Assessing the Geothermal Potential of the Lower Carboniferous Fell Sandstone

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Abstract

After a hiatus of more than two decades, there is now a renewed interest in the exploration of deep geothermal resources in the UK as the country strives towards reaching net-zero greenhouse gas emissions. The Lower Carboniferous Fell Sandstone Formation (Mississippian) and laterally equivalent strata beneath Newcastle Upon Tyne was postulated to be one such deep geothermal system, heated by the inflow of high temperature brines along the Ninety-Fathom Fault and several of its footwall splay faults. In 2011 a consortium led by Newcastle University commenced with the drilling and testing of the Science Central Deep Geothermal Borehole (Science Central Borehole, recently renamed Helix) to examine whether low enthalpy geothermal energy might be recoverable from the Fell Sandstone. The Science Central Borehole proved the presence of the Fell Sandstone and a temperature of 73.3^{o}C at 1740m however, low hydraulic conductivity within the formation did not allow for commercial production (Younger *et al.*, 2016).

The findings of Younger *et al*. (2016) highlight the need to gain a better understanding of the reservoir properties of deep geothermal aquifers like the Fell Sandstone. This study further investigates the Fell Sandstone Formation across northern England, comparing petrographic data obtained from both outcrop and borehole samples. Well logs, optical microscopy, scanning electron microscope (SEM) analysis and statistical analysis are utilised to identify lateral changes in both the lithology and diagenetic history of the Fell Sandstone and examine what impacts these variations have had reservoir quality. An estimate of the geothermal resource within the Fell Sandstone Formation has been calculated based on these findings.

A lateral trend of decreasing net to gross down the paralic palaeo-river system combined with diagenetic compaction and pervasive cementation has resulted in significantly reduced

porosities and permeabilities within the subsurface Fell Sandstone, compared to values obtained from outcrop. Despite these poor porosities and permeabilities the high temperatures recorded at Science Central prove that if future endeavours are able to intersect the Ninety-Fathom Fault, then there is still the opportunity for geothermal resource development.

Table of Contents

Table of Figures:

Declaration

I declare that this thesis, presented for the degree of Master by research in Earth Science at Durham University, is the result of my own original research and has not been previously submitted to Durham University or any other institution. Where relevant, other individual's research is acknowledged by the author and referenced appropriately.

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A special thank you goes to the members of the Earth Science Department without whose efforts to keep the Department open as a safe place to work, this project would not have been possible.

Finally, thank you to my family for their encouragement, love and support throughout the past year. Thank you to my friends for providing the laughs and motivation, particularly during the times spent under lockdown.

Chapter 1 – Introduction

1.1 Project Rationale

Heating accounts for half of all energy consumption in the UK and over 30% of its greenhouse (Gluyas *et al.,* 2018). In 2019, the UK the amended its long-term emissions targets from an 80% cut to net-zero emissions by 2050 in adherence to the Paris Agreement (Averchenkova *et al.,* 2021). In order to achieve net-zero by 2050 the UK must decarbonise its heating. With this goal in mind, a review, conducted by Gluyas *et al.* (2018), of the country's geothermal potential has shown that the UK is host to a substantial geothermal heat resource. With estimated geothermal source regions overlapping with or adjacent to major population centres (Fig. 1.1), it is technically possible to utilise low-enthalpy geothermal heat for space heating. The drilling of the Eastgate (I) borehole in 2004 proved that the Weardale Granite, part of the North Pennine Batholith located in Northeast England, is one such potential geothermal resource (Manning *et al.,* 2007; Younger *et al.,* 2016; Gluyas *et al.,* 2021), located south of the city of Newcastle-upon-Tyne (NZ220682). Following on from the Eastgate borehole projects (Eastgate 1 and Eastgate 2), the Weardale Granite continues to be the subject of geothermal investigation. This study focuses on the aquifer and geothermal potential, of the Lower Carboniferous Fell Sandstone Formation, located in the Northumberland Basin. The Fell Sandstone has long been exploited as a potable aquifer in northern Northumberland (Hodgson & Gardiner, 1971; Bell, 1978; Turner *et al.* 1993; Younger, 1995, 1998; Younger *et al.,* 2016). Analysis of samples taken from outcrops between Rothbury and Berwick-upon-Tweed yielded porosity values of up to 20-30% (Bell, 1978; Younger, 1992). Such high porosity, along with transmissibility and recharge values (lab determined permeability of 1.74×10^{-6} m/s from core samples taken from the Shirlawhope

Well, Longframlington; Bell, 1978) mean that the Fell Sandstone is potentially one of the most important/promising aquifers within the Carboniferous sequence (Hodgson & Gardiner, 1971; Jones *et al.,* 2000). It is for these reasons that the Fell Sandstone was chosen as the target for a deep geothermal well drilled at Science Central in Newcastle by Newcastle and Durham universities, Newcastle County Council and the British Geological Survey (BGS) (Younger *et al.,* 2016). The rationale behind the project was that the Fell Sandstone reservoir, if present beneath Newcastle, was potentially being heated via geothermal convection associated with the Weardale Granite and therefore could be utilised as a geothermal resource. The well, drilled to 1821m, did encounter 376.5m of the Fell Sandstone as predicted and proved a temperature of 73^{o}C at 1740m. With a calculated heat flow of 88 ± 1 mWm^{-2}, a value considerably higher than average background heat flow values for the UK (~50 mWm^{-2}; Fig. 1.1) (Younger *et al.,* 2016), the Fell Sandstone is potentially a significant geothermal heat resource. However, the well failed to flow upon testing. It is unclear whether the low transmissivity recorded at the Science Central Deep Geothermal Borehole is the result of local influences or representative of the Fell Sandstone at depth. There are a number of possible reasons behind the Fell Sandstone's low transmissivity:

- Formation porosity could have been reduced as a result of local cataclasis in association with the nearby Ninety Fathom Fault system.
- Pore space could potentially have been infilled/occluded by the precipitation of barite from brines flowing along the Ninety Fathom Fault. Evidence of fault associated barite cementation is seen in the Permian Yellow Sands at Cullercoats Bay to the east of Newcastle (Younger *et al.,* 2012).
- Damage caused during drilling could have negatively affected the formation's production capabilities.

- The intrinsic aquifer properties of the Fell Sandstone in this area may be poorer than elsewhere.

More information on the porosity and transmissivity of the Fell Sandstone at depth is needed in order to determine whether it could be utilised as a deep geothermal resource. This is the focus of this thesis.

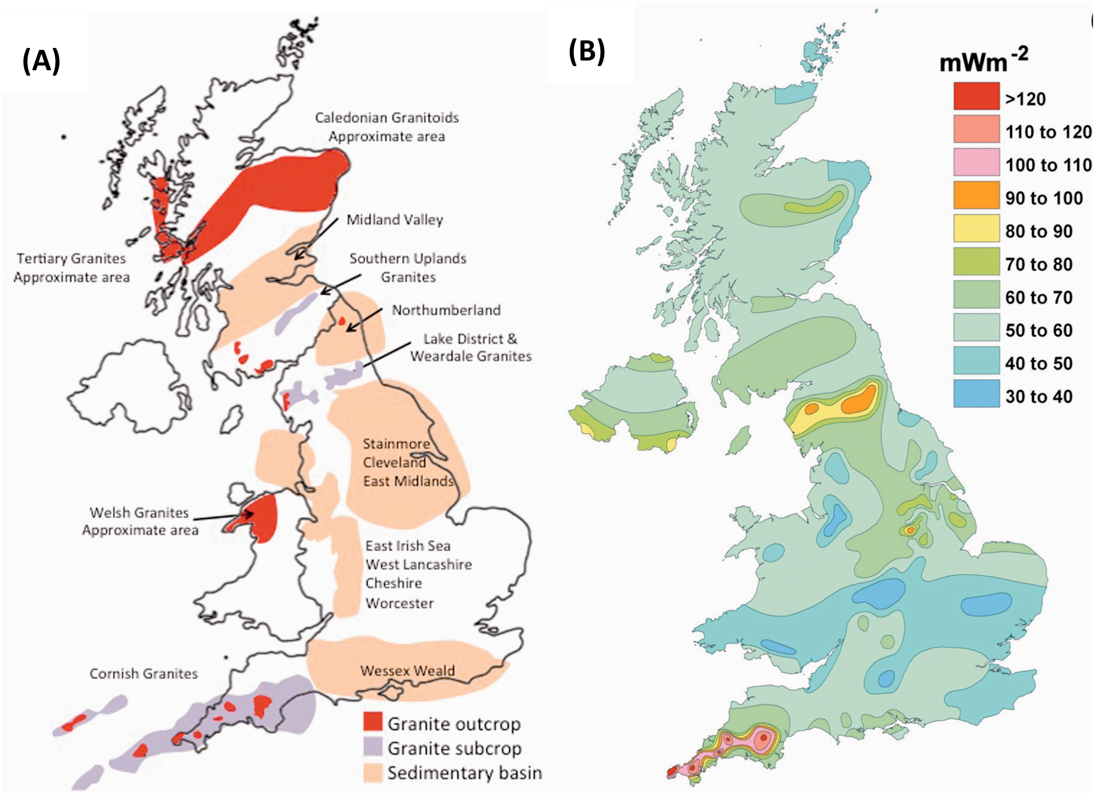

Figure 1.1: (A) a map showing the locations of UK sedimentary basins and granite batholiths; (B) heat flow across the UK (from the British Geological Survey) (modified from Gluyas et al., 2018).

1.2 Project Aims

This project's main aim is to ultimately map the reservoir properties, namely porosity and permeability, of the Fell Sandstone across its range in Northumberland and Cumbria using a combination of sample, well and seismic data. Up to 60% of the cost of a geothermal project is spent on the drilling phase (Arup, 2011; Hirst *et al.,* 2015). If the controls on reservoir properties can be further understood, better predictions regarding reservoir quality can be made in the future, helping to reducing the risk associated with geothermal development in the Northeast.

Key project aims include:

1. To better understand the lithology and reservoir properties of the Fell Sandstone at depths greater than 1km, specifically aspects such as cementation, porosity and permeability. The Formation has long been exploited as a public fresh water supply North of Rothbury where it is found near the surface, however, a greater understanding of its intrinsic properties at depth is needed. This will be achieved through petrographic analysis of borehole cuttings and samples collected during fieldwork as well as well flow performance data.
2. The analysis of borehole cuttings, from the Science Central Borehole, for the presence of barite cement. The determination of whether barite cement is present within the Fell Sandstone at this location may help to shed light on the reasons behind the failure of the Science Central Borehole.
3. To evaluate the importance of secondary porosity development at Science Central in order to compare to data from existing boreholes. Well reports, from other boreholes that penetrate the Fell Sandstone, will be analysed as part of this project to determine whether the varying development of secondary porosity is a significant influence on formation porosity and permeability in England.

1.3 Area of Study

This project focuses on the Fell Sandstone within the Northumberland Trough, an extensional half-graben, comprising of the Northumberland, Tweed and Solway basins, which extends across Northern England and into the Central North Sea. The Fell Sandstone has been penetrated by a number of both terrestrial and offshore boreholes within this Carboniferous basin (Kearsey *et al.*, 2018), evidencing that it is laterally persistent. The borehole data, examined in this project, are taken from sites across Cumbria and Northumberland as well as the Central North Sea. Physical samples taken from the Science Central and Errington 1 boreholes, stored at the British Geological Survey Core Store, are also investigated in this study. In addition to these BGS samples, physical samples have also been collected through fieldwork at Bowden Doors, an outcrop of Fell Sandstone located to the west of Belford, Northumberland (Fig. 1.2).

Figure 1.2: The Fell Sandstone as seen at outcrop at Bowden Doors in Northumberland (Fig. 1.3).

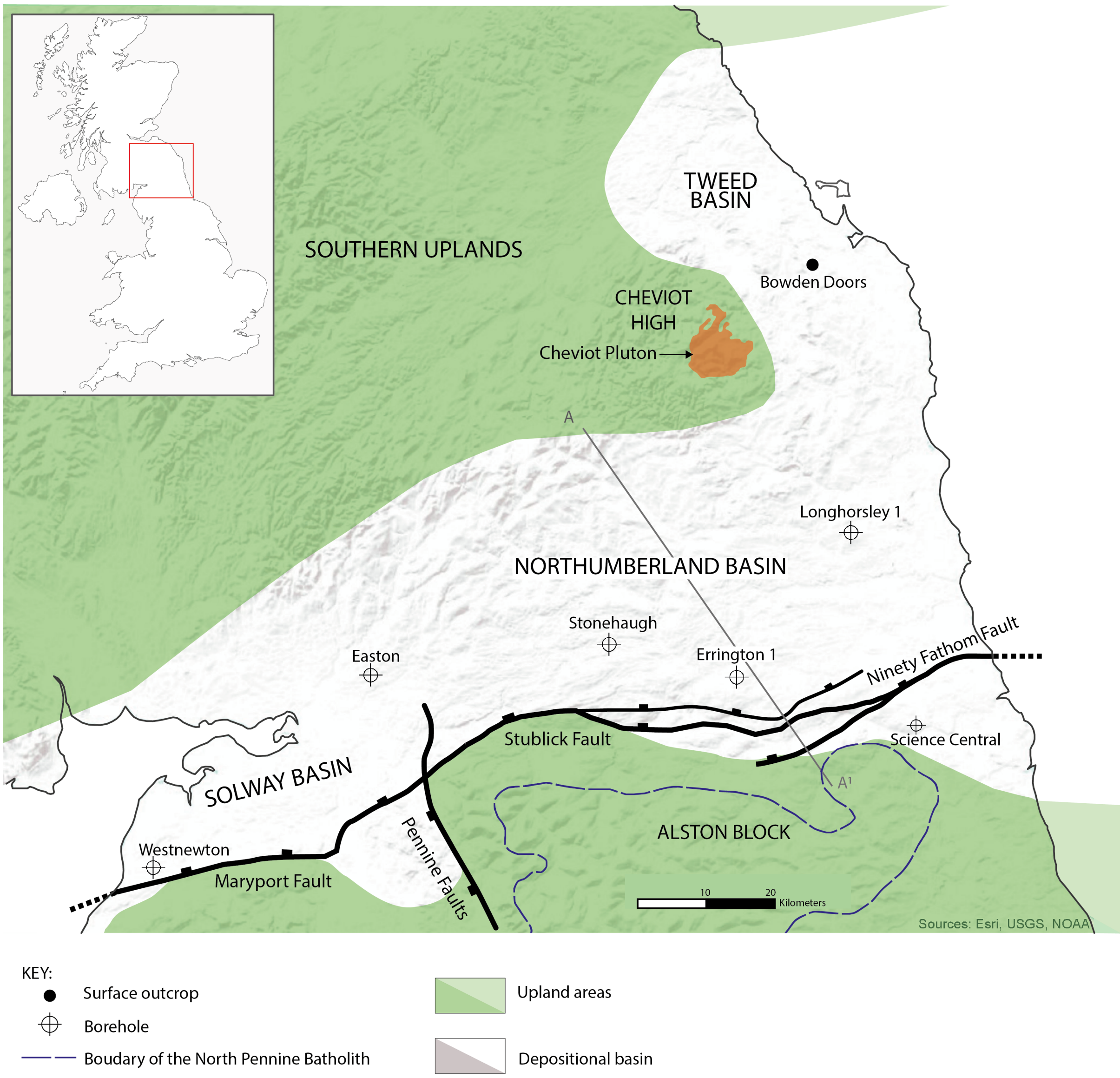

Figure 1.3: A palaeogeographical map of the onshore Northumberland Trough, separated into the Northumberland, Solway and Tweed Basins. The southern margin of the basin is bounded by upland Lake District Block (SW) and the Alston Block, underlain by the North Pennine Batholith (modified from Younger et al., 2016 and Howell et al., 2019). A-A^1 represents the cross section represented in Fig. 2.1.

1.4 Nomenclature

In order to adhere to previous UK literature, the traditional NW European Carboniferous chronostratigraphic subdivisions have been adopted. The Carboniferous succession of the

Northumbrian Trough has been the subject of research articles for the best part of a century. During that time the nomenclature for the Fell Sandstone Formation, along with the Carboniferous succession as a whole has been subject to change. The current lithostratigraphical nomenclature is outlined in Waters *et al*., (2007) and Dean *et al*., (2011).

Chapter 2: Structural and depositional history of the Northumberland Trough

2.1 Regional setting - The Northumberland Trough

The structure of Northern England, during the Early Carboniferous, was dominated by a 'block-and-basin' tectonic framework (Martin, 1995; Howell *et al.,* 2019) resulting from a prolonged period of rifting that began in the Late Devonian and persisted into the Carboniferous. The Northumberland Trough, a north-east south-west oriented half graben, is one such extensional basin; bounded by the Alston Block to the south along the Stublick-Ninety Fathom Fault system, and the Southern Uplands to the north (Fig. 1.3). The south easternmost extent of the Southern Uplands is marked by the Cheviot High. The term Northumberland Trough was first used by Rayner (1953) and encompasses three separate basins: the Solway Basin to the West, the Northumberland Basin to the East and the smaller Tweed Basin to the North East of the main Northumberland Basin (Fig. 1.3). During the Carboniferous, the Northumberland basin was located in a low latitude, warm, temperate climate (Raymond, 1985). Deposition occurred in a range of marine, shoreface, river dominated deltaic and braided fluvial environments (Leeder, 1974; Turner *et al.,* 1993; Waters *et al.,* 2012; Booth *et al.,* 2020).

2.1.1 Formation of the Northumberland Basin

The initiation of the Northumberland Trough has been discussed a number of times in previous research (Leeder, 1982; Chadwick & Holliday, 1991; Howell *et al*., 2020). The current paradigm, as stated by Howell *et al.,* (2020), is that rifting began through the extensionaltranstensional reactivation of pre-existing fault structures, created during the Caledonian Orogeny, at the end of the Devonian Period (Davies *et al.,* 2012). Subsidence within the Northumberland basin was primarily controlled by the reactivated Maryport-Stublick-Ninety Fathom Fault System (Chadwick & Holliday, 1991), which bounds the southern margin of the trough, trending ENE-WSW. Rifting occurred under a NE-SW oriented extensional regime. Whilst subsidence occurred across the entire Northumberland Trough, the controlling influence of the Stublick -Ninety Fathom Fault System has resulted in the development of an asymmetric basin profile (Fig. 2.1) (Martin, 1998). During this period of subsidence, the Northumberland Trough was an active centre of deposition (Johnson, 1984).

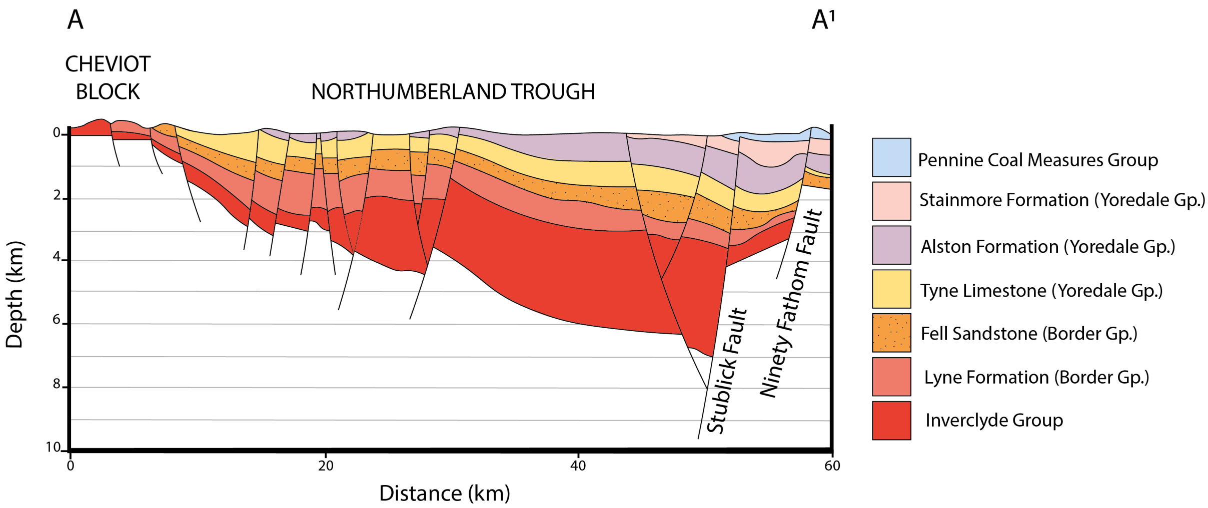

Figure 2.1: Cross section through the Northumberland Trough. Edited from Howell et al., (2019) and based on the structural interpretations of Chadwick et al., 1995).

