.	N.A.	N.A.	8.1-28.4	1.8-3.9	0.12-1.24	68
Context 1384	STAN37-47	11	2.2-16.8	3.5	61.3	6.6	10	349.2	56.6	18.6	8.6-19.1	1.3-4.1	0.24-1.09	55

Table 1A (cont.)

Site details	Sample code	No. of samples	Natural Remanent Magnetisation				After demagnetisation				Magnetic Fabric			% in range
			Int. $\times 10^{-6} \text{Am}^2 \text{kg}^{-1}$	Dec. deg.	Inc. deg.	α_{95} deg.	Demag field mT	Dec. deg.	Inc. deg.	α_{95} deg.	Specific susceptibility $\times 10^{-6} \text{m}^3 \text{kg}^{-1}$	h%	q	
Hartlepool														
Upper	HP1-13 & 16-21	19	2.9-9.7	343.6	71.3	3.3	10	348.6	71.2	2.4	5.6-7.6	1.4-4.1	0.24-1.33	32
Lower	HP14,15 & 22-27	8	2.1-35.4	358.7	72.2	7.6	10	1.2	71.1	5.5	3.7-11.1	1.2-8.5	0.22-1.63	50
West Heslerton														
	WHES 1-25	25	2.2-16.4	8.9	76.7	8.8	15	3.1	65.1	5.8	3.5-29.7	5.0-7.1	0.08-0.96	83
Wood Hall														
Contexts 12 & 13	WH 1-15	16	0.32-6.48	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	0.9-1.3	9.8-22.3	0.18-1.21	93
Context 805	WH 1A-14A	14	15.4-446.3	354.7	61.6	3.0	10	353.4	62.2	1.9	1.6-43.4	3.2-11.3	0.05-0.71	86
Context 803	WH 50-63	14	0.18-0.73	116.2	19.2	13.6	N.A.	N.A.	N.A.	N.A.	2-3	3.4-11.4	0.19-0.52	100

Table 1B: Results of step-wise demagnetisation and IRM determinations for typical pilot samples. In the column 'Sample No.' the first sample mentioned was that demagnetised, the second was the one on which IRM tests were carried out.

Site details	Demagnetisation					Magnetic mineralogy			
	Sample No.	No. of pilots	Stability Index	MDF mT	% remaining in given field	SIRM $\times 10^{-6} \text{Am}^2 \text{kg}^{-1}$	% acquired in 1T	<i>S</i>	$(B_o)_{cr}$ mT
ABC Cinema									
Context 2307	ABC46/47	8	4.1	10-12.5	5 at 40mT	5822	99	1.00	15
Context 2311	ABC69/69	4	4.7	10-12.5	5 at 40mT	-	-	-	-
Context 2313	ABC77/77	3	22.5	25	6 at 60mT	14917	98	0.96	28
Context 4006	ABC17/17	8	1.1	15	6 at 40mT	1296	95	0.86	29
Stakis Hotel									
Context 4159	SK9/5	5	5.3	30	10 at 60mT	5793	98	0.92	30-35
Bluebridge Lane									
Context 1	YMA9/7	3	0.9	25	13 at 50mT	916	96	0.77	22
Context 2	YMA15/17	3	2.1	22	10 at 40mT	999	95	0.79	24

Table 1B (cont.)

Site details	Demagnetisation					Magnetic mineralogy			
	Sample No.	No. of pilots	Stability Index	MDF mT	% remaining in given field	SIRM $\times 10^{-6} \text{Am}^2 \text{kg}^{-1}$	% acquired in 1T	s	$(B_o)_{cr}$ mT
Caldicot									
Context 174	CAL15/9	6	9.4	20	12 at 40mT	805	99	0.90	25
Context 173	CAL54/54	6	9.9	20-25	15 at 40mT	722	99	0.91	25
Prudhoe									
	PRU8/7	12	2.5	7.5	11 at 40mT	1626	95	0.76	26
	PRU41/41		2.3	12.0	5 at 40mT	1540	95	0.81	26
Farnley									
	FAR66/68	8	8.3	20-25	16 at 100mT	1100	94	0.68	29-30
	FAR76/76		0.6	7.5	2 at 30mT	1035	98	0.92	15
Stanwick									
Context 1388	STAN4/4	3	6.0	15	2 at 40mT	4115	99	0.90	13
Context 1387 (lens)	STAN15/15	4	16.4	30-40	45 at 40mT	1084	94	0.70	37

Table 1B (cont.)