The basement of the Northumberland Trough is made up of a combination of Lower Palaeozoic and Lower Devonian sedimentary, volcanic and intrusive rocks (Chadwick et al., 1993; Martin, 1995). A succession of Carboniferous age sedimentary strata, ranging from Tournaisian to Late Westphalian, represents the main basin fill with in excess of 6km of sediment to the south of the Northumberland Basin. The succession thins to the north with approximately 1500m preserved across the Tweed Basin (Martin, 1995). Active tectonic extension ceased in the Late Visean to Early Namurian, giving way to passive thermal subsidence which continued into the Westphalian (Fraser & Gawthorpe, 1990).

2.1.2 Faulting in the Northumberland Trough

As previously mentioned, the southern side of the Northumberland Trough is bounded by the north dipping Maryport-Stublick-Ninety Fathom Fault System (M-S-NF Fault System), one of the largest geological fault systems in the UK. This fault system is segmented, comprising of the Ninety Fathom Fault to the east, the centrally located Stublick Fault and the Maryport Fault, bounding the Solway Basin to the west (Fig. 1.3; Fig. 2.2) (DePaola *et al.,* 2005). The Stublick Fault is the largest of the three faults both in terms of length and displacement with the lower Palaeozoic basement of the Northumberland Trough being vertically displaced by an estimated 2km (assuming an average seismic velocity of 4000 m s^{-1}; Jenkins & Torvela, 2020). Across central Northumberland the Stublick fault trends east to west, only realigning to trend NE-SW at its north easternmost extent, suggesting that it potentially formed as a relay ramp breaching structure between pre-existing NE-SW right stepping faults (Jenkins & Torvela, 2020). As a theorised *en echelon*, right-stepping continuation of the Stublick Fault System (Jenkins & Torvela, 2020), the Ninety Fathom Fault runs roughly parallel to the north-eastern end of the Stublick Fault, trending northeast. The Science Central borehole has proven that this fault system is host to geothermal convection associated with the Weardale Granite underlying the Alston Block to the south.

A series of mostly south dipping, *en echelon* faults form the northern margin of the Northumberland and Solway basins. This northern basin bounding fault system is antithetic to the Maryport-Stublick-Ninety Fathom Fault System. The throw on this northern basin bounding fault system increases to the west, resulting in the Solway Basin having an almost symmetrical cross-sectional profile, as opposed to the asymmetrical Northumberland Basin (Fig. 2.1) (Chadwick *et al.,* 1995; Jenkins & Torvela, 2020). However, details regarding the geometries of individual faults in this area is largely unknown (Jenkins & Torvela, 2020).

A series of smaller intrabasinal faults is also present within the Northumberland Trough (Fig. 2.1; Fig. 2.2). These extensional faults inherited the existing tectonic framework left over from the Caledonian Orogeny, like the Stublick-Ninety Fathom Fault system, and thus broadly trend ENE-WSW. The most significant of these intrabasinal faults are the south dipping Antonstown Fault and the north dipping Sweethope Fault (Fig. 2.2). Together these faults from a minor graben within the Northumberland Trough, however today, with a maximum throw of 0.1s and 0.2s TWT (seismic velocity is typically 2500-4000 m s^{-1} for sedimentary rocks) respectively, where they intersect the Fell Sandstone, the vertical displacement across these faults is relatively minor. Other notable faults include the Causey Park Fault, the Hallington Reservoir Fault and the Stobswood Fault. At present day, the throw on these faults is minor, however, they are laterally extensive with lengths of up to tens of kilometres (Jenkins & Torvela, 2020).

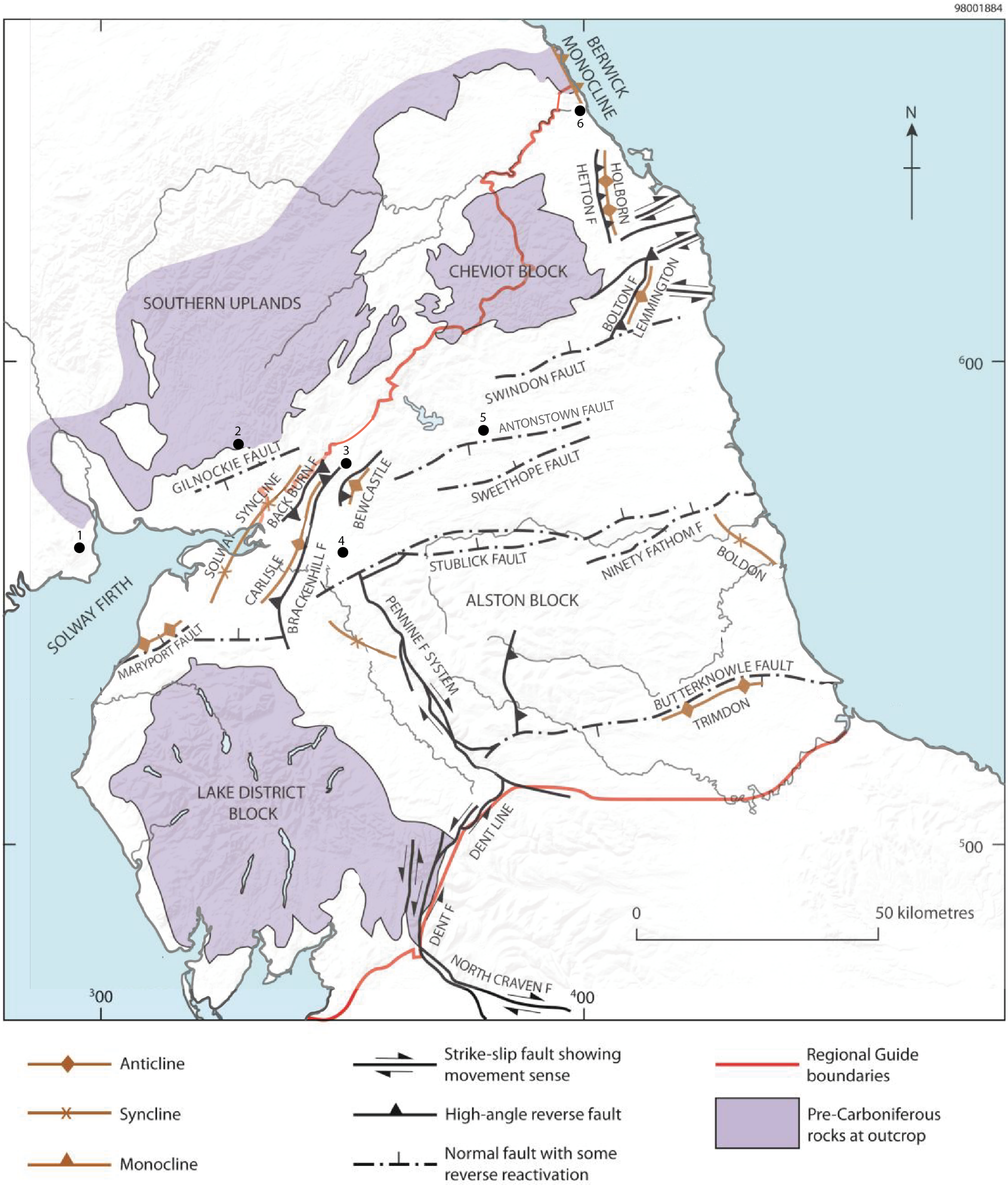

Figure 2.2: the location of wrench and extensional structures across the Northumberland Trough as well as the rest of northern England. Modified from Leslie et al. (2015).

2.2 The Carboniferous succession in the Northumberland Trough

2.2.1 Sedimentology

Sediments deposited during the Devonian and Carboniferous within the Northumberland Trough were primarily derived from the Fennoscandian High. This upland area was part of a mountain range comprised of uplifted Precambrian to Early Paleozoic rock, created during the Caledonian Orogeny, which spanned the northwestern USA, Canada, Greenland, Scotland and Scandinavia (McKerrow *et al.,* 2000; Woodcock & Strachan, 2000; Nance *et al.,* 2010, Booth *et al.,* 2020).

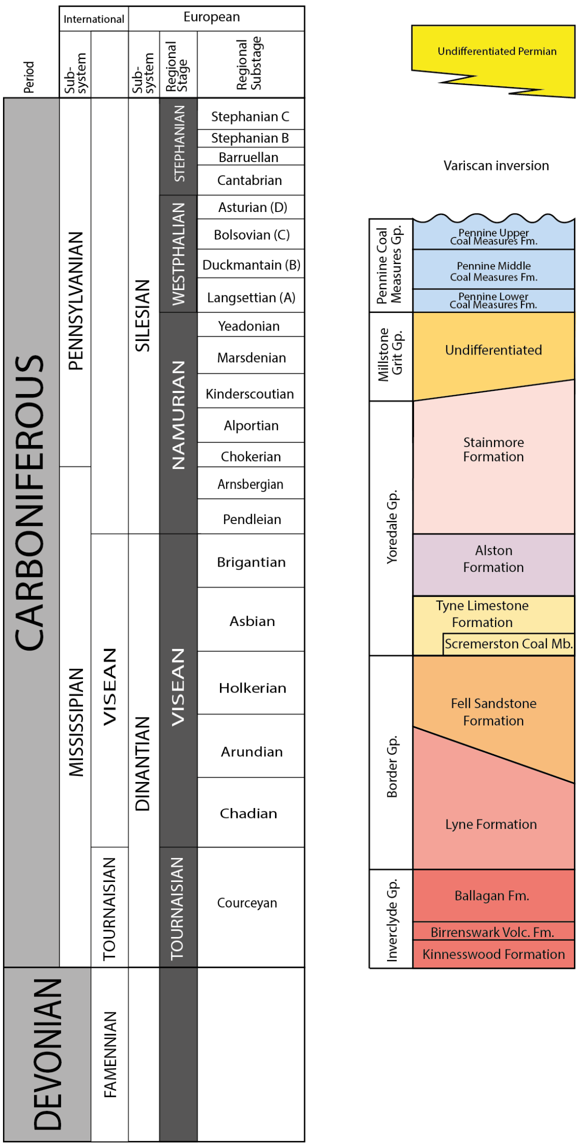

Figure 2.3: Chronostratigraphic and lithostratigraphic nomenclature for the Northumberland Basin. Derived from Waters et al. (2007).

2.2.1.1 Inverclyde Group

Deposition within the Northumberland Trough, as well other extensional basins in the north of England during the Early Carboniferous, was influenced by basal marine transgressions, governed by the rate of tectonic subsidence (Monro, 1986).

The Inverclyde Group represents the oldest Carboniferous strata present in the Northumberland Trough (Fig. 2.3). The group is subdivided into three formations: the Kinnesswood Formation, the Birrenswark Volcanic Formation and the Ballagan Formation (Fig. 2.3; Fig. 2.4) (Waters *et al.,* 2012). The basal Kinnesswood Formation is composed of interbedded sandstones, mudstones and calcretes deposited, at the onset of extension, along the margins of the Southern Uplands and the Cheviot Hills resulting in the formation of alluvial fans (Chadwick *et al.,* 1995). The overlying Ballagan Formation is comprised of sandstones interbedded with mudstones, limestones, gypsum and anhydrite, representing fluvial to fluvial-deltaic sedimentation as well as alluvial fan deposits (Waters *et al.,* 2007). The evaporite deposits represent deposition in lacustrine and arid coastal plain environments which were subjected to periodic desiccation (Waters *et al.,* 2012). Studies of the Ballagan Formation have shown that overall, the environment at the time was that of a dynamic coastal plain dominated by overbank flooding, sabkhas and palaeosols, and subjected to short lived marine flooding events (Bennet *et al.,* 2016; Kearsey *et al.,* 2016, 2018).

2.2.1.2 Lyne Formation

Overlying the Inverclyde Group, the Lyne Formation (Lower Border Group), which comprises of cyclic sequences of shallow marine limestone with characteristic oolitic pellet beds (Dean *et al.,* 2011), mudstone, siltstone and sandstone, represents the onset of sedimentation in wetter conditions with increasingly variable bathymetry (Waters *et al*., 2007). The cyclic sequences, interpreted by Leeder (1974), represent the interruption of shallow marine carbonate deposition by periodic influxes of clastic sediment from advancing delta systems from the north and northeast. These periods of deltaic sedimentation were followed by abandonment or withdrawal of the delta systems and the return of carbonate deposition, facilitated by basin subsidence. Periodic and abrupt abandonment is evidenced by the absence of extensive back-swamp deposits (Monro, 1986). In northern Cumbria (southwest Northumberland Trough) the formation is subdivided into the Lynebank, Main Algal, Bewcastle and Cambeck members (otherwise known as the Cambeck Beds) (Day *et* al., 1970; Dean *et* al., 2011). The Cambeck beds are stratigraphically equivalent to the Lower Fell Sandstone Formation to the northeast due to the diachronous boundary between the two formations (Fig. 2.6). The presence of the Lyne Formation has not been proved in the eastern region of the Northumberland Trough and is not present in the Tweed Basin around Berwick upon Tweed. Here the Fell Sandstone rests unconformably upon the Ballagan Formation (Fig. 2.3; Fig. 2.4) (Greig, 1988; Waters *et al*. 2007).

2.2.1.3 Fell Sandstone Formation

The depositional onset of Fell Sandstone (Middle Border Group) during the middle rifting phase (Howell *et al*., 2019) represents an increase in clastic sediment supply, to the Northumberland Trough, from the Fennoscandian High to the north east. Thickening trends (Fig. 2.1) evidence deposition occurring across a tectonically active floodplain with syn-depositional subsidence and uplift of the source region allowing the river system that deposited the Fell Sandstone to prograde across the Tweed, Northumberland and Solway Basins during the Chadian, Arundian and Holkerian (Monro, 1986; Turner *et al.*, 1993). The gradual progradation of the Fell River System is represented by the formation's diachronous lower boundary with the Lyne Formation (Fig. 2.3; Fig. 2.6). Formation outcrops are found in the Tweed Basin, south of Berwick-Upon-Tweed and along the margins of the Cheviot Hills towards Brampton. The Fell Sandstone successions around the margins of the Cheviot Hills, seen at Bowden Doors and within the Alnwick and Longframlinton boreholes (Fig. 2.7), are the most sand rich Fell Sandstone successions within the Northumberland Trough (88-100%; Howell *et al.*, 2020). Moving southwest the sand richness of the formation decreases to a low of 14% in the Solway Basin (Howell *et al.*, 2020). This lateral variation is discussed further in section 2.3. The upper boundary of the Fell Sandstone Formation is also diachronous.

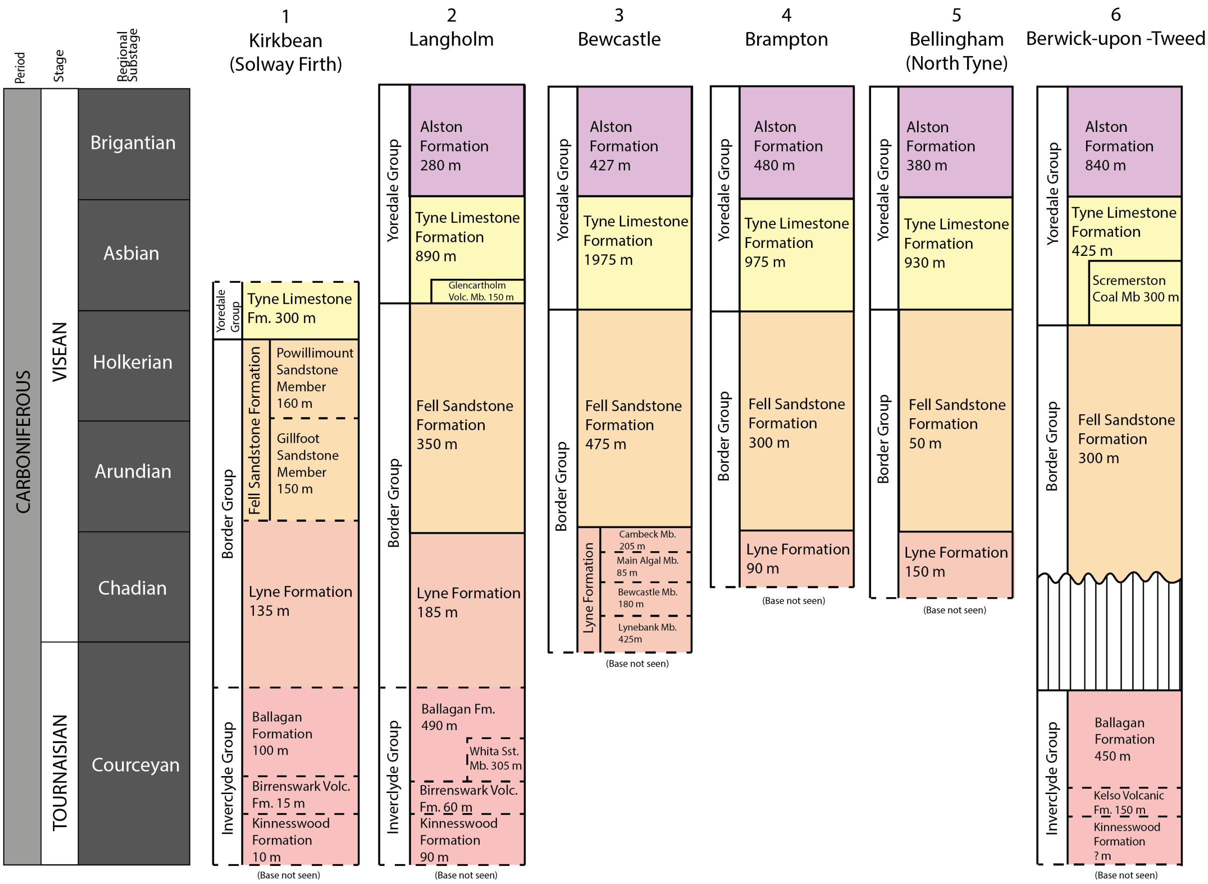

Figure 2.4: Correlation of Carboniferous successions in the Northumberland Trough. Locations are identified in Fig 3. Modified from Water et al. (2012)

2.2.1.4 Tyne Limestone Formation and the Scremerston Formation

The Fell Sandstone Formation is succeeded by Tyne Limestone Formation to the southwest of the Northumberland Trough and the laterally equivalent Scremerston Formation

(Scremerston Coal Group) in the Tweed Basin and the North Sea. Part of the Yoredale Group (Fig. 2.4), the cyclic sedimentary sequences of these two formations (Deposited during the Asbian) mark the end of dominantly braided fluvial deposition in the Northumberland Trough (Smith and Holliday, 1991; Waters *et al.*, 2007; Booth *et al.*, 2020). Instead, deposition during the Asbian occurred in a number of distinct depositional environments (Leeder *et al*., 1989; Kearsey *et al*., 2018; Booth *et al.*, 2020). Recent work by Booth *et al.* (2020) has identified four such depositional environments: open marine, delta front, lower delta and upper delta plain.