Site details	Demagnetisation				Magnetic mineralogy				
	Sample No.	No. of pilots	Stability Index	MDF mT	% remaining in given field	SIRM $\times 10^{-6} \text{Am}^2 \text{kg}^{-1}$	% acquired in 1T	s	$(B_0)_{cr}$ mT
Stanwick (cont.)									
Context 1387 (section)	STAN23/23	4	1.8	12.5-15	6 at 40mT	1628	96	0.83	25
Context 1384	STAN37/37	3	0.6	12.5-15	20 at 20mT	1007	92	0.66	20
Hartlepool									
Upper	HP19/19	7	5.4	15-20	7 at 50mT	632	99	0.96	27
Lower	HP24/24		5.4	30-40	20 at 50mT	1843	99	0.96	32
West Heslerton									
	WHES22/11	5	14.0	17.5-25	14 at 40mT	1814	96	0.88	20
Wood Hall									
Contexts 12 & 13		4	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Context 805	WH3A/10A	2	6.0	20-25	5 at 50mT	72800	98	0.98	23
Context 803	WH60/60	1	N.A.	N.A.	N.A.	69	89	0.80	25

Table 1C: Summary of archaeological and archaeomagnetic information for contexts considered datable. All magnetic directions are corrected to Meriden.

Site details	Context Description	Dec. deg.	Inc. deg.	α_{95} deg.	Archaeological date	Dating evidence	Archaeomagnetic date
ABC Cinema							
Context 2307	river flood	359.9	66.6	2.0	late 1 st /2 nd Century AD after 2311 and 2313	pottery stratigraphy	AD50-AD150
Context 2311	river flood	359.8	65.5	3.3	AD160-200 after 2313, before 2307	pottery stratigraphy	AD40-AD180
Context 2313	river flood	2.2	68.5	1.5	before 2307 and 2311	stratigraphy	AD20-AD100
Stakis Hotel							
Context 4159	river flood	1.0	69.6	1.3	late 1 st Century AD	pottery	AD20-AD80
Caldicot							
Context 174	silted-up stream		long section		before 837BC-993BC after context 173	radiocarbon stratigraphy	350BC-1950BC
Context 173	silted-up stream		long section		before 800BC-1260BC 1650BC-1850BC	radiocarbon archaeomagnetism	1950BC-2500BC
Farnley							
	over-bank river flood	43.7	78.1	3.1	late/mid Bronze age after 4600BC-4940BC	standing stones above radiocarbon	550BC-1850BC

Table 1C: Summary of archaeological and archaeomagnetic information for contexts considered datable. All magnetic directions are corrected to Meriden.

Site details	Context Description	Dec. deg.	Inc. deg.	α_{95} deg.	Archaeological date	Dating evidence	Archaeomagnetic date
Hartlepool							
Upper	estuarine	348.6	71.2	2.4	before 4330BC-4470BC after 4750BC-5010BC	radiocarbon radiocarbon	6000BC-6500BC
West Heslerton							
	primary silt in well	2.8	63.7	5.8	AD 450 - AD 850	pottery from nearby structures	AD50-AD500
Wood Hall							
Context 805	primary silt in ditch	353.4	61.2	1.9	AD 1200-1325 before AD 1327	nation-wide survey of moats documentary sources	AD1300-AD1350

Table 1D: Results of linear regression through intensity and susceptibility data for each context. t-test from Miller & Miller (1984), where r is the correlation coefficient, n is the number of samples.

Site	Context	Gradient	Y axis intercept	r ²	n	t	Significant at 95% confidence?
ABC Cinema	2307	1.079	4.419	0.913	21	14.13	Yes
ABC Cinema	2311	1.613	4.291	0.705	21	6.75	Yes
ABC Cinema	2313	0.224	4.364	0.907	18	12.47	Yes
ABC Cinema	4006	0.959	3.723	0.715	30	8.38	Yes
372 Stakis Hotel	4159	0.876	4.362	0.977	33	36.67	Yes
Modern Analogue	1	0.132	8.035	0.214	9	1.381	No
Modern Analogue	2	0.023	10.178	0.680	10	4.127	Yes
Caldicot	174	0.695	3.809	0.951	28	22.38	Yes
Caldicot	173	0.692	3.818	0.936	33	21.24	Yes
Prudhoe	1	2.837	10.236	0.558	8	2.75	Just
Prudhoe	2	0.916	10.731	0.491	8	2.40	No
Prudhoe	3	-4.881	16.598	0.546	8	2.69	Just

Table 1D (cont.)

Site	Context	Gradient	Y axis intercept	r ²	n	t	Significant at 95% confidence?
Prudhoe	4	0.598	12.420	0.104	7	0.76	No
Prudhoe	5	-0.786	12.180	0.058	7	0.56	No
Prudhoe	6	2.937	8.895	0.346	8	1.78	No
Prudhoe	7	-1.048	13.317	0.067	7	0.60	No
373 Prudhoe	8	1.258	9.882	0.314	8	1.66	No
Farnley	1	0.488	11.090	0.0477	7	0.50	No
Farnley	2	0.674	10.763	0.093	8	0.78	No
Farnley	3	1.676	7.500	0.579	8	2.87	Just
Farnley	4	1.815	7.561	0.420	5	1.48	No
Stanwick	1388	0.900	22.883	0.530	7	2.38	No
Stanwick	1387	0.873	3.558	0.419	27	4.25	Yes
Stanwick	1384	0.426	9.087	0.449	11	2.71	Just

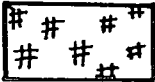
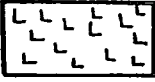






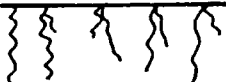

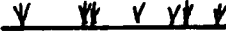


Table 1D (cont.)

Site	Context	Gradient	Y axis intercept	r ²	n	t	Significant at 95% confidence?
Hartlepool	Upper	0.003	6.636	0.000	19	0.00	No
Hartlepool	Lower	0.176	5.368	0.668	8	3.48	Yes
West Heslerton		2.657	3.041	0.761	12	5.65	Yes
Wood Hall	12 & 13	0.004	1.049	0.003	15	0.20	No
Wood Hall	805	0.545	11.972	0.954	13	15.03	Yes
374 Wood Hall	803	1.908	1.843	0.433	14	3.03	Yes
Banpo Sediments	Upper	0.505	63.624	0.098	11	0.99	No
Banpo Sediments	Middle	0.834	63.382	0.131	6	0.78	No
Banpo Sediments	Lower	0.846	42.63	0.862	6	4.36	Yes

APPENDIX 2

Key to symbols used in section drawings

Key to symbols used in section drawings

	.....	Charcoal or Wood
	.....	Clay
	.....	Organic lenses
	.....	Peat
	.....	Sand
	.....	Silt
	.....	Soil
	.....	Stones or Gravel
	.....	Roots
	.....	Unexcavated
	.....	Vegetation
	.....	Sample holder (end view)
	.....	Sample holder (side view)

Sample holders are to scale unless otherwise specified

APPENDIX 3

Table 3A	Direct historical observations of declination in China
Table 3B	Results of measurements on groups of Chinese samples
Table 3C	Results of measurements of pilot Chinese samples

Table 3A: Direct historical observations of declination in China (after Needham, 1962 p310)

Date	Author	Name of book	Place of observation.	Latitude ° ' "	Longitude ° ' "	Declination °
c720	Yi-Xing	Unknown	Changan (Xi'an)	34 16	108 57	3-4 E
Mid 9th	Unknown	<i>Guan shi Di Li Zhi Meng</i> (Master Kuan's Geomantic Instructor)	Probably Xi'an	34 16	108 57	c. 15 E
c. 900	Unknown	<i>Jiu Tian Xuan Nu Qing</i> <i>Nang Hai Jue Jing.</i> (The Nine-Heaven Mysterious-Girl Blue-Bag Sea Angle Manual)	Probably Xi'an	34 16	108 57	c. 7.5 E
c. 1030	Wang Ji	In commentary on <i>Guan shi...</i>	Probably Kaifeng	34 52	114 38	slightly W
c. 1086	Shen Gua	<i>Meng Qi Bi Tan</i> (Dream Pool Essays)	Kaifeng	34 52	114 38	5-10 W
1115	Kou Zong Shi	<i>Ben Cao Yan Yi</i> (The Meaning of the Pharmacopoeia Elucidated)	Kaifeng	34 52	114 38	c. 15 W
c. 1174	Zeng San-Yi	<i>Tong Hua Lu</i> (Mutual Discussions)	Hangzhou	30 17	120 10	5-10 W
c. 1230	Chu Hua-Gu	<i>Chu Yi Shou Zuan</i> (Discussions on the Dispersal of Doubts)	Probably Hangzhou	30 17	120 10	7.5 W