The emplacement of the Glencartholm Volcanics and Oakshaw Tuff, to the north of the Northumberland Basin, near the top of the Fell Sandstone succession suggests that renewed extensional faulting occurred during this period (Lumsden *et al.*, 1967; Day, 1970). Syn-depositional faulting during the Asbian is further evidenced by the significant changes in thickness within clastic sediment layers across basin bounding faults (Kearsey *et al*., 2018). Subsidence combined with Glacio-eustatic sea level changes (Wright *et al*., 2001) led to episodic marine flooding events, allowing both localised and laterally continuous carbonate limestones to be deposited (Fig. 2.5). Glacio-eustatic fluctuations in sea level during the Asbian led to the submergence of previously upland areas, such as the Alston Block and the Lake District, and the establishment of carbonate platforms (Fig. 2.5; Whitbread & Kearsey, 2016). These established carbonate platforms facilitated the deposition of carbonates such as the Great Scar Limestone, contemporaneous with the Tyne Limestone and Scremerston formations (Fig. 2.6). The limestone units of the Scremerston Formation are generally thicker and more consistent further south where these periodic marine transgressions had a greater effect (Kearsey *et al*., 2018).

2.2.1.5 Alston Formation

The Alston Formation as seen beneath Newcastle is comprised of thin alternating limestone, mudstone, siltstone and fine to very fine, carbonate cemented sandstone units (Younger *et al.*, 2016); forming regular repeating cyclothem sequences locally known as 'Yoredale cycles' (Fig. 2.5) (Frost, 1968; Leeder, 1974). The base of the Alston Formation marks the end of the Asbian Substage and the beginning of the Brigantian Substage. Deposition, occurring in both deltaic and marine environments, also coincides with the end of active tectonic extension in the region and the onset of passive thermal subsidence. This period of thermal subsidence resulted in the further submergence of the block-and-basin structure that had dominated deposition up until this time (Fig. 2.5). The formation has been encountered across the entirety of the Northumberland Trough.

2.2.1.6 Stainmore Formation

Deposited in the early Namurian (Pendleian to late Kinderscoutian), the Stainmore Formation consists of repeating, coarsening upwards sequences of laterally persistent marine limestone, mudstone, siltstone and quartzitic sandstones, similar to those seen in the underlying Alston Formation (Waters *et al.*, 2014). Deposition occurred within a shallow marine carbonate shelf and deltaic setting (Elliot, 1975; Waters *et al.*, 2014). Coarsening upward cycles likely represent delta system progradation.

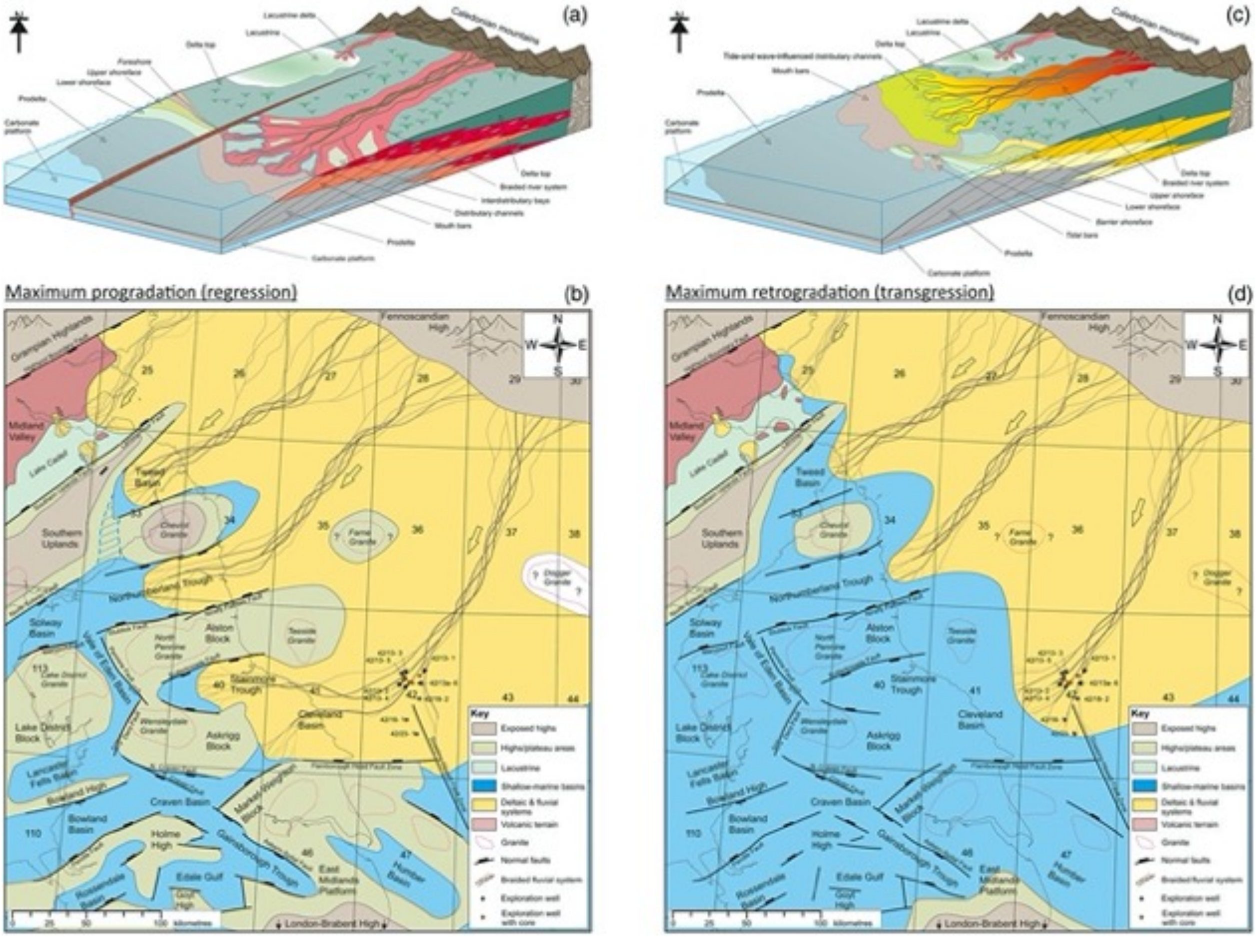

Figure 2.5: Conceptual regional palaeogeographies depicting the variation between maximum progradation and retrogradation in Yoredale cyclicity. Clastic sediment is derived from the northwest. Lateral variation is interpreted to be a function of glacio-eustatic sea level change, differential subsidence and autocyclic depositional controls (Booth et al., 2020).

2.2.1.7 Millstone Grit Group

The Millstone Grit Group is typified by a cyclic depositional sequence consisting of fluviatile quartz-feldspathic sandstone, mudstone, coal and seatearths. The group is dominated by fluviatile, sheet-like, coarse grained sandstones separated by minor marine flooding surfaces. This distinguishes it from the underlying, carbonate dominated Stainmore Formation (Waters *et al.*, 2014).

The group is absent from the Solway and Tweed Basins but is present across much of the Alston Block and the southwestern region of the Northumberland Basin (Fig. 2.6). Deposition occurred during the late Kinderscoutian Substage through to the Yeadonian (late Namurian).

2.2.1.8 Pennine Coal Measures

During the early Westphalian (Westphalian A) deposition took place in a fluvio-lacsutrine environment. During this time the mudstone-dominated, coal bearing Pennine Coal Measures were deposited. The Coal Measures have disappeared from much of the Northumberland Trough due to uplift and erosion but can be found along the southern margin of the basin and across County Durham (Fig. 2.6).

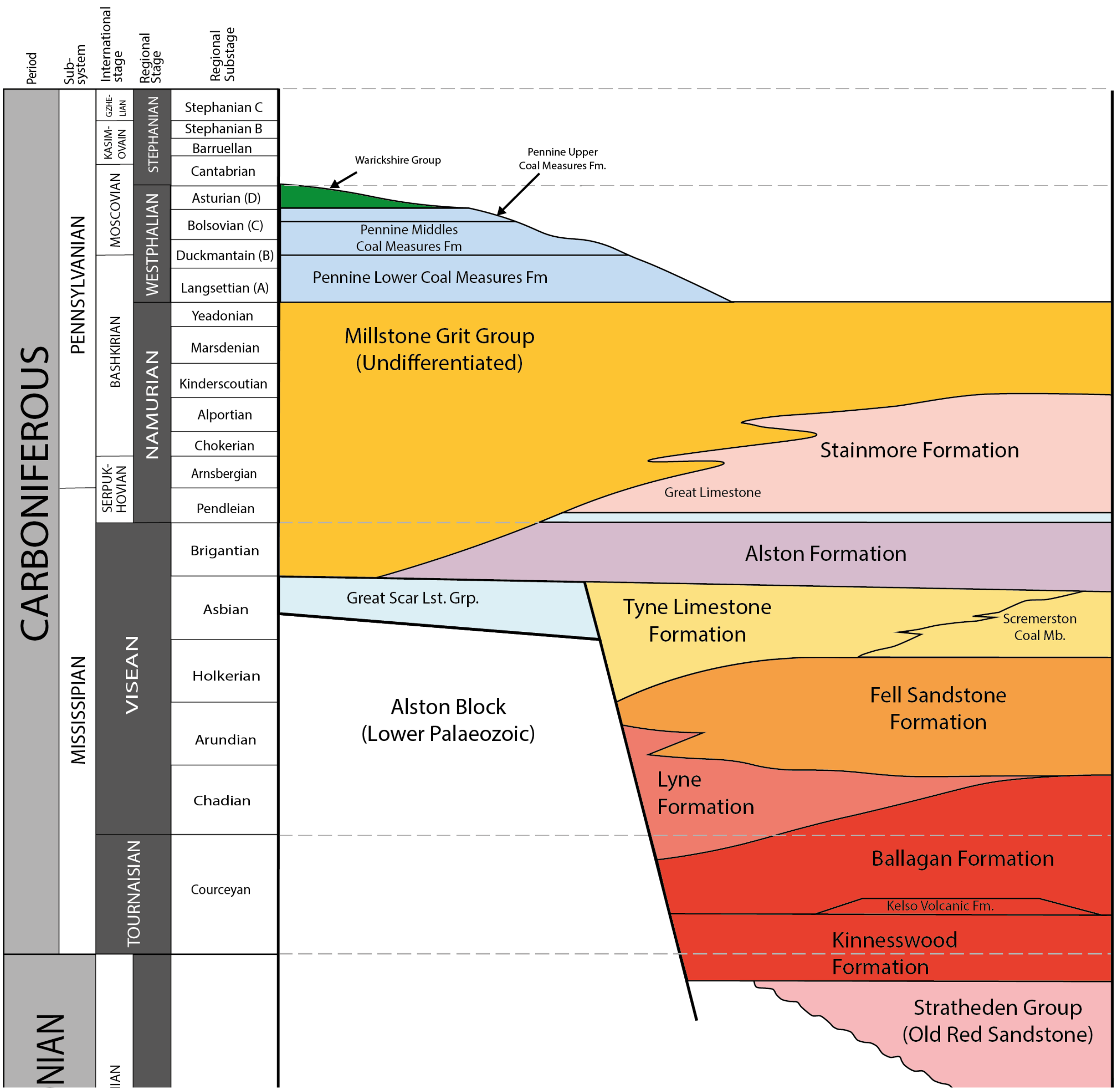

Figure 2.6: Generic onshore stratigraphic relationships of Devonian to Carboniferous strata from the Northumberland Trough to the Alston Block. Modified from Kearsey et al. (2015). Nomenclature from Browne et al. (2002) and Waters et al. (2007).

2.2.2 The end of deposition during the Carboniferous

Sedimentation halted in the late Westphalian onwards as the Northumberland Trough underwent tectonic inversion associated with the Variscan Orogeny. During this time subduction accretion led to the closure of the Rhaeic Ocean (Booth *et al.*, 2020) and the collision of Gondwana with Laurentia to the south. This resulted in widespread uplift and erosion, however, its effects were only mildly felt in the Northumberland Basin (Cornfield *et* *al.*, 1996). Reverse faulting and folds such as the Bewcastle Anticline evidence this period of inversion in Northern England (Martin 1995).

2.3 Introduction to the Fell Sandstone

2.3.1 Facies

Deposition of the Fell Sandstone in the Northumberland Trough began in the Tweed Basin to the North-East, during the Chadian. As previously mentioned, the base of the Fell Sandstone is diachronous with equivalent strata in the central and south-western parts of the Trough. The fluvial system advanced southwest across the Northumberland Trough through the Arundian, extending across the entire basin by the Holkerian (Turner *et al*., 1993). Deposition in the more distal parts of the basin took place in a mixed fluvio-deltaic to shallow marine environment. The top of the Fell Sandstone is also diachronous, grading upwards into the succeeding Yoredale Group (Turner *et al*., 1993).

Recent research, conducted by Howell *et al* (2020), identified three distinct facies associations within the Fell Sandstone Formation. These include:

- Fluviatile facies - Primarily consists of fining upward, erosive-based, arenitic sandstone sequences deposited within fluvial systems (Fig. 2.7). Grain size of generally is fine to coarse though additionally these sandstone units are interbedded with thin (<30cm), subordinate overbank silt and mudstone beds. The presence of marine ostracods in these mudstones (Turner *et al.*, 1997) is evidence short lived marine incursions (Uba *et al.*, 2009). These sand bodies are commonly cross-bedded with both trough-cross-beds and planar-cross-beds (Fig. 2.7) forming solitary sets and cosets (Turner &

Monro, 1987). Planar and ripple laminations are present above the cross-bedded sands, in the upper part of these sand units when preserved. Rarer water escape structures overturned cross-beds can be seen at outcrops such as Bowden Doors. In addition to cross-bedded and laminated sandstones, erosive-based, structureless sandstones also occur; interpreted to be transverse scours created by bank collapse (Fig. 2.7). Occasional clastic pebble bands can be found at the base of these sand units.

- Fluviodeltaic facies – This facies association consists of alternating limestones and coarsening upwards mudstone to sandstone successions; a sequence akin to that of Yoredale cyclothems (Frost & Holliday, 1980). The thickness of these coarsening upwards sequences ranges from a minimum thickness of several metres to tens of metres with laterally extensive limestone units commonly marking the base of thicker successions (Howell *et al.,* 2020). Deposition likely took place in a prograding deltaic to shallow marine environment. Mudstone layers are often fossiliferous, containing shell fragments, ostracods and crinoids and were likely deposited in very shallow marine settings (Turner *et al.*, 1997). Sandstone units are typically thinner than those comprising fluvatile facies and are medium to fine grained with examples of Trough and planar crossbedding, indicative of channel fill material (Bridge, 1993). Palaeosols/seatearths are often overlying these channel sand units, representing periods on non-deposition as a result of channel avulsion (Nemec & Postma, 1993).
- Shallow marine facies – Deposited in a dominantly marine environment, the shallow marine facies association is mainly comprised of alternating mudstones and limestones (Howell *et al.*, 2019). Fluctuating clastic sediment supplies likely prevented prolonged carbonate deposition (Moun, 1984). Occasional, stratigraphically thin, coarsening upwards sequences of mudstone and sandstone, similar to those seen in

flluviodeltaic facies, likely represents periods of sub-aerial exposure (Smith & Holliday, 1991) and the distal end of deltaic sedimentation (Blair & McPherson, 2008; Howell *et al.*, 2019).

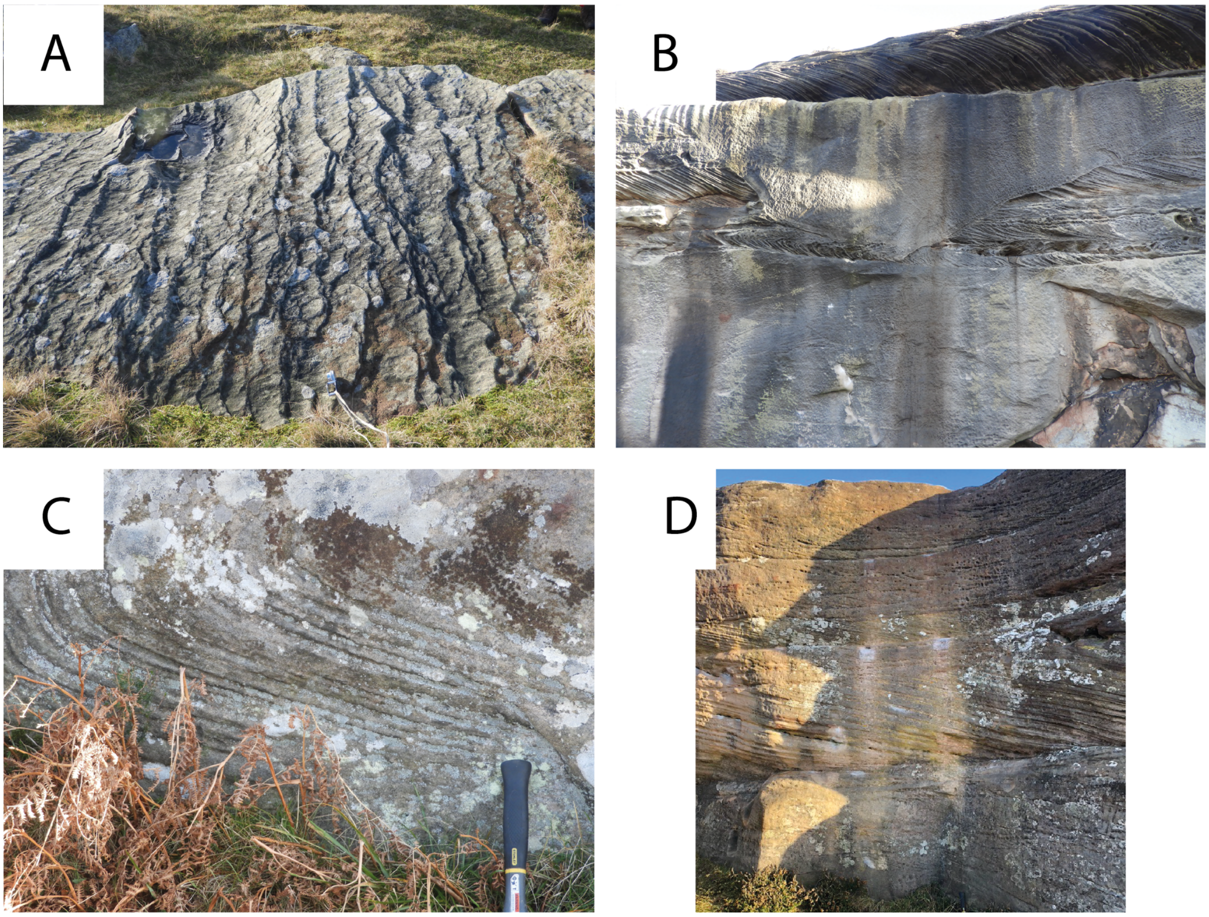

Figure 2.7: Fluvial sedimentary structures observed within the Fell Sandstone at Bowden Doors including: A) Ripple bedforms, B) Structureless sandstone overlain large scale tabular crossbedded strata. Redistribution of these sands through asymmetric channels has created homogenous asymmetric channel fills. C) overturned/recumbent crossbedding. D) vertical successions of both planar and trough crossbedded sets.