Table 3A (cont.)

Date	Author	Name of book	Place of observation.	Latitude ° ' "	Longitude ° ' "	Declination °
c. 1280	Cheng Qi	<i>San Liu Xuan Za Zhi</i> (Three Willows Miscellany)	Probably Hangzhou	30 17	120 10	7.5 W
c. 1580	Xu Zhi-Mo	<i>Lo Jing Jie</i> (Analysis of the Magnetic Compass)	Probably Beijing	39 54	116 28	c. 7.5 W
c. 1625	J.A. Schall & Xu Guang-Qi	<i>The Magnetic Compass in China</i>	Beijing	39 54	116 28	5.5-7.5 W
c. 1680	Mei Wen-Ding	<i>Kui Ri Ji Yao</i> (Essentials of the Sundial)	Nanjing Suzhou	32 4 31 23	118 47 120 25	3 W 2.5 W
1690	de Fontaney	<i>The Magnetic Compass in China</i>	Canton	23 8	111 16	2.5 W
1708	Regis & Jartoux	Observations Mathematiques, Astronomiques.....Paris, 1729	Jiayuguan Shanhaiguan	39 49 40 2	98 32 119 37	3 W 2 W
1817	Wylie		Canton	23 8	111 16	0
1829	Wylie		Beijing	39 54	116 28	1.5 W

Table 3B: Results of the measurements of the groups of samples in this study, as described in Chapter 4. All directions are corrected to Xi'an.

Site name	Sample code	Date	No.of samples	Natural Remanent Magnetisation					After Demagnetisation		
				Intensity $\mu\text{Am}^2\text{kg}^{-1}$	Dec. deg.	Inc. deg.	α_{95} deg	Demag. field mT	Dec. deg.	Inc. deg.	α_{95} deg.
Terracotta Army	TERR1-14	206BC	14	69.0-873.3	345.0	35.6	2.5	10	343.1	33.2	2.4
Banpo Fireplace	B1-7	4000±150BC	7	7.6-67.6	3.6	53.6	13.8	10	352.1	48.7	9.3
Banpo Sediments	Upper BS1-11	-	11	31.2-60.1	331.8	44.2	4.7	-	-	-	-
	Middle BS12-20	-	6	23.6-32.6	332.4	48.6	9.5	-	-	-	-
	Lower BS21-30	-	6	11.0-28.1	331.4	49.8	5.5	-	-	-	-
Yaozhou Yao	Kiln 1 Y1-10	1300±50AD	10	14.8-1412.0	6.2	52.6	3.6	10	3.5	51.1	3.7
	Kiln 2 Y11-20	1100±50AD	9	61.1-2368.1	356.7	49.4	5.6	20	354.6	49.2	5.3
	Kiln 3 Y21-32	900±50AD	12	13.5-3674.6	349.6	51.7	3.8	7.5	345.8	50.8	3.0
	Kiln 4 Y33-45	1000±50AD	12	2.1-1820.0	350.4	50.1	6.2	10	345.0	48.6	4.5

Table 3C: Results of stepwise demagnetisation and IRM determinations for typical pilot samples. In the column 'Sample No.' the first sample mentioned was that demagnetised, the second was the one on which IRM tests were carried out. MDF denotes Median Destructive Field.