2.3.2 Depositional environment

As described in previous literature, the Fell Sandstone was deposited as part of a large, perennial, sand rich river system (Fig. 2.8). This Early Carboniferous river system drained south west towards the Solway Basin (Turner *et al.*, 1987). Overall, deposition occurred as part of both a low sinuosity braided and a meandering river system (Turner *et al*., 1993; Waters *et al*., 2007). The sediment that constitutes the Fell Sandstone was derived from a steadily uplifting source to the northeast of the Northumberland Trough (Robson, 1956; Frost, 1969; Leeder, 1974), most likely the Caledonide Mountains (Fennoscandian High) (Kearsey *et al.*, 2018), formed during the Caledonian Orogeny. The Cheviot and Alston Blocks also acted as minor source regions. The presence of grains of sandstone interpreted to be of aeolian origin in the Fell Sandstone at the Science Central Borehole strata (Younger *et al.*, 2016) suggests that some sediments were possibly sourced from a more arid environment. In the northeast of the Northumberland Trough the Fell Sandstone is dominated by fluviatile facies (Fig. 2.9). The depositional environment varied laterally across northern England during the Chadian, Arundian and Holkerian substages. Marine influence during this period was greater in the Solway Basin due to marine transgressions moving into northern England from the southwest. As a result, deposition within the Solway basin during the Chadian to Holkerian mainly occurred as part of a shallow marine to fluvio-deltaic environment with a more limited siliciclastic input and increased carbonate content (Turner *et al.*, 1997). Ultimately, the Fell Sandstone pinches out to the southwest (Fig. 2.6), where the fluvial/fluvio-deltaic depositional environment is replaced by a shallow marine setting.

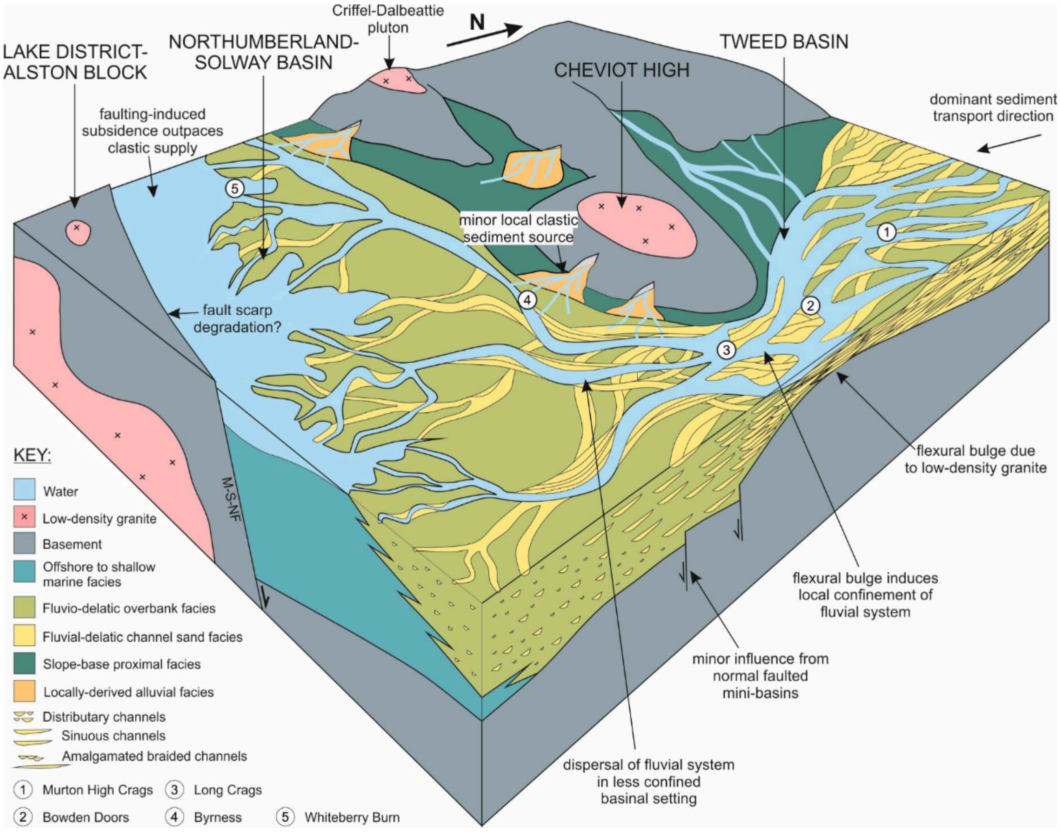

Figure 2.8: A schematic 3D tectono-stratigraphic model for the deposition of the Fell Sandstone Formation in the Northumberland Trough. Modified from Howell et al. (2019).

2.3.3 Petrography

To the North-East of the Northumberland Trough the Fell Sandstone Formation has been described as a fine to medium to coarse grained, mica poor (<5%; Bell, 1978), sub-arkosic sandstone (Smith, 1967). At Bowden Doors the formation is comprised of over 90% sandstone (Turner *et al.*, 1993). However, this high sand percentage is not laterally persistent. Analysis of the formation around Berwick-Upon-Tweed by Turner *et al.* (1993) shows that the Fell Sandstone, in this location, is made of up to 40% finer grained lithologies such as mudstone and shale. The high sand percentages observed in the Belford area (SW of Berwick) are likely the result of the increased lateral confinement of the river system by the Cheviot High (Fig.

2.9). Along the margin of the Cheviot High, between the Tweed and Northumberland basins there likely would have been increased sediment reworking and as a result, reduced preservation of overbank facies (Howell *et al*., 2020). Moving into the central and western parts of the Northumberland Trough (Solway Basin), in northern Cumbria, gamma ray log analysis (Howell *et al.*, 2020) shows that the Fell Sandstone passes into a continuation of the cyclical successions seen in the underlying Lyne Formation. However, within the Fell Sandstone, the sandstone units are thicker and the limestones thinner (Day *et al*., 1970). At outcrop north-east of Bewcastle (Fig. 2.2; Fig. 2.4), the Fell Sandstone is typically medium to fine grained with occasional coarser clastic beds (Howell *et al.*, 2020). The proportion of sand within the Fell Sandstone decreases away from the clastic sediment source from >95% around the margins of the Cheviot High to as low as 14% in the western Solway Basin (Howell *et al*., 2020). The lateral changes in sand and overbank sediment preservation were interpreted by Monro (1986) to represent the change from a proximal to a medial, then distal fluvial setting. This model, however, is too simplistic (Howell *et al.*, 2019). Overbank mudstones are preserved at Murton High Crags (GR: NT962495) (Howell *et al.,* 2020), an exposure upstream of the sand dominated exposures along the margin of the Cheviots, and the Fell Sandstone has been correlated with similar fluvial successions beneath the North Sea, several hundred kilometres North (Kearsey *et al*., 2019) as well as the central North Sea to the West (Arsenikos *et al*., 2015; Monaghan *et al*., 2018). Howell et al (2020) concluded that for these reasons the sand dominated exposures along the margin of the Cheviots cannot be regarded as proximal deposits.

2.4 Geological evolution of the region

The lack of a post-Carboniferous overburden makes it difficult to construct an accurate evolutionary history for the Northumberland Trough. As mentioned, the region was uplifted during the Variscan Orogeny towards the end of the Carboniferous (Westphalian). It is difficult to estimate how much of the Westphalian to Namurian succession was lost during this event. When evaluating the burial history of the Fell Sandstone at the Errington 1 borehole (Fig. 2.9), drilled in 2004, it was inferred that up to 1.25km of sediment was deposited and subsequently eroded at the end of the Carboniferous (ROC, 2005). Sedimentation resumed in the Permian and continued through the Mesozoic (Fig. 2.9). Apatite fission track studies indicate a maximum palaeotemperature at the end of the Cretaceous (~60 Ma) (Bray *et al.*, 1992; Holliday, 1993). From this it can be inferred that burial depth within the trough reached its maximum during this time. A second phase of uplift occurred during the Tertiary with much of North West Europe being uplifted. It is estimated that the Carboniferous sequence in the Northumberland Basin was uplifted by up to 1.8km during the Tertiary (ROC, 2005) If accurate, the Fell Sandstone, which is buried to a depth of approximately 1300m in central Northumberland, would have reached a maximum burial depth of approximately 3-3.5km (Fig. 2.9).

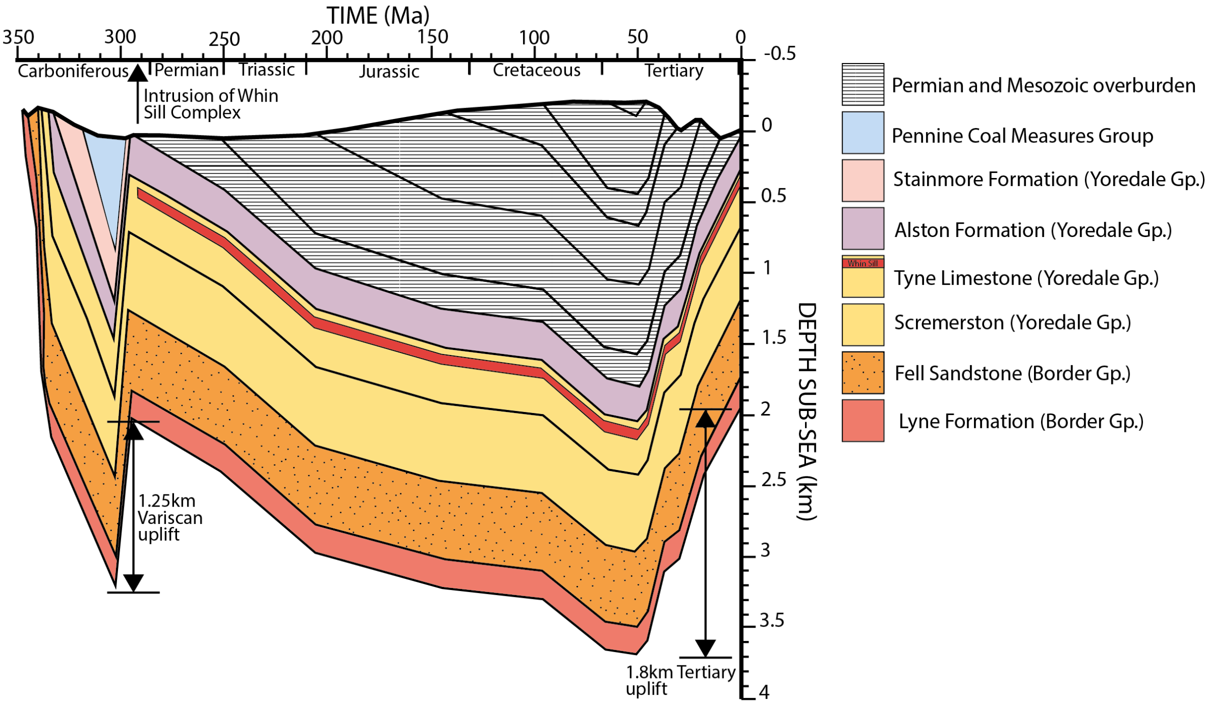

Figure 2.9: Burial History of the Carboniferous sequence at the Errington 1 borehole. Modified from ROC (2005).

2.5 Controls on reservoir quality

One of the aims of this project is to map the reservoir properties of the Fell Sandstone. If the low permeability observed at the Science Central Borehole is not the result of damage during drilling or barite cementation then the reservoir quality of the Fell Sandstone must have been reduced by the effects of burial diagenesis, compaction and/or faulting. Depositional and diagenetic controls must be considered as they can strongly influence reservoir quality.

2.5.1 Depositional controls

Initially, aspects such as porosity, within sandstones, are controlled by deposition. Sorting is the most important influence on depositional porosity within sandstones due its strong dependency on grain packing arrangements (Worden & Burley, 2009). Poorly sorted sands with a range of grain sizes have a lower depositional porosity, when compared to well-sorted sands, as spaces between larger grains are infilled with smaller grains (Beard & Weyl, 1973; Worden & Burley, 2009). However, poorly sorted sands are also more resistant to mechanical compaction (Fawad *et al.*, 2010) meaning that initial is more likely to be preserved. In the northeast of the Northumberland Trough, the Fell Sandstone is described as well sorted (Howell *et al.*, 2019) and medium grained on average (mean value of 0.33mm) (Bell, 1978), however, information on grain sorting is generally sparser in the southern part of the Northumberland Trough where the Fell Sandstone is not found at outcrop. In more distal locations further south grain size generally decreases to mostly fine to very fine grained at Science Central (with the exception of some medium and coarse-grained units) (Younger *et al.*, 2016). The variation in grain size is potentially greater here also due to increased overbank facies preservation. Significant grain size variation is potentially a contributing factor the poor reservoir quality of the Fell Sandstone at Science Central. Grain angularity is also a factor. Sandstones comprised of angular grains have a high stress related compressibility, compared with sandstones with more rounded grains, due to the possibility of grain fracturing and crushing at grain contacts (Fawad *et al.*, 2010).

As mentioned in 2.3.3 the net to gross ratio of the Fell Sandstone changes, moving in the direction of the paleocurrent from highs in excess of 95% along the Cheviot margin to a low of 14% in the Western Solway Basin (Howell *et al.*, 2019). The abundance of finer grained clays can influence how much initial porosity is lost through mechanical compaction as clay compacts under lower stresses than harder minerals such as quartz. The presence of clay, namely clay coatings, also influence factors relating to chemical diagenesis as clay coatings can inhibit the precipitation of quartz cement as they reduce the available quartz surface area thus preserving porosity (Ajdukiewicz & Lander, 2010). Additionally, quartz registers as a seven on Moh's scale of hardness and is generally more resistant to mechanical compaction than other lithic minerals. A sandstone's composition, therefore, potentially has a bearing on its overall compressibility as lithic sands, when compacted, are more compressible and undergo a greater degree of crushing and porosity loss when compared to monocrystalline quartz rich sands (Chuhan *et al.*, 2002).

Sand body thickness is also an important aspect to consider. Thicker sand units would mean a greater level of connectivity within the formation, thus resulting in improved reservoir quality. This is linked to the net to gross ratio as a greater abundance of mud/siltstone layers between sand units can lead to increased compartmentalisation within the formation.

Syn-depositional subsidence across intrabasinal normal faults may have acted to laterally confine the Fell Sandstone River System, potentially separating it into a number of locally confined active braid plains (Turner *et al.*, 1993). Such intrabasinal confinement would have promoted the development of stacked fault bounded sand bodies, similar to those seen at the Bowden Doors outcrop (GR: NU069327).

2.5.2 Diagenetic controls

Diagenesis within sandstones encompasses a broad range of both physical and chemical alterations that occur between burial and low-grade metamorphism. Diagenetic alterations can be grouped into one of three regimes (Worden & Burley, 2009): eogenesis (early diagenesis), mesogenesis (associated with burial) and telogenesis (associated with uplift). Once removed from the influence of the depositional environment sandstone continues to be altered through mesogenesis (burial diagenesis). The term mesogenesis was first defined by Schmidt & Macdonald (1979) as the physical and chemical processes that act on a sediment once it is removed from the influence of the depositional environment and before the onset of metamorphism. Telogenesis, associated with uplift, relates to the impact the influx of meteoric water has on exhumed sediments (Worden & Burley, 2009).

The depth of burial is a strong influence on how much initial depositional porosity may be lost during compaction. The maximum burial depth of the Fell Sandstone generally increases to the south due to the asymmetric profile of the Northumberland Trough (Fig. 2.10) likely resulting in laterally varying levels of mechanical compaction across the formation. Mechanical compaction is dominant at depth less than 2km and temperatures below approximately 80^{0}C. At 80^{0}C and above, or below 2km depth, mesogenesis is dominated by processes relating to chemical compaction. Significant quartz cementation within sandstone reservoirs beings to occur at temperatures above 80-90^{0}C (Ajdukiewicz & Lander, 2010), linked the acceleration of quartz dissolution (Fossen *et al.*, 2007), resulting in further intergranular porosity loss as pore space is infilled by authigenic quartz. The interpreted regional evolution of the Northumberland Trough indicates that the Fell Sandstone, having been buried to depths greater than 2km during two separate depositional phases, has undergone both mechanical and chemical compaction. Generally, highest porosities are preserved where compaction and secondary mineralisation are kept to a minimum (Ajdukiewicz & Lander, 2010).

The Carboniferous strata in Northern England strata has been uplifted and partially exhumed during the two tectonic inversion events, during the Late Carboniferous and the Tertiary (Fig. 2.9). The effects of telogenesis during these two inversion events could have resulted in a further feldspar dissolution, enhancing secondary porosity within the Fell Sandstone, which was likely exposed to influxes of meteoric water. Mineral dissolution can result in the creation of vuggy pores, intergranular cavities larger than typical intergranular pores. However, due to the southerly dip of the Fell Sandstone, linked to the basin profile, the impacts of telogenesis were likely not uniformly felt across the formation's range.

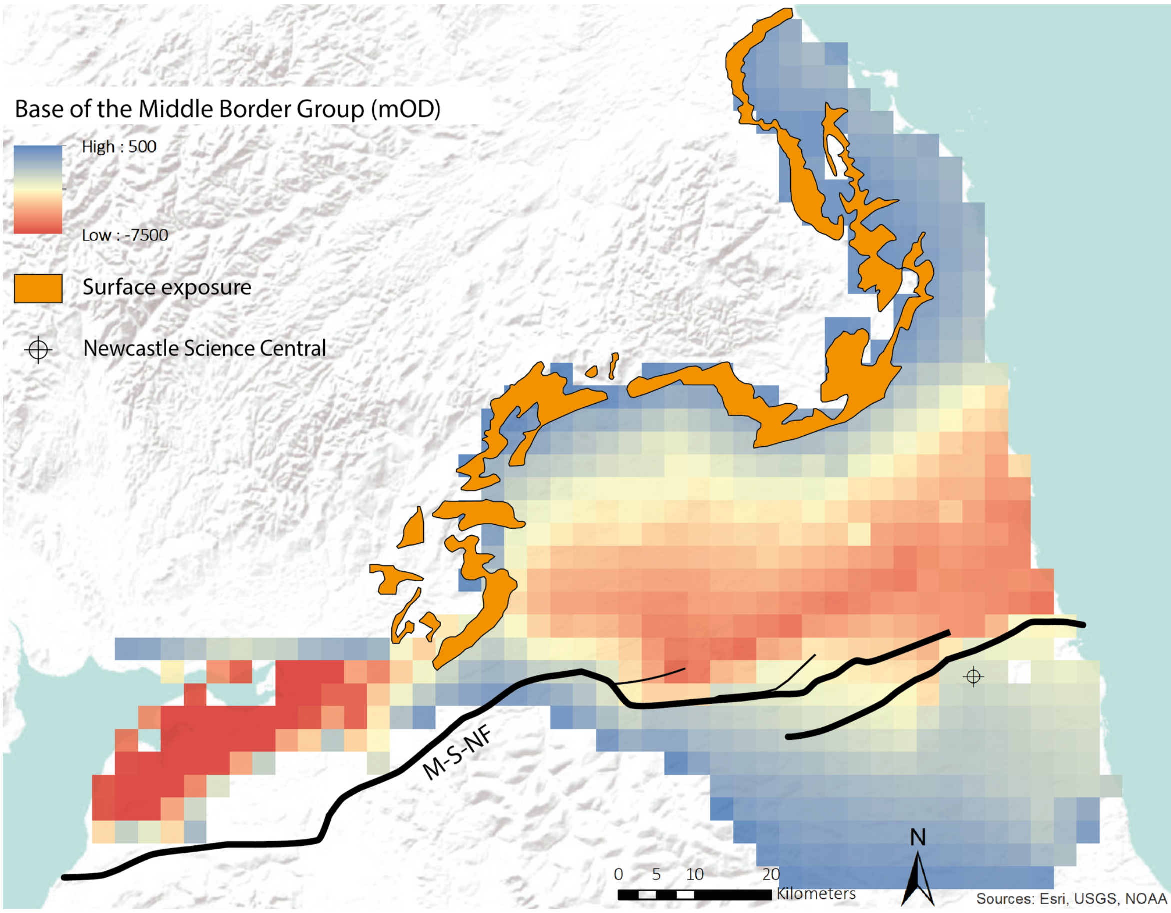

Figure 2.10: Depth of the base of the Fell Sandstone and Border Group in the Northumberland Trough. Surface exposure modified from Younger et al. (2016). Depth data downloaded from the BGS.

2.6 Rationale for targeting the Fell Sandstone for deep geothermal exploration

2.6.1 Geothermal exploration in the Newcastle upon Tyne area

Over time there has been increasing realisation that the Newcastle area has higher geothermal heat flows than most other parts of the UK (Younger *et al.*, 2016). In 1961 a drilling project, conducted by the Department of Geology at Durham University, exploring the

Weardale Granite in County Durham discovered that hot rocks existed at depth in the area, prompting further investigation into the Weardale Pluton (Gluyas *et al.*, 2018). Since then, equilibration temperatures of up to 160^0C have been recorded from connate water fluid-rock throughout collieries in the region (Younger *et al*., 2015). In 2004 a well was drilled at Eastgate (Eastgate 1; BGS reg. no. NY93 NW97) and reported on by Manning et al. (2007). Drilled to a depth of 998 m, the well encountered naturally fractured granite with a bottom hole temperature of 46^0C being recorded. Whilst Eastgate 1 had a measured heat flow of $111mW/m^2$ and was capable of producing water at a rate of 140 m^3/h, the subsequent drilling of an appraisal well (Eastgate 2; BGS reg. no. NY93 NW98) roughly 700m away from the original site confirmed that the fracture permeability of Eastgate 1 was locally associated with a bounding fault. Fracturing was not pervasive throughout the Weardale Granite. Despite this setback, the north-east of England is estimated to have one highest heat flows in the UK (Gluyas *et al.*, 2020).

2.6.2 Drilling of the Science Central Borehole

The most recent geothermal exploration in the area was the drilling of the Newcastle Science Central Borehole, conducted by a consortium led by Newcastle University and including Durham University, the British Geological Survey and Newcastle City Council. The project is documented by Younger *et al*. (2016). The hypothesis behind the project was that high temperature barium rich Na-Cl brines could be circulating within the lower reaches of the Ninety-Fathom Fault Zone, which has long been associated with the significant and persistent flow of brines. As an example, flow rates of 1.4 million litres per day have been registered in association with the Rising Sun Fault, a footwall splay of the Ninety Fathom Fault (Younger *et* *al*., 2016). Barite ($BaSO_4$) cement can be seen in the Permian Yellow Sands at Cullercoats Bay (NZ364711) providing further evidence for the once widespread circulation of these brines.

The Fell Sandstone was selected as the target for the drilling project as it was hoped that the favourable aquifer properties of the formation exhibited at outcrop and between Rothbury and Berwick-upon-Tweed persisted at depth beneath Newcastle (Fig. 2.11). The main concern at the start of drilling was whether the Fell Sandstone would be present at all beneath Newcastle as this had not been proven at the time.

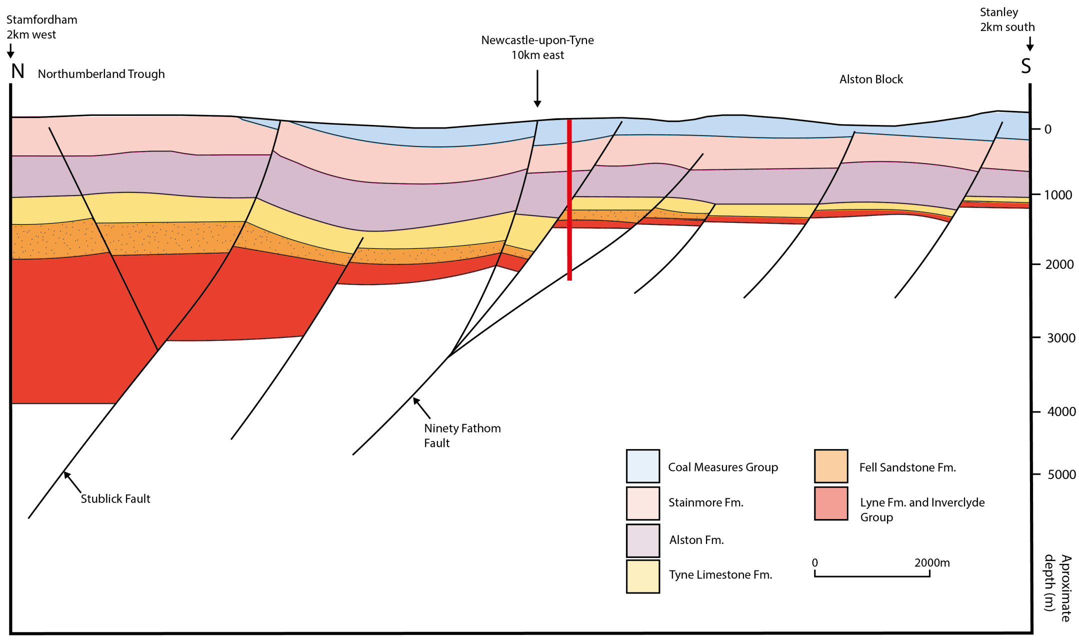

Figure 2.11: A seismic profile located 10km west of the Science Central Deep Geothermal Borehole. The equivalent position of the borehole is represented as a red line. The borehole intersects a major footwall-splay associated with the main Ninety Fathom Fault as well as the Fell Sandstone to the south of the main fault. Modified from Younger (2010).

2.6.3 The Fell Sandstone Formation at Science Central

At the completion of drilling, the Science Central Borehole penetrated 1821m of Carboniferous strata. Full details of the Carboniferous stratigraphy, including the Fell Sandstone at Science Central, are provided by Younger *et al.* (2016). As predicted the Fell

Sandstone Formation was encountered between 1418.5m and 1795m however, notable differences from the Fell Sandstone at outcrop in Northumberland were recorded. The Fell Sandstone at Science Central is divided into seven separate units, by Younger *et al.*, based on gamma log response (A-G; Fig. 2.12). The formation predominantly consists of fine to very fine grained sub-rounded sandstone heavily interbedded with layers of micaceous mudstone and siltstones. The grain size here is in line with more distal Fell Sandstone Deposits located to the west near Bewcastle and the Solway Basin as opposed to the medium to coarse grained arenites observed at outcrop in Northumberland (Turner *et al.*, 1993; Martin, 1995).

Whilst the Science Central Borehole proved the existence of the Fell Sandstone beneath Newcastle and provided further evidence of the high heat flow in the area, with a reliable bottom-hole temperature of 73.3^{0}C at 1772m (Younger *et al.*, 2016), it was not able to produce significant amounts of water upon testing. Analysis of the Fell Sandstones permeability, obtained through the analysis of water recovery levels from 805m, and effective aquifer thickness yielded an estimate for average hydraulic conductivity (K) of 7×10^{-10} m d^{-1}. This estimate was six orders of magnitude lower than estimates for intergranular permeability reported for the Fell Sandstone in the Berwick area. Using Archie's Law, the porosity was inferred to be <3.5%; considerably lower than the values of up to 30% reported for surface exposures (Hodgson & Gardiner, 1971; Bell, 1978; Turner *et al*., 1993). Younger *et al*. (2016) concluded that carbonate and silica cementation, in the upper and lower parts of the formation respectively, had reduced the permeability of the Fell Sandstone by occluding pore necks thus reducing the interconnectivity of the remnant porosity.

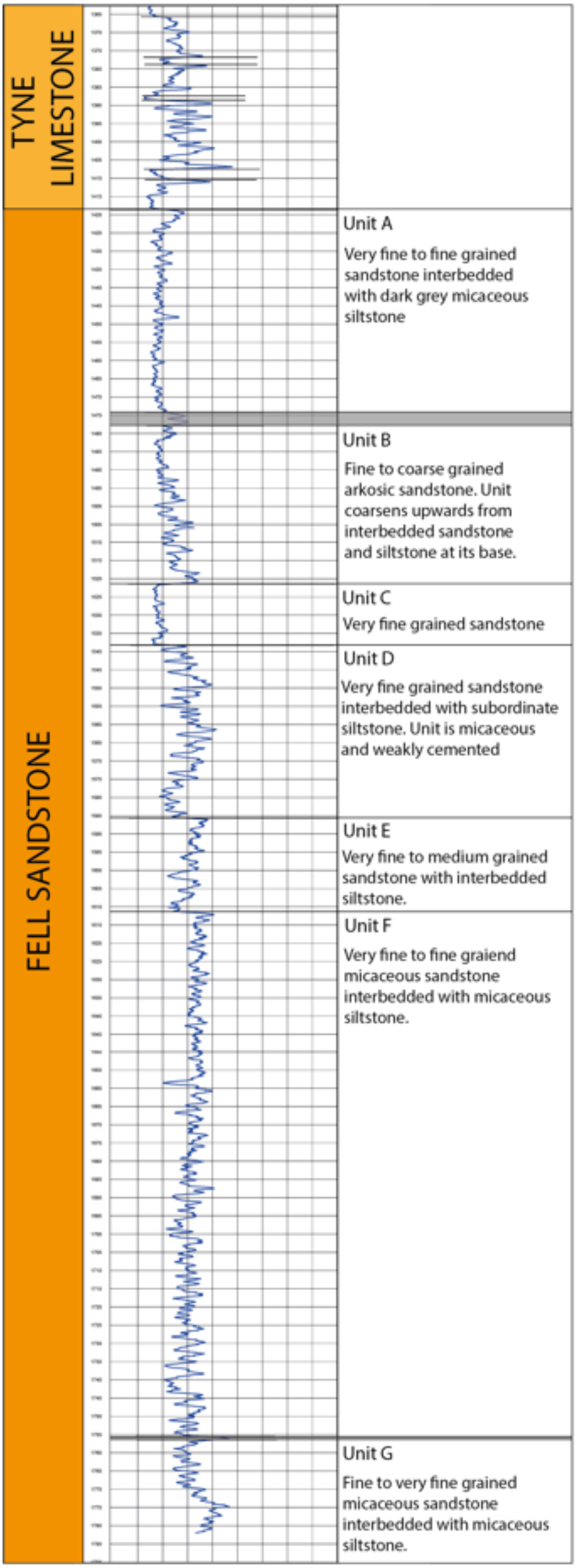

Figure 2.12. Interpreted gamma ray for the Fell Sandstone at Science Central. Gamma Ray log curve and unit descriptions modified from Younger et al. (2016).

Chapter 3: Research methodology

3.1 Determining stratigraphic and facies controls on reservoir quality

This section outlines the methodology, results and interpretations of the wireline and compositional log analysis undertaken during this study.

3.1.1 Sources of data

Scans of wireline logs from the Easton, the Errington, Longhorsley, Stonehaugh and the Westnewton boreholes were acquired through the UK Oil and Gas Authority release agent, IHS Markit.

Gamma ray curves and lithological descriptions for the Fell Sandstone, from the Science Central Borehole, were provided by Newcastle University.

For offshore wells, wireline log scans were available through the UK National Data Repository. These wireline logs include gamma ray, sonic, resistivity and lithology logs. Brief lithological descriptions were also included, providing semi-quantitative geological descriptions regarding lithology, grain size, sorting, clay content, cementation, trace minerals and visible porosity.

3.1.2 Wireline and composition logs

Gamma ray (GR) logs were used to predict the varying lithologies in boreholes by measuring the intensity of the spontaneous emission of gamma ray radiation. Most rock types emit varying amounts of gamma ray radiation. The amount of gamma ray radiation produced is dependent on the amount of potassium 40, uranium and thorium within the rock.

Variation in radioactivity and gamma ray emission reflects a change in lithological composition which in turn, is often associated with changes in the depositional environment (Tzortzis and Tsertos, 2002). Gamma ray radiation typically increases with shale content due to relatively high concentrations of potassium. Clean sandstones and carbonates on the other hand have comparably low concentrations of potassium, uranium and thorium and therefore give lower gamma ray readings. Gamma ray logs can therefore be used as a tool for calculating shale/clay content within a formation.

GR logs can also be used to estimate grain size trends which can then be used as a tool for understanding depositional facies. Within sandstones, GR response increases as grain size decreases, as finer grained sandstones typically have a higher shale/clay content. This means that GR logs represent vertical grain size profiles (Selley, 1979; Rider, 1990). The idea of using GR logs to interpret facies deposition was first proposed by Selley (1978), who proposed that the shape of well-log curves can be used to interpret depositional facies.

Sonic or acoustic logs are primarily used to estimate the porosity of a formation. This is done by measuring the travel time of a compressional wave through the formation which is then used to estimate the velocity of the waves through said formation. Sonic logs display vertical changes in interval transit time (Δt), measured in microseconds per foot (μs/ft). Dense formations, that have undergone a higher degree of compaction and/or cementation therefore have a lower intergranular porosity, generally give a faster (smaller) Δt value. Formations with a greater level of fluid filled porosity will return a slower (larger) Δt value. A scale of 40 μs/ft to 140 μs/ft is commonly used as most formations give transit times between these two values.

Sonic logs do have their limitations. Sonic logs are only sensitive to primary intergranular porosity and cannot account for secondary and fracture porosity. On their own, sonic logs are unreliable tools for lithological identification. Interval transit time is affected by the level of compaction, making it difficult to accurately interpret lithology. Shale, in particular can vary greatly in density, with density tending to increase with age, and thus give a range of Δt values.

Neutron logs are primarily used to determine the porosity of a formation. The formation is bombarded with neutrons which are sensitive to the amount of hydrogen within a formation, the abundance of which is linked to the rock's porosity. Formations with a high amount of hydrogen will return a lower neutron count, indicative of high porosity. Rocks with lower porosities will also contain less hydrogen.

Neutron logs can also be a useful tool for lithological identification when combined with corresponding formation density logs (neutron density crossplot). The separation between the two curves is influenced by formation's lithology and porosity. There is a small amount of negative separation for clean sandstones and for pure limestones there is no separation between the density and neutron logs. The presence of shale within a formation will cause neutron porosity readings to be considerably higher than normal, due to the effect of bound water contained within it, resulting in a large positive separation. As the volume of shale decreases so too does the large positive separation.

Resistivity logs are used to interpret the nature of fluids present in a formation. This can be done through the comparison of shallow penetration (LLs) and deep penetration (LLd) dual-laterologs. LLs logs show the resistivity of the zone affected by mud filtrate, immediately surrounding the borehole. LLd logs show the resistivity of the uncontaminated rock. It is possible to estimate a formations permeability by evaluating the separation between these two lines. No separation between the LLs and LLd lines indicates that the formation being analysed is impermeable. However, if the LLs line has a lower resistivity than the LLd line then the formation is permeable. If a formation is found to be permeable, it is also potentially possible to predict the type of fluid present within the rock. The separation of the two resistivity lines will be greater for formations with fresh water than for formations with saline water, and greater still for formations containing hydrocarbons. Both types of laterolog have a bed resolution of approximately 2 feet. Resistivity logs are displayed on a logarithmic scale of 0.2 Ωm to 20 Ωm up to 0.2 Ωm to 20,000 Ωm.

3.1.3 Net to gross and sand body thickness

Net to Gross (NTG) is defined as the amount of reservoir (Net) within an interval of interest (Gross) and expressed as a fraction between 0 and 1. An interval with no reservoir rock will have a NTG value of 0 whilst an interval that is composed of 100% reservoir rock will have an NTG value of 1. The equation for NTG, derived from Hannis, (2016) is shown below.

$$\text{Net to Gross (NTG)} = \frac{\text{Total reservoir thickness (net)}}{\text{Total thichness of interval (gross)}}$$

Here, gamma ray profiles have been used in tandem with lithological logs to determine how both the net to gross ratio and sand body thickness, for the Fell Sandstone, vary laterally across the Northumberland Trough. Burial depth and stratigraphic thicknesses are also derived from gamma ray profiles for each borehole. Channel width estimates have been made based on aspect ratios from existing datasets (Reynolds, 1999; Gibling, 2006).

A total of six gamma ray profiles for the Fell Sandstone have been digitised for analysis: taken from the Easton, Errrington, Longhorsley, Stonehaugh and the Science Central boreholes as well as the offshore well 41/01-1. Data for gamma ray log derived net sand is supplemented by existing data from both individual well reports and scientific literature (Turner *et al.*, 1993; Turner *et al.*, 1997; Howell *et al.*, 2019). Gamma ray logs have also been used to make interpretations on petrological characteristics such as grain size as well as the depositional environment.

Neutron density crossplots from the Errington and Longhorlsey boreholes have been digitised to aid in lithological identification and interpretation of the Fell Sandstone at these two sites.

3.1.4 Stratigraphic correlation

An attempt is made to correlate the Fell Sandstone succession between the six onshore wells analysed. This has been done in order to better observe potential reservoir thickness changes across the Northumberland Trough and to aid depositional environment interpretations. Correlation of the different Fell Sandstone successions will help to elucidate the lateral continuity of potential reservoir quality sand bodies, thus aiding in reservoir geometry calculations (Chapter 3.3).

3.1.5 Facies association interpretation

This study uses the facies associations set out by Howell *et al.,* (2019). The depositional environment has been interpreted, based on facies association, with the aim of better understanding reservoir potential. Interpretations on the depositional environment have been made based on gamma ray responses and lithological descriptions.

3.1.6 Porosity and permeability

Porosity and permeability data are only available from wells where core sample or sidewall core analysis has been undertaken and is as such only available from a limited number of onshore and offshore wells.

This project looks at porosity and permeability (poroperm) data for the Fell Sandstone, obtained through conventional core analysis, from the Errington, Longhorsley and Stonehaugh boreholes. Onshore poroperm data have been supplemented with data from offshore wells, located in the North Sea that penetrate the Fell Sandstone in order to draw comparisons between onshore and offshore successions. Offshore porosity permeability data for the Fell Sandstone has been taken from exploration wells 41/01-1 and 43/02-1, located in the 41st and 43rd quadrants of the Central North Sea respectively.

Only limited core derived poroperm data is available for the Fell Sandstone at Longhorsley and none at Errington as no cores or sidewall cores were taken when the borehole was drilled. Neutron porosity data, obtained through wireline log analysis, from both boreholes, courtesy of the UK Oil and Gas Authority, has been examined. For both boreholes, neutron porosity values (NPHI, v/v), derived from prominent sand bodies within the fell sandstone succession, have been plotted against bulk density (RHOB, g/cm^3). Zones A, B, D and H were selected for the Errington Fell Sandstone in order to identify any general trends across the succession. For the Fell Sandstone at Longhorsley, sand bodies were defined based on gamma ray readings.

The succession from the Westnewton borehole was excluded from this analysis due to its distal location and the fact that the formation passes into a dominantly carbonate succession at this location. Located over 40km southwest of the Easton Borehole, the comparison of poroperm data from Westnewton, with data from the central and eastern Northumberland Trough, would likely be of little benefit.