Site name	Sample No.	Demagnetisation Characteristics			Mineral Magnetic Properties			
		Stability Index	MDF mT	% remaining in given field	SIRM mAm ² kg ⁻¹	% acquired in 1T	<i>S</i>	(B _o) _{cr} mT
Terracotta Army	TERR5/8	31.4	12.5	11% at 1T	20.650	93	0.72	22
Banpo Fireplace	BAN7/4	6.5	10	5% at 40mT	1.288	99	0.81	20
Banpo Sediments	BS1/1	2.4	10	10% at 40mT	4.887	92	0.89	17
Yaozhou Yao Kiln	Y10/10	60.0	20	20% at 1T	9.425	85	0.49	25

APPENDIX 4

Listing of Dr. R. Sternberg's program for the weighting
and smoothing of archaeomagnetic data

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PROGRAM STERN
C   R.Sternberg's prog for weighting and smoothing AM data.
C   Adapted by Cathy Batt Summer 1991

C   SETTING THE ARRAY SIZE AND TYPES
REAL DEC(500), XINC(500), WEIGHT(500), A95(500), T1(500),
*   T2(500)
REAL W1, W2, TBEG, TEND, TDELTA, TWNDO, XNN, XNNN,
*   SUMWGT, OVLAP, DELTA, WGT, D, XI, SUML, SUMM, SUMN,
*   R, Z, AVGDEC, AVGINC, EX, COSINE, ALPHA

C   READING IN AM DATA
OPEN(99, FILE='DATAIN', STATUS='OLD')
OPEN(88, FILE='DATAOUT', STATUS='OLD')
NPT=0
10  CONTINUE
    NPT=NPT+1
    READ(99, *, END=20) DEC(NPT), XINC(NPT), A95(NPT), T1(NPT),
*   T2(NPT)
C   WRITE(6, *) DEC(NPT), XINC(NPT), A95(NPT), T1(NPT), T2(NPT)
    GO TO 10

20  CONTINUE
    NPT=NPT-1

30  CONTINUE
C   ENTER PARAMETERS REQUIRED
WRITE(6, *) 'PLEASE ENTER FIRST AND LAST YEAR'
READ(5, *) TBEG, TEND
IF (TBEG.EQ.0.0 .AND. TEND.EQ.0.0) GO TO 70
WRITE(6, *) 'PLEASE ENTER TIME INCREMENT AND WINDOW'
READ(5, *) TDELTA, TWNDO

C   SETTING UP START WINDOW
W1=TBEG-TDELTA
W2=W1+TWNDO

C   MOVING THE WINDOW
40  CONTINUE
    W1=W1+TDELTA
    W2=W2+TDELTA
C   WRITE(6, *) 'W1 AND W2', W1, W2
    IF (W1.GE.TEND) GO TO 80
    XNN=0.0
    XNNN=0.0
    SUMWGT=0.0
    DO 50 I=1, NPT
        WEIGHT(I)=0.0
        IF (W2.LE.T1(I)) GO TO 50
        IF (W1.GE.T2(I)) GO TO 50
        CALL WINDOW (W1, W2, T1(I), T2(I), OVLAP)
        DELTA=T2(I)-T1(I)
C   WRITE(6, *) 'DELTA', DELTA
        WGT=OVLAP/DELTA
C   WRITE(6, *) 'WGT', WGT
        WEIGHT(I)=WGT
C   WRITE(6, *) 'WEIGHT(I)', WEIGHT(I)

C   INTRODUCE A95 INTO WEIGHT
C   WRITE(6, *) 'A95(I)', A95(I)

```

```

      IF (A95(I) .LT. 1.0E-5) A95(I)=0.5
      WEIGHT(I)=WEIGHT(I)/A95(I)
C     WRITE (6,*) 'WEIGHT(I)', WEIGHT(I)
      SUMWGT=SUMWGT+WEIGHT(I)
C     WRITE (6,*) 'SUMWGT', SUMWGT
      XNN=XNN+1.0

C     WRITE (6,*) 'XNN', XNN
      XNNN=XNNN+WGT
C     WRITE (6,*) 'XNNN', XNNN
50    CONTINUE

      IF (SUMWGT.NE. 0) GOTO 55
      WRITE(88, *) 'NO POINTS IN INTERVAL', W1, W2
      GOTO 40
55    DO 60 I=1,NPT
      WEIGHT(I)=WEIGHT(I)/SUMWGT
C     WRITE (6,*) 'WEIGHT'
C     WRITE (6,*) WEIGHT(I)
60    CONTINUE

C     CALLING THE SMOOTHING ROUTINE
      CALL AL95(NPT, XNN, DEC, XINC, WEIGHT, AVGDEC, AVGINC,
*     ALPHA, IER)

      WRITE (88, *) AVGDEC, AVGINC, ALPHA, W1, W2, XNN, XNNN

C     MOVE WINDOW ALONG
      GO TO 40

70    CONTINUE
80    END

SUBROUTINE WINDOW (W1, W2, T1, T2, OVLAP)
  IF (W1.GT.T2) GO TO 210
  IF (W2.LT.T1) GO TO 210
  IF (W1.LE.T1) GO TO 200
    IF (W2.LT.T2) OVLAP=W2-W1
    IF (W2.GE.T2) OVLAP=T2-W1
    GO TO 220
200  CONTINUE
    IF (W2.LT.T2) OVLAP=W2-T1
    IF (W2.GE.T2) OVLAP=T2-T1
    GO TO 220
210  CONTINUE
    OVLAP=0.0
220  CONTINUE
    RETURN
    END

SUBROUTINE AL95(NPT, XNN, DEC, XINC, WEIGHT, AVGDEC, AVGINC,
* ALPHA, IER)
  DIMENSION DEC(500), XINC(500), WEIGHT(500)
C   DATA TO CONVERT BETWEEN DEGREES AND RADIANS
  DATA RADDEG/57.29578/

C   INITIALISE ERROR CODE
  IER=0

```

```

      ALPHA=-1.0
      AVGDEC=-1.0
      AVGINC=-1.0

C     CHECK NO OF POINTS
      IF (IFIX(XNN) .GT. 1) GO TO 300
      IER=1
C     WRITE (6, *) 'NO POINTS IN THIS INTERVAL '

C     CHECK FOR INVALID DEC OR INC
300   CONTINUE
C     WRITE(6,*)'IER', IER
      DO 310 I=1,NPT
C       WRITE (6,*) 'WEIGHTL', WEIGHT(I)
C       WRITE (6,*) 'AFTER WEIGHT'
          IF (WEIGHT(I) .EQ. 0.0) GO TO 310
      D=DEC(I)
      IF (D .LT. -180.0 .OR. D .GT. 180.0) IER=2
      IF (ABS(XINC(I)) .GT. 90.0) IER=2
C       WRITE (6,*) IER
      IF (IER .NE. 2) GO TO 310
C       WRITE (6,*) 'INVALID RAW DEC OR INC'
          GO TO 340
310   CONTINUE

C     SUM COMPONENTS OF UNIT VECTORS
      SUML=0.0
      SUMM=0.0
      SUMN=0.0
      DO 320 I=1,NPT
C       IF (WEIGHT(I) .LT. 1.0E-5) GO TO 320
C     CONVERT DEGS TO RADS
      D=DEC(I)/RADDEG
      XI=XINC(I)/RADDEG
      COSXI=COS(XI)
      SUML = SUML + COS(D) * COSXI * WEIGHT(I)
      SUMM = SUMM + SIN(D) * COSXI * WEIGHT(I)
      SUMN = SUMN + SIN(XI) * WEIGHT(I)
320   CONTINUE

C     COMPUTE LENGTH OF RESULTANT VECTOR
      R = SQRT (SUML*SUML + SUMM*SUMM + SUMN*SUMN)

C     COMPUTE MEAN DEC AND INC
      AVGDEC = ATAN2(SUMM, SUML) * RADDEG
      IF (AVGDEC .GT. 180.0) AVGDEC = AVGDEC - 360.0
      IF (AVGDEC .LT. -180.0) AVGDEC = AVGDEC + 360.0
      Z = SUMN/R
      AVGINC = ASIN(Z) * RADDEG

C     WRITE(6,*) 'IM AT C'

C     COMPUTE ALPHA-95
      IF (XNN .LT. 1.0005) GO TO 350
330   CONTINUE
C     WRITE (6,*) 'XNN=', XNN
      EX = 1.0 / (XNN - 1.0)
      COSINE = 1.0 - (1.0 - R)/R * (20.0 **EX - 1.0)
C     WRITE (6, *) EX, XNN, R, COSINE
      ALPHA = ACOS (COSINE) * RADDEG

```



```
340 RETURN
350 ALPHA=0
RETURN
END
```