3.2 Petrographic sample and thin section data analysis

The foremost aim of this project is to investigate the reservoir potential of the Fell Sandstone and to elucidate the importance of lateral change in the depositional environment and burial diagenesis upon it. This section outlines the methodology of the thin section analysis undertaken on samples from Bowden Doors, the Errington 1 borehole and the Science Central borehole. A total of 36 samples were analysed (16 from Bowden Doors, 13 from Errington 1 and 7 from Science Central).

3.2.1 Rationale

Lateral changes in both depositional and post-depositional diagenetic controls have likely resulted in notable variation in the Fell Sandstone's formation characteristics across its range. The main purpose of this thin section analysis is to compare the petrological characteristics of the Fell Sandstone encountered at Science Central, Errington 1, and at outcrop in order to identify how the formation changes both petrographically and in terms of reservoir characteristics.

The washed Fell Sandstone cuttings acquired from the Errington 1 Borehole were taken from a burial depth range similar to that of the Fell Sandstone at the Science Central Borehole (1340-1976m compared with 1418.5-1795m respectively). Errington 1 is located approximately 27km to the northwest of the Science Central Borehole. Comparison of thin sections from these two boreholes can therefore help to elucidate whether the poor reservoir quality identified at Science Central is the result of local alteration or representative of the Fell Sandstone at depth in the Northumberland Trough.

Additionally, the Fell Sandstone as seen at the Errington 1 borehole is not situated in close proximity to the Ninety-Fathom Fault. Comparisons of thin sections from the Science Central and Errington boreholes are made to help identify the potential impacts the Ninety-Fathom Fault has had on reservoir quality at Science Central.

3.2.2 Sources of data

In addition to the samples analysed during this study, thin section descriptions and point count data from the Longhorsley, Stonehaugh and Easton boreholes, are presented. Sample descriptions and point count data for these boreholes are provided courtesy of ROC Oil who commissioned a petrographic study, undertaken by Corex UK, in 2002. A total of ten samples were analysed, three from the Longhorsley borehole and seven from the Stonehaugh borehole. Thin section descriptions from the Easton 1 borehole are provided courtesy of Blackbourn (1990).

SEM analysis was conducted on samples from the Stonehaugh borehole by Corex UK in 2002, as part of their petrographic study of the Fell Sandstone. Three samples were mounted using Araldite and coated with gold for analysis. No SEM data is available for the Longhorsley borehole. Limited SEM descriptions are also available for the Fell Sandstone from the Easton borehole. Two Fell Sandstone samples were analysed by Blackbourn (1990) and briefly surmised within a petrographic report for the Easton borehole. Brief summations of the results of this analysis are presented here.

3.2.3 Thin section analysis

Samples from the Bowden Doors outcrop, the Science Central Deep Geothermal Borehole and the Errington 1 borehole were selected for thin section analysis. Thin sections (76 x 26mm) were prepared using a blue-stained epoxy resin in order to highlight porosity. These samples are representative of the Fell Sandstone targeted for geothermal exploration and as seen at outcrop in Northumberland.

Sixteen thin sections were created using samples taken from Bowden Doors. Nine samples were taken from the main outcrop, present at the field site, and seven from a second outcrop located stratigraphically below the main outcrop. This was done in order to obtain samples from as much of the stratigraphic succession, visible at Bowden Doors, as possible.

A total of twenty samples were provided in the form of unwashed drill cuttings from the Science Central Borehole. All twenty samples were inspected, using a binocular microscope, to assess how much mud was present in the samples. From this, seven samples, taken at depths of: 1420m, 1480m, 1520m 1540m, 1760m, 1780m and 1795m were selected for thin section analysis. Before being used to create thin sections, the samples were washed using distilled water, to remove any excess drilling mud, and dried at 30^{0}C over a period of twelve hours. The samples taken from 1420m, 1480m, 1520m and 1540m depths represent the very fine-grained sandstone units, interbedded with subordinate siltstone and mudstone (Fig. 10, Unit A, Unit B and Unit D), found near the top of the formation. The samples from 1760m, 1780m and 1795m represent the lower part of the formation, identified as by Younger *et al.,* (2016) as fine to very fine sandstone heavily interbedded with micaceous siltstones and mudstones (Fig. 2.12, Unit G). Lithologies, for the depths from which samples were taken, were identified prior to sample analysis using the gamma ray log and general unit descriptions from Younger *et al* (2016). The comparison of these two sets of samples will help to elucidate how the formation changes with depth/over time.

For the Errington 1 borehole, samples were provided in the form of washed drill cuttings (samples that had been cleaned and dried in advance). The Fell Sandstone at Errington 1 is approximately 643m in thickness so samples were selected at regular 50m intervals between 1350m and 1950m (measured depth) in order to analyse the entirety of the Fell Sandstone penetrated by the Errington 1 borehole. The four stratigraphically highest samples (1350m, 1400m, 1450m and 1500m) represent the two thick sandstone units present at the top of the Fell Sandstone Formation (Zone A and Zone B). These sandstone units were identified to have the highest measured porosity within the Fell Sandstone at Errington 1 (ROC, 2005). All remaining samples represent the alternating sandstone, sandy siltstone and mudstone units (Zones C-H) that make up the bulk of the formation.

Point counting was conducted, using the software Petrog, to provide estimates for detrital grain composition and abundance, clay mineral abundance, the prevalence of cementation, and porosity. Counts of 300 were obtained for each sample. Quantitative estimates for porosity were successfully obtained for the Bowden Doors thin section samples, however, due to sample disaggregation, it was not possible do this for the samples from Science Central or Errington 1. For this reason, sample porosity was also calculated using JPOR imaging software. Photomicrographs were recoloured and then processed to obtain quantitative estimates for visible porosity. Qualitative estimates for porosity and pore connectivity are made for each thin section. Raw compositional data, obtained from point counting, were collated in an excel database and analysed to obtain average formation compositions for each of the three sites. The abundance of detrital quartz, feldspar and lithic grains was calculated for each sample to create a ternary plot of QFL (Quartz, Feldspar and Lithics) composition. Overall clay abundances were identified for each sample to produce an average net to gross value for the three sites. These net to gross values were then compared with existing sample descriptions for the Fell Sandstone in order to better identify how the sand richness of the formation changes laterally.

Textural data were also obtained using Petrog for each thin section. One hundred grains were measured per sample to provide estimates of grain size, sorting and roundness. Major length grain size measurements were collated into a database and used to create overall grain size distribution plots for each sample from the three sites. Standard deviation in grain size was calculated and used to create plots of normal distribution for each site. Photos of each sample were taken using an optical microscope (photos taken at x5, x10 and x20 magnification).

3.2.4 SEM analysis

In addition to point counting, eight samples were selected for SEM analysis, two sample were selected from Bowden Doors, three from the Science Central borehole and three from the Errington 1 borehole. For Science Central, samples from 1480m and 1540m depth were selected as they represent two prominent sand bodies, identified through gamma ray log analysis (Fig. 2.12, Unit B and D). They were also identified to have the highest mineral grain abundances, out of all the science central samples, during point counting. A thin section sample from 1760m depth (Fig. 2.12, Unit G) was also selected for comparison. Samples from depths of 1400m, 1500m and 1550m were selected, from the Errington 1 borehole, for the same reasons, representing the two prominent sand bodies near the top of the formation.

For Bowden Doors, two samples taken from the main outcrop of the Fell Sandstone, were selected.

A Hitachi TM 100 scanning electron microscope was used as it operates under low vacuum conditions, allowing specimens to be imaged without being coated with an electrically conducting material. The thin sections were attached to the SEM's specimen mount using PELCO Carbon Conductive Tabs in order to prevent the build-up of charge.

3.3 Geothermal resource estimation

The geothermal gradients recorded at Errington and Longhorsley (27^0C/km and 26.5^0C/km respectively) are broadly in line with the average geothermal gradient for the UK (26 ^{o}C/km; Busby, 2010), indicating that high heat flows are only locally associated with the Weardale Granite and the basin bounding fault system. A point further evidenced by a temperature gradient of 37.7^oC/km, recorded in the Throckley Borehole (NZ14566762), located in close proximity to the Stublick Fault and only 4km northwest of the Ninety Fathom Fault. A bottom-hole temperature of 73^oC at 1740m (Younger *et al.,* 2016) proves the potential viability of the Fell Sandstone at Science Central as a geothermal prospect.

Within the Central Northumberland Basin, despite not being heated by the Weardale Granite, the relatively high burial depth (>1km) of the Fell Sandstone between Longhorsley and the S-NF Fault system means that it still could be host to a low enthalpy geothermal resource.

The geothermal resource of the Fell Sandstone in the Northumberland Trough is calculated here.

3.3.1 Calculating the Fell Sandstone's potential geothermal resource

Due to differences in burial depth and thickness on either side of the fault system (Fig. 3.1) the formation has been divided along the S-NF Fault System for simplicity. Aquifer base depth data, for the Fell Sandstone and Border Group, was sourced from the BGS and used with log derived thickness data to estimate overall formation volume.

North of the S-NF Fault System (Area 1; Fig. 3.1) an average formation thickness of 512m was calculated, based on recorded thicknesses from the Errington and Longhorsley boreholes. The aquifer depth data, from the BGS, utilised in this study represents the Middle Border Group as a whole and thus includes both the Fell Sandstone Formation and the underlying Lyne Formation. The presence of the Lyne Formation has not been proven in the eastern Northumberland Trough or beneath Newcastle-upon-Tyne and as such its extent and thickness in these regions is not a certainty. Due to this uncertainty a slab model has been used to derive gross formation volume, from average stratigraphic thickness, in the Northumberland Basin. Reservoir volume at temperatures in excess of 40^0C has been calculated. Based on available seismic and borehole data the base of the Fell Sandstone was estimated to be buried to a maximum depth of 2km (Fig. 3.1). The geothermal gradient in the Northumberland Basin was assumed to be 26^0C/km, in line with values quoted from the Errington and Longhorsley boreholes.

An estimated thickness of 377m, the recorded formation thickness for the Fell Sandstone at Science Central, was used for the formation south of the S-NF Fault System due to a lack of borehole data in this area. South of the S-NF Fault the BGS aquifer depth data correlates to burial depth observed in the Science Central Borehole. It was therefore assumed the BGS aquifer base data is representative of the base of the Fell Sandstone south of the S-NF Fault System (Fig. 3.1, Area 2). Here, formation base depth was overlaid with temperature in order to calculate the volume of the reservoir at temperatures >40^{o}C. Mean temperature south of the S-NF Fault System was also calculated. An average geothermal gradient of 36^{o}C/km was used for Area 1, based on temperatures recorded in the Science Central Borehole.

As previously discussed, the net to gross ratio of the Fell Sandstone is not consistent across the Northumberland Trough. Based on values derived from the boreholes examined in this study, net to gross ratios of 0.5 and 0.47 are used for the Fell Sandstone north and south of the S-NF Fault System respectively.

For the Fell Sandstone south of the S-NF Fault system a porosity range of between 1% and 3.5% (2.3% average) was defined based on the results of JPOR thin section image analysis and the inferred porosity value quoted by Younger *et al.* (2016). For the Fell Sandstone north of the S-NF Fault System a porosity range of 1-7% (5% average) was used, based on the results of JPOR image analysis conducted on samples from Errington 1 and sidewall core data from the Longhorsley borehole (ROC Oil UK, 2002). This study does not account for the influence of fracture porosity.

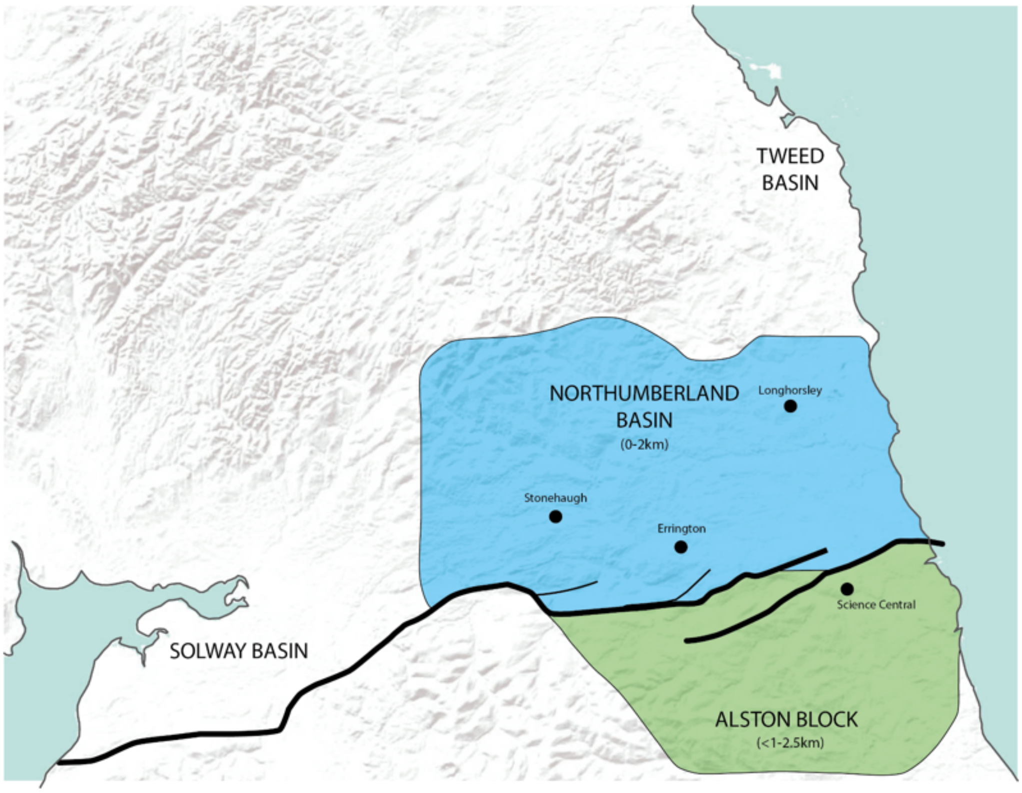

Figure 3.1: Extent of the Fell Sandstone in the Northumberland basin (Area 1) and overlying the Alston Block, south of the S-NF Fault System (Area 2) S-NF Fault System is represented by the black line.

The geothermal resource stored within the pore filling brines has been calculated using the following equation:

$$Q = V_{por}\, C_p\, \rho_f\, \Delta T$$

Where V_{por} represents pore volume (m^3), C_p represents the specific heat capacity ($Jkg^{-1}K^{-1}$), ρ_f represents pore fluid density and ΔT represents the difference in temperature (^oC). Water has been assumed to be extracted from the Fell Sandstone but not replenished. As such, only the heat content of the brines in place was calculated. Correspondingly a water saturation of 100% has been used. The pore filling fluids are highly saline brines (Younger *et al.*, 2016) and as such will have a lower specific heat capacity than pure water (Qu, 2016). For this study a specific heat capacity of 3.5 $Jkg^{-1}K^{-1}$ was used.

Chapter 4: Results

4.1 Stratigraphic analysis

4.1.1 Formation net to gross and sand body thickness

Borehole	Grid Reference	Date	Depth of Fell Sandstone MD (m)		Net to Gross	Net reservoir thickness (m)	Reference
			Top	Base			
Alnwick	41462 61210	1989	0	104	0.98	102	Turner *et al.* (1997)
Easton	34412 57169	1990	262.0	717.0	0.38	196	Howell *et al.* (2019)
Errington	39774 57135	2004	1340.0	1976.0	0.53	305	-
Longframlington	41323 60089	1964	-	-	0.95	>150	Bell (1978); Turner *et al.* (1993)
Longhorsley	41444 59255	1986	1320.9	1632.0	0.7	267	-
Science Central Deep Geothermal Borehole	42401 56433	2011	1418.5	1795.0	0.53	177	-
Stonehaugh	37899 57619	1975	212.4	601.1	0.42	109.5	-
Westnewton	31230 54355	1989	1588.0	2044.0	0.14	63	-

Table 4.1: Calculated net to gross values and net reservoir thicknesses for the Fell Sandstone in boreholes across the Northumberland Trough.

4.1.1.1 Longhorsley

The Fell Sandstone, where is it penetrated by the Longhorsley 1 borehole, has a total formation thickness of 381.3m (1321m to 1702.3m measured depth). Gamma Ray log analysis reveals that the succession is dominated by stacked fluvial sand bodies, interbedded with subordinate and stratigraphically thin siltstone and clay beds. Sand body thicknesses ranges from 2m to 45m (10m median sandstone thickness) (Fig. 4.5). Sandstone gamma ray readings are consistently low throughout the formation (between 15 and 45 API), indicating uniform deposition. Siltstone and clay/shale layers are typified by comparatively high gamma ray responses with API values in excess of 75.

The neutron-density cross-plot for the Longhorsley succession reveals that the majority of the formation has a minor negative separation, typical of clean sandstones. Sandstone density ranges between 2.5 and 2.65 g/cm^3, a range typical of low porosity sandstones. The intervening siltstone and clay layers within the formation returned variable density and neutron porosity readings, this is likely due to varying levels of compaction, however they are clearly distinguishable from the sand units. Silt stone and clay intervals are marked by a positive separation or a decrease in density and a corresponding increase in apparent neutron porosity. A coarsening upwards sequence (1500-1550m, Fig. 4.1) is identified, visible as a gradually increasing negative separation between the two curves.

Formation NTG, based off gamma ray analysis, was calculated to be 0.7 with a net reservoir thickness of 267m (Table 4.1; Fig. 4.4).

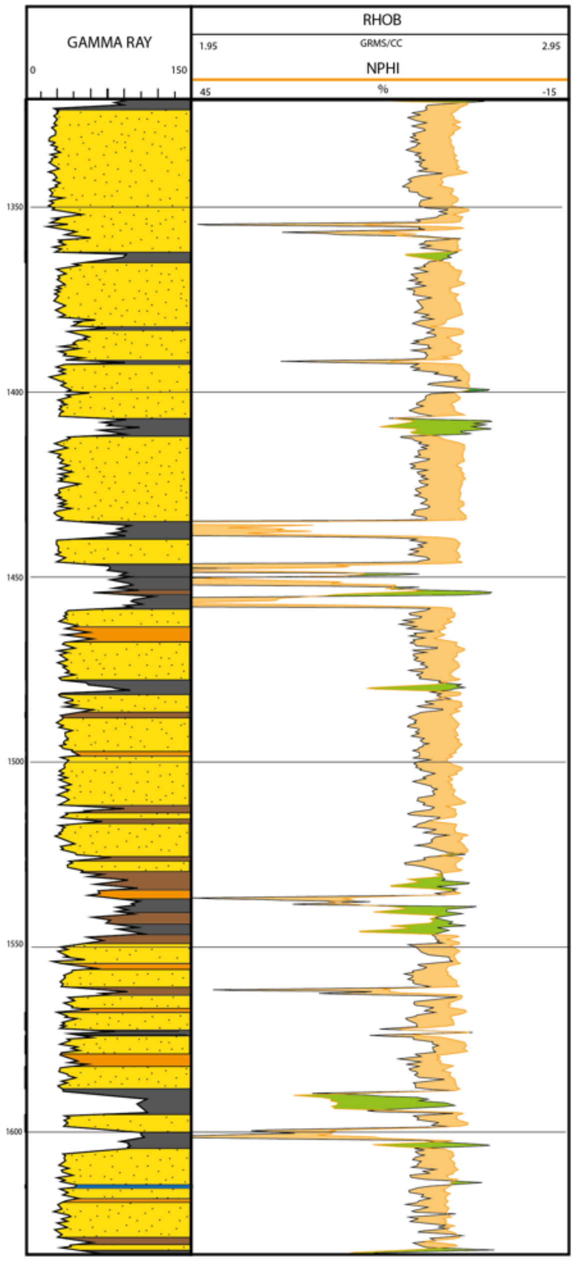

Figure 4.1: Wireline logs for the Fell Sandstone from the Longhorsley borehole.

4.1.1.2 Science Central

The seven subdivisions, defined on the basis of gamma ray response by Younger *et al.* (2016), were adopted for the Fell Sandstone at Science Central. A number of prominent, clean, sand bodies have been identified in the upper half of the formation, defined by characteristically low gamma ray responses (<30 API). Two major sand bodies, with a combined thickness of 54m, exist at the top of the formation (Zone A, Fig. 4.2). Zones B, C and D largely consist of three cyclic coarsening upwards sequences, between 10m to ~30m thick. The lowest of these sequences, stratigraphically, is visible between 1550m and 1520m (MD) where the gradually decreasing gamma ray profile represents the transition from siltstone into very fine-grained sandstone. Subordinate siltstone interbeds exist throughout the formation, the abundance of which increases with depth, based on increasing gamma ray response. Gamma ray response generally increases with depth with the highest gamma ray responses recorded at the base of the formation (Zone G; Fig. 4.2). Sandstones below 1600m (MD) have slightly higher API (15-45 API), indicative of an increase in mud content.

The majority of the sandstone units identified within the formation measure less than 2m in thickness. Sandstone unit thickness varies from <1m up to a maximum of 28m (Zone A, Fig. 4.2; Fig. 4.5). The thickest sandstone units are concentrated in the upper part of the formation (Zone A – D) (1.4m median sandstone thickness). Based on available sand body thicknesses, sandstone body widths are estimated to fall within the range of 10m to 2800m.

Formation NTG at this location was calculated to be 0.47 (formation net thickness estimated to be 176.5m) (Table 4.1; Fig. 4.4), based on gamma ray response and lithological descriptions from Younger *et al.* (2016).

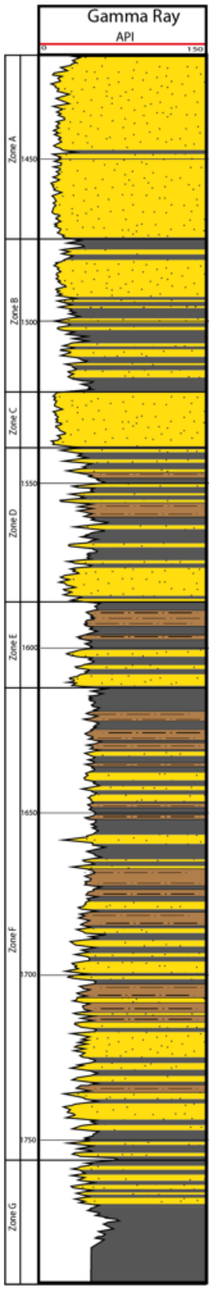

Figure 4.2: Gamma ray curve for the Fell Sandstone at Science Central with interpreted lithologies based on gamma ray response and lithological descriptions from Younger et al. (2016).

4.1.1.3 Errington

Maximum stratigraphic thickness for the Fell Sandstone was observed within the Errington 1 borehole which penetrates the formation between 1340m and 1983m (MD) (643m gross stratigraphic thickness). Unit subdivisions defined by ROC (2005) are adopted for this analysis. Two prominent sandstones, identified by well defined, blocky gamma ray curves (20-40 API) and minor negative separation on the neutron-density cross-plot (Fig. 4.3), are present in the upper part of the formation (Zone A and B, Fig. 4.3). The uppermost sandstone (Zone A) consists of two distinct units, separated by a thin shaley bed (<2m), with a combined thickness of 55m. The lower sandstone (Zone B) similarly can be further subdivided into three different units (combined thickness of 64m), separated by thin intervening shale beds. Sandstone density, across the whole formation, consistently ranges between 2.5 and 2.65 g/cm^3, typical of sandstones with <10% neutron porosity.

Below 1510m (MD) the formation is composed sandstone interbedded with subordinate siltstone and claystone/shale beds. Furthermore, below 1510m (the base of Zone B) sandstone thickness ranges from 1m to a maximum thickness of approximately 15m. The majority of sandstones are less than 5m thick (3m median sandstone thickness) (Fig. 4.5). Sandstones present below 1500m (MD) also return a higher gamma ray value, typically between 25 to 45 API, likely due to an increase in mud/shale content. Based on available sandstone thicknesses, sandstone body widths are estimated to fall within the range of 10m to 2700m. Occasional limestone beds are identified below between 1750m and the base of the formation.

Negligible separation was observed between shallow and deep dual laterolog curves (LLs and LLd respectively), again indicative of low formation porosity.

Formation NTG, based on gamma ray response, was estimated to be 0.47 at this location with a total net reservoir thickness of 305m (Table 4.1; Fig. 4.4).

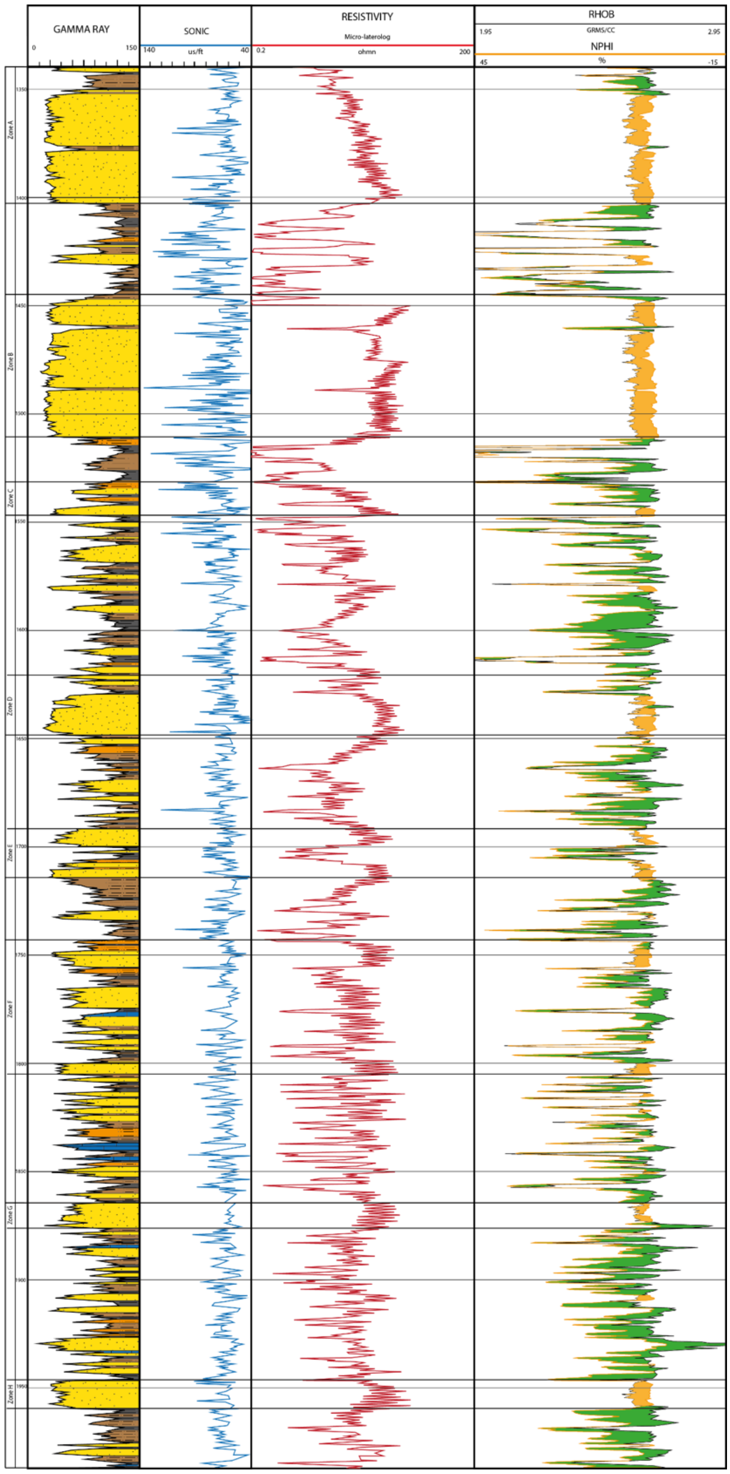

Figure 4.3: Wireline logs for the Fell Sandstone at Errington with formation lithology.

4.1.1.4 Stonehaugh

Gamma ray log analysis shows that the Fell Sandstone at Stonehaugh (Fig. 4.6) consists of sandstone units (1-18m thick), siltstones and shales. Gross formation thickness is 256m (345-601m MD) Intervening siltstone and shale layers are typically less than 15m thick. The top 100m of the succession is composed of three coarsening upwards sequences (30m thick on average) capped by a thick sandstone unit (15m thick). Thin, subordinate limestone beds are identified between 390m and 415m (MD). Aside from four more prominent sand bodies, sandstone thickness ranges between 1m and 7m (median sandstone thickness is 3m) (Fig. 4.5). Thicker sand bodies are characterised by very low gamma ray readings (<15-30 API).

At Stonehaugh, the Fell Sandstone Formation has a calculated NTG of 0.43 (Table 4.1; Fig. 4.4), based on gamma ray response, with a total reservoir thickness of 109.5m.

4.1.1.5 Easton

The Gamma Ray signature of the Fell Sandstone at Easton resembles the succession observed at Stonehaugh (39km ENE; Fig 4.6), consisting of interbedded sandstones (0.5-12m thick), siltstones, shales and occasional limestones (<2m thick). The Formation has a gross thickness of 455.7m (262.1-717.8m MD) with the lower boundary defined as the top of the underlying Cambeck Beds (Lower Border Group). The vast majority of sandstones identified have a measured thickness <5m (median sandstone thickness is 2m) (Fig. 4.5). Relatively clean sandstones with gamma ray values typically between 20-35 API are identified between 380-440m and 600-650m (MD), separated by thin shaley interbeds.

Formation net to gross was calculated to be 0.38 (Table 4.1; Fig. 4.4), based on gamma ray response, with a net reservoir thickness of 196m.

4.1.1.6 Westnewton

The formation at Westnewton is dominated by limestone with subordinate sandstones, siltstones, shales and dolostones. Four coarsening upwards sequences of shales, siltstones, sandstones and limestones are visible between 1700m and 1825m. Aside from these deltaic sequences, there is little evidence of the siliciclastic Fell Sandstone (Fig. 4.6); the succession seen at Westnewton represents a laterally equivalent, shallow marine succession.

Westnewton has the lowest NTG of all the boreholes analysed with a value of 0.14 (Table 4.1; Fig. 4.4), based on gamma ray response.

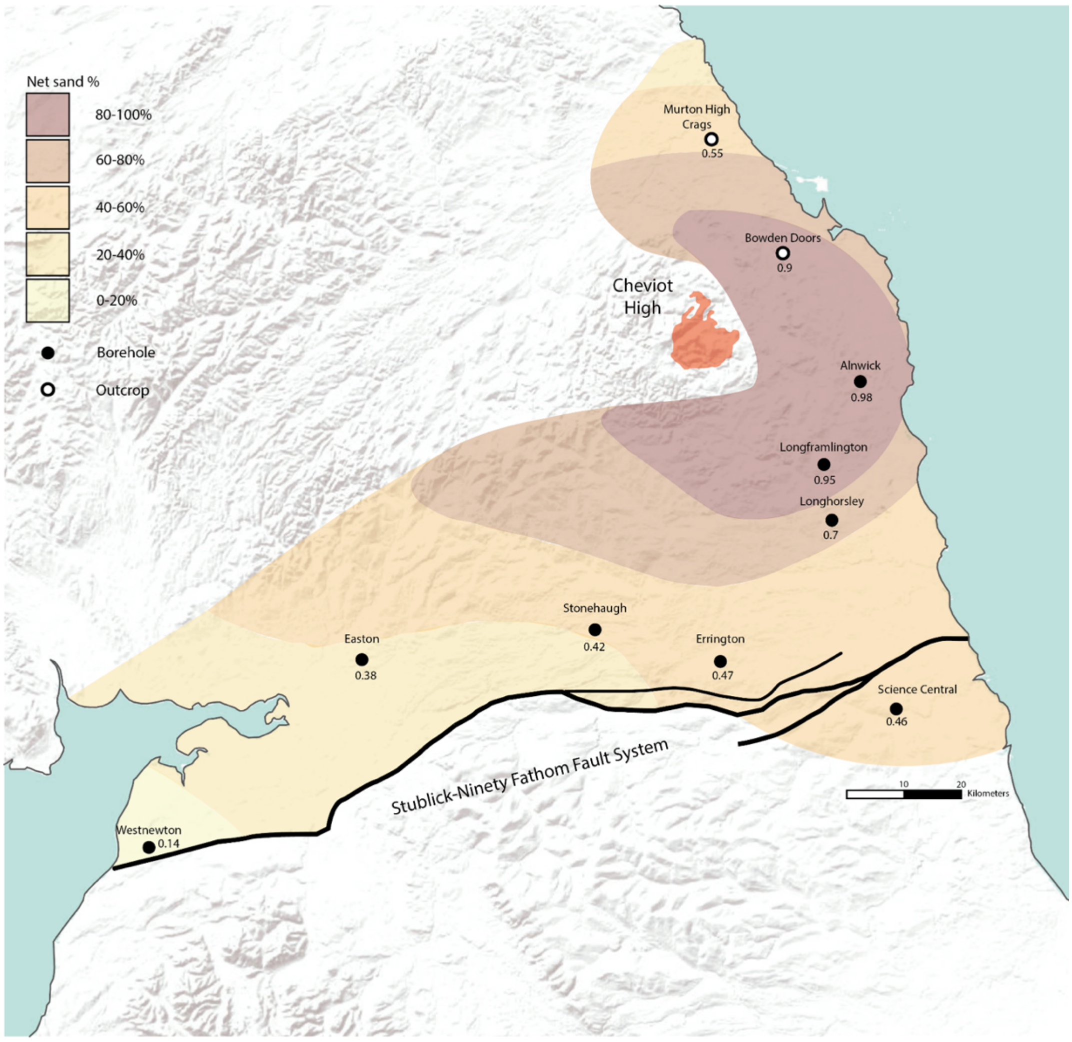

Figure 4.4: A Map of the Northumberland Trough depicting net to gross distribution for the Fell Sandstone. Net to Gross data is derived from analysis of gamma ray curves (courtesy of the UK OGA) and existing literature (Turner et al., 1993; Turner et al., 1997; Howell et al., 2019).

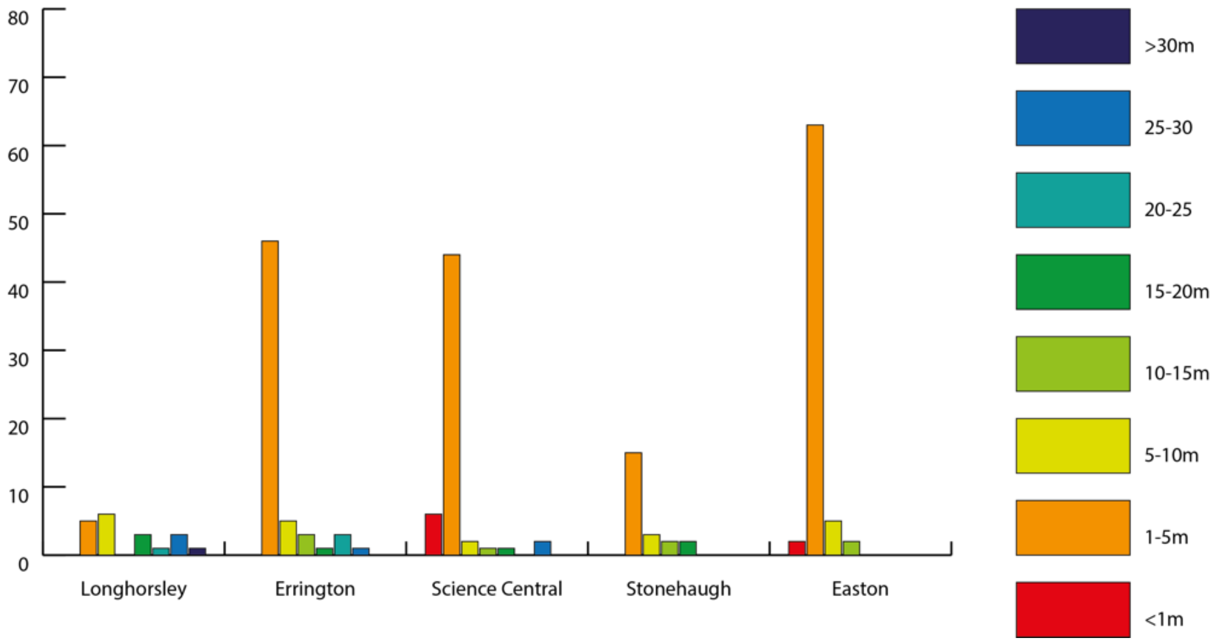

Figure 4.5: Comparative sandstone thickness distribution for five of the boreholes investigated in chapter 3.1. The Westnewton borehole was excluded due to a lack of siliciclastic Fell Sandstone.

4.1.1.7 Stratigraphic correlation

Sandstone units have been correlated for the Fell Sandstone penetrated by the Longhorsley, Science Central, Stonehaugh, Easton and Westnewton boreholes (Shown in Fig. 4.6). It is impossible to correlate sand bodies within the formation with confidence within the central and western Northumberland Trough (Solway Basin) owing to the large lateral distances between borehole sites and uncertainty over the lateral continuity of individual sand bodies, which cannot be measured from wireline logs. However, the trend of decreasing reservoir net to gross and sand body thickness to the southwest is visible.

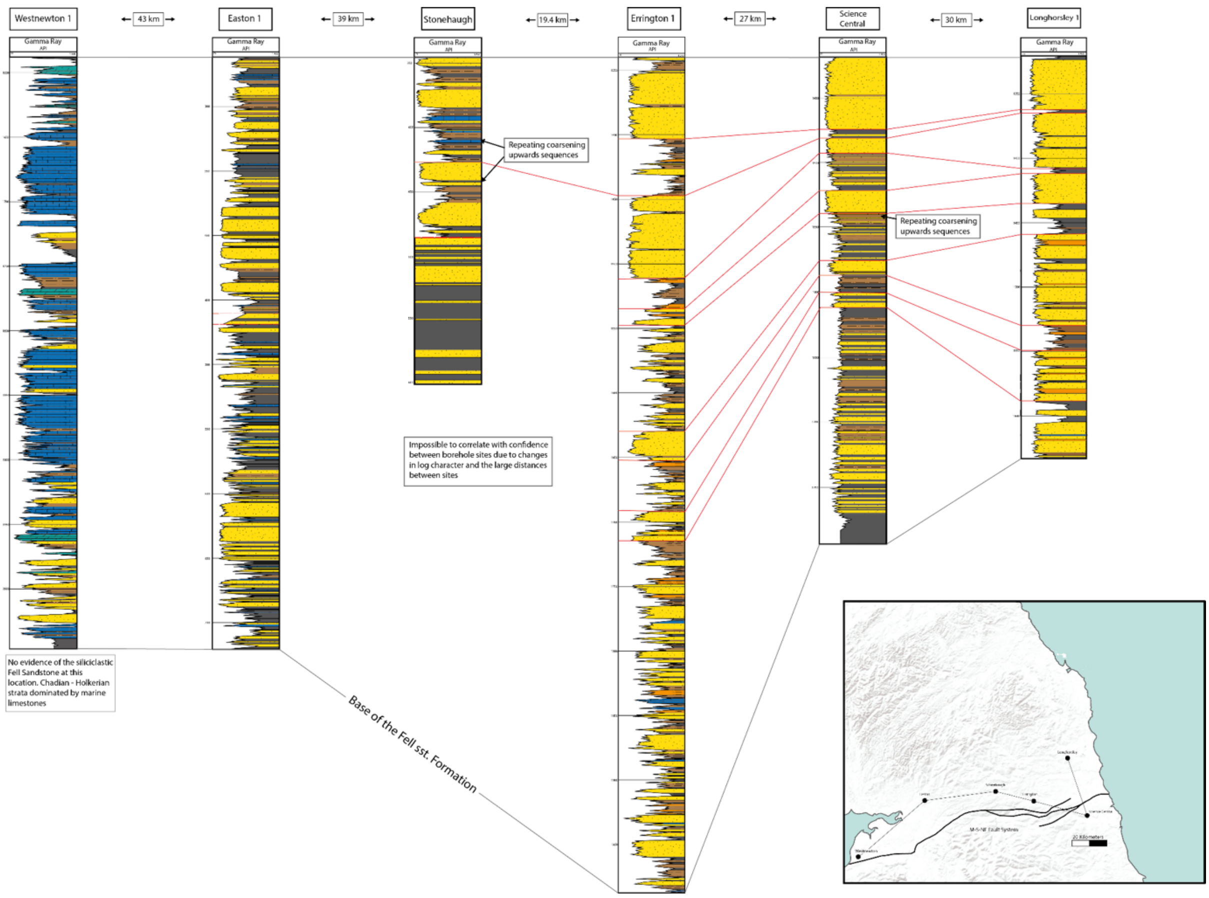

Figure 4.6: Regional stratigraphic correlation of the Fell Sandstone across the Northumberland and Solway basins. Based off ROC (2005).

4.1.2 Depositional environment and facies interpretation

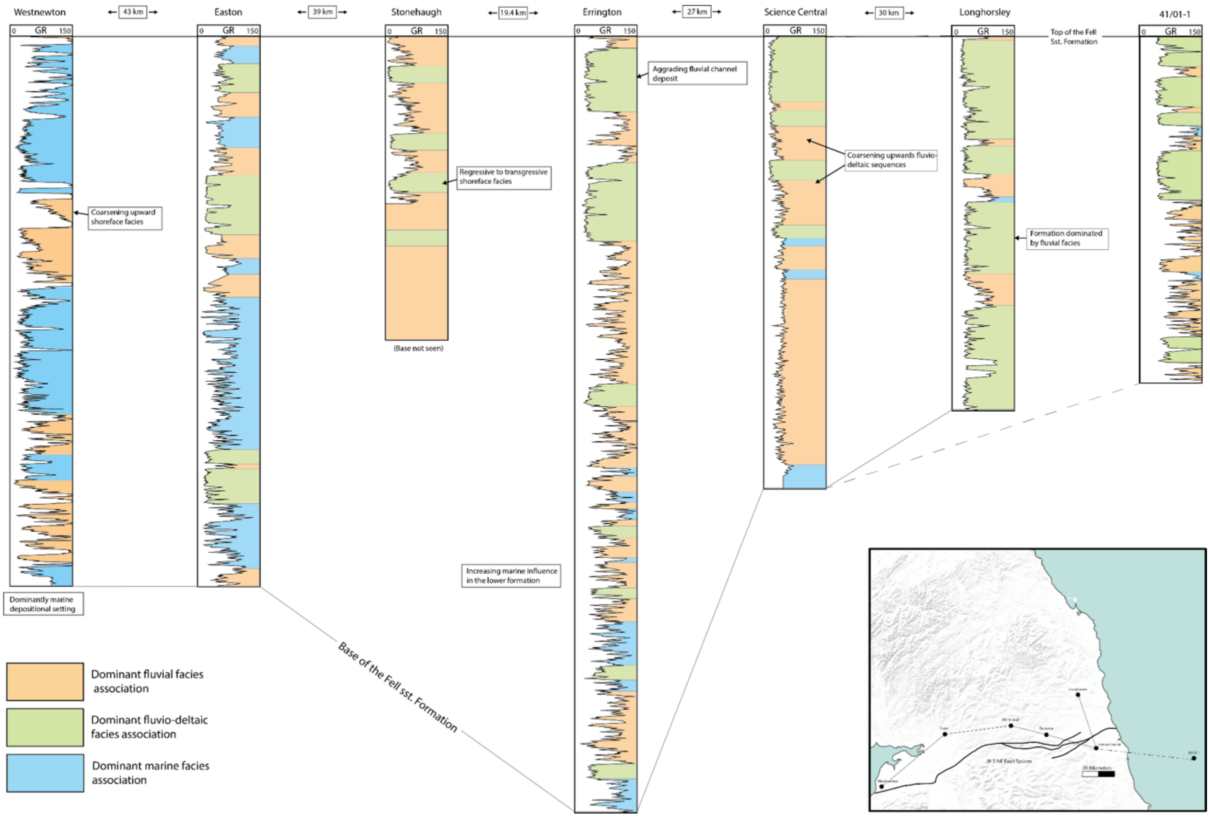

Figure 4.7: Lateral variation in facies deposition for the Fell Sandstone. Onshore wireline logs provided courtesy of the UK Oil and Gas Authority. Offshore wireline logs were sourced from the UK National Data Repository (NDR).

The lateral variation in depositional facies, within the Fell Sandstone, across the Northumberland and Solway basins is represented by figure 4.7. The Fell Sandstone at Longhorsley is dominated by braided fluvial channel deposits typical of fluvial facies associations. Intervening, coarsening upwards siltstone and shale sequences that are topped by vertically thin sandstones (<5m) represent fluvio-deltaic and delta front deposits. There is little evidence of marine depositional facies within the Fell Sandstone northeast of the Longhorsley Borehole. At Errington 1, the prominent sandstone units in the upper part of the formation (zones A and B) are interpreted as braided river channel deposits, deposited within a fluvial depositional environment (fluvial facies association). The rest of the formation (1510-

1983m) consists of dominantly fluvio-deltaic deposits (fluvio-deltaic facies association), defined by cyclic coarsening upwards successions of shales, siltstones and vertically thin shaley sandstones, with intermittent marine shale and limestone deposits (marine facies association). The successions observed at Science Central and Stonehaugh share similarities with the Errington succession, comprising of mainly fluvio-deltaic muds, siltstones and shaley sandstones forming repeating coarsening upwards sequences (Fluvio-deltaic facies association). Like at Errington, the Fell Sandstone succession at Science Central is capped by thick braided fluvial sands, which likely represent a basin-wide progradation of the fluvial system. Marine influence increases moving down the basin profile towards the M-S-NF Fault System (Fig. 4.8). A total of four transgressive sequences are identified within the Fell Sandstone at Errington, Longhorsley and Science Central (Fig. 4.8). Sand bodies defined by an even or fining upwards gamma ray profile, with a vertical thickness >5m are interpreted to be fluvial channel deposits.

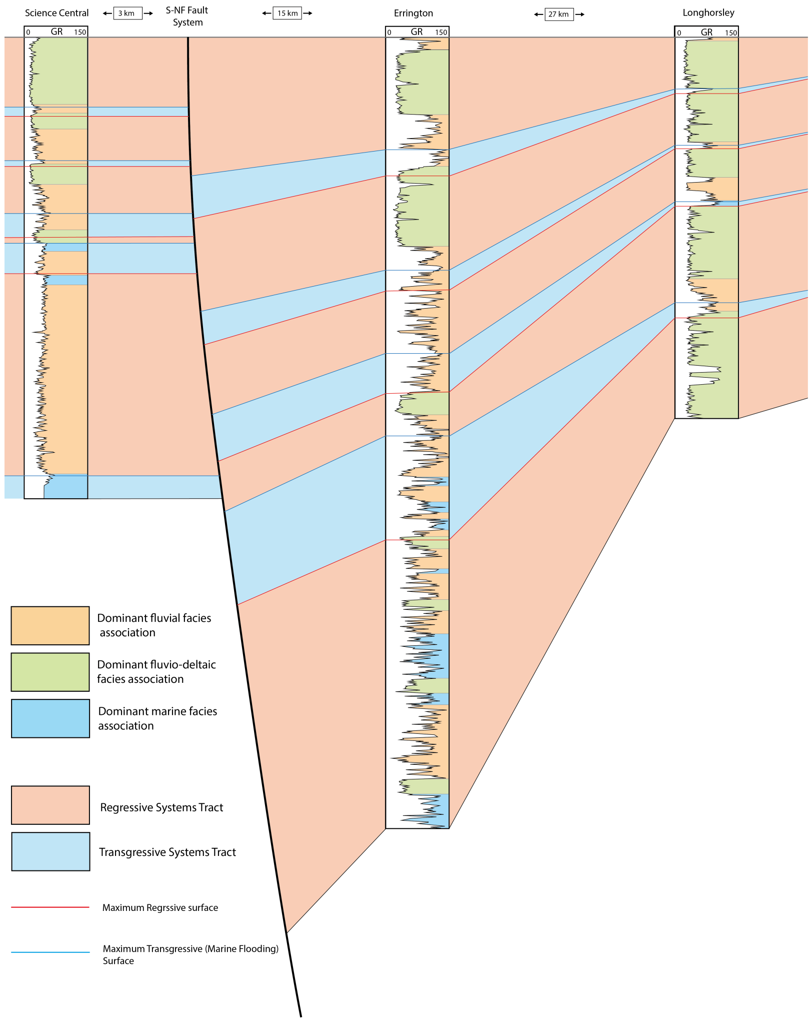

Figure 4.8: Correlation of transgressive and regressive systems tracts within the eastern Northumberland Basin. Based facies associations within the Longhorsley, Errington and Science Central Boreholes.

Marine influence continues to increase to the southwest, moving into the Solway Basin with the Easton succession comprised of fluvial, deltaic and shallow marine deposits in almost equal part. Only 4 fluvial facies sequences are identified, and these are separated by thick mixed carbonate-mud facies with subordinate sandstones. The succession at Westnewton is dominated by shallow marine limestone deposits interbedded with subordinate shales and siltstones (marine facies association). The coarsening upwards sequences (1725-1775m) represent distal deltaic deposits (fluvio-deltaic facies association) and likely represent the farthest extent of the Fell Sandstone River System (Fig. 4.9).

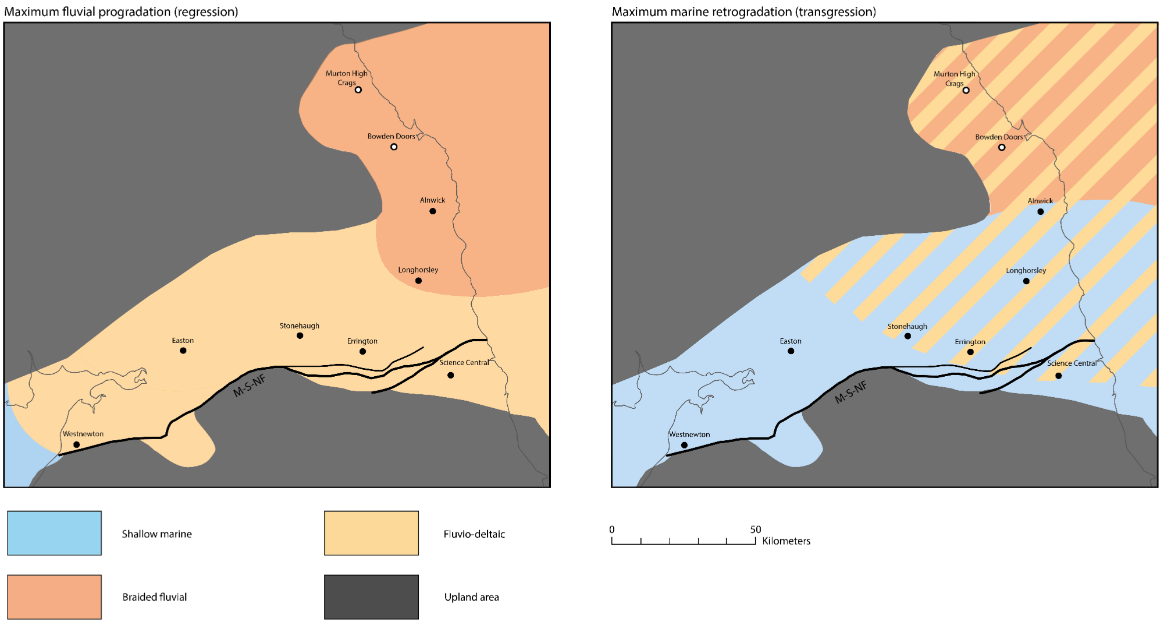

Figure 4.9: Interpreted facies deposition depicting the lateral variation between maximum progradation and retrogradation of the Fell Sandstone River System, during the late Chadian to Holkerian. Such variations are controlled by differential subsidence.

4.1.3 Porosity and permeability

4.1.3.1 Neutron porosity results

Comparison of neutron-density cross-plots for the Errington and Longhorsley successions reveals that, on average, formation neutron porosity is higher at Longhorsley than at Errington (Fig. 4.10). Average neutron porosity is calculated at 0.04 for Fell Sandstone sand bodies at Longhorsley whilst at Errington, average neutron porosity is comparatively lower at 0.03. Neutron porosity readings for Longhorsley, when combined with bulk density measurements, provide sandstone porosity values that broadly fall within the range of 3% to 8% with an estimated average porosity of approximately 6% ±1%. At Errington, sandstone porosity values fall within the range of 3% to 6% with an estimated average porosity below 5%.

Neutron porosity was also plotted against bulk density for individual sandstone units within the Errington borehole succession (Zones A, B, D and H; Fig. 4.14; Fig. 4.11). The highest neutron porosities are recorded in Zone A (average sandstone porosity equal to 0.05). Neutron porosity is lower in Zones B and H (average sandstone porosity equal to between 0.045 and 0.05 for both zones) and lower still in Zone D (<0.04 average porosity).

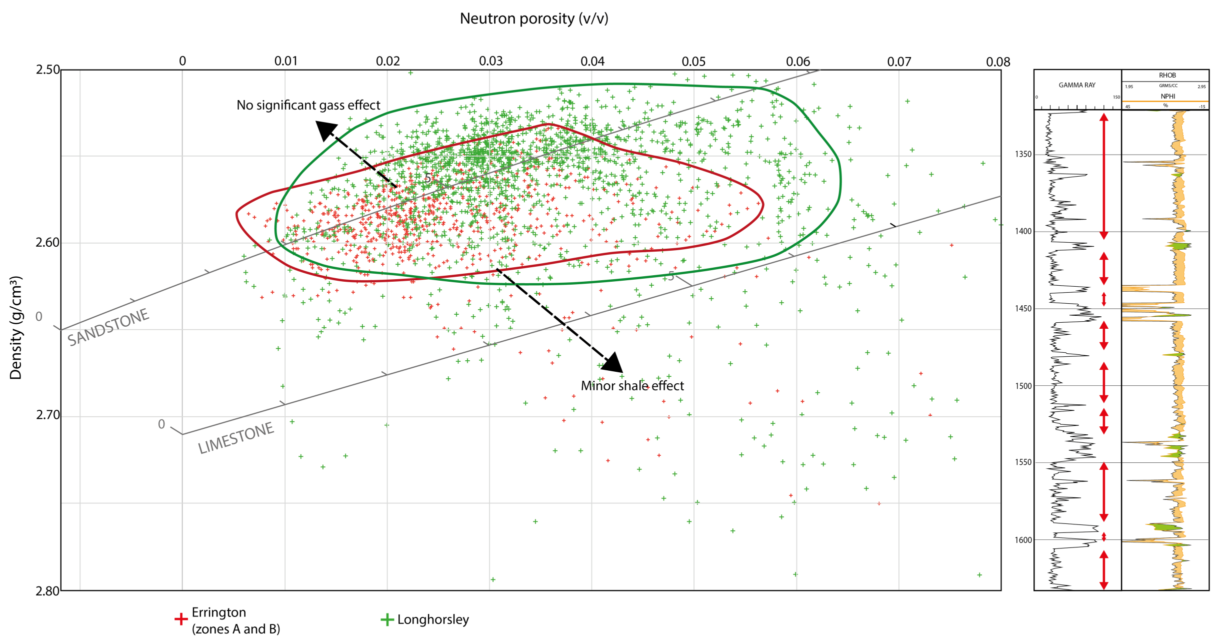

Figure 4.10: Sandstone neutron porosity- bulk density plots for the Fell Sandstone at Longhorsley and Errington 1 (Zones A and B; FIG 4.3). Analysed Longhorsley sand bodies defined by gamma ray response.

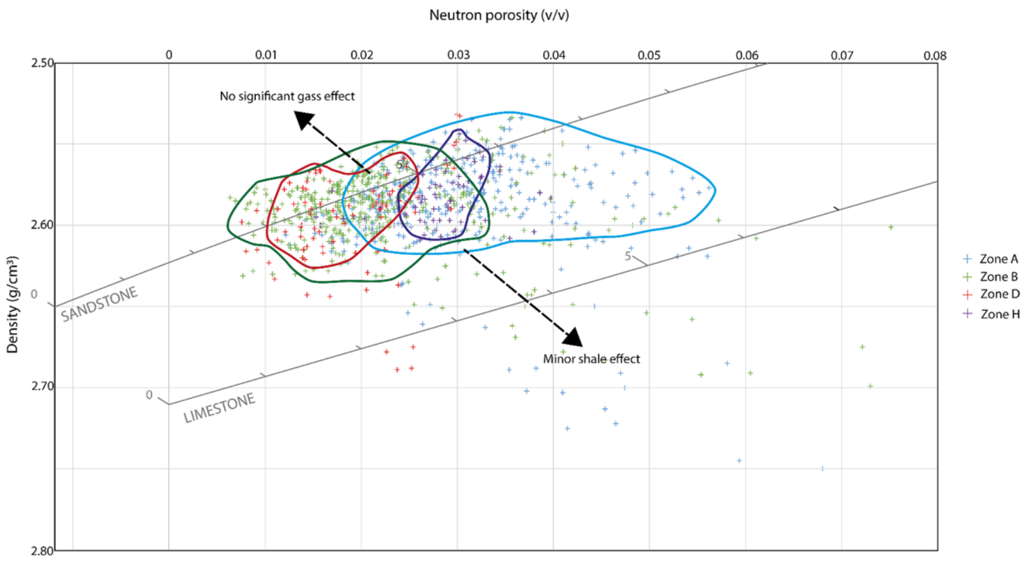

Figure 4.11: Neutron porosity- bulk density plots for prominent sand bodies, within the Fell Sandstone, at Errington (Zones A, B, D and H; Fig 4.3).

4.1.3.2 Core derived porosity permeability results

A positive correlation between the core porosity and permeability within the Fell Sandstone is visible in Figure 4.12. Good reservoir quality is observed in well 43/02-1 with 5-16% porosity and permeabilities between 1 and 73 mD (millidarcy). The Fell Sandstone at Stonehaugh shows a range of porosity and permeability values (1-15% porosity, 0.01-223mD permeability) separated into two distinct clusters. High poroperm values observed in Stonehaugh are comparable to those shown in well 43/02-1. Both locations show a tight linear trend. The limited sidewall core data available for Longhorsley reveals that the Fell Sandstone at this location is typified by low porosity and permeability (4.5-6.3% porosity, <0.03mD permeability), similar to the lower range of values observed at Stonehaugh.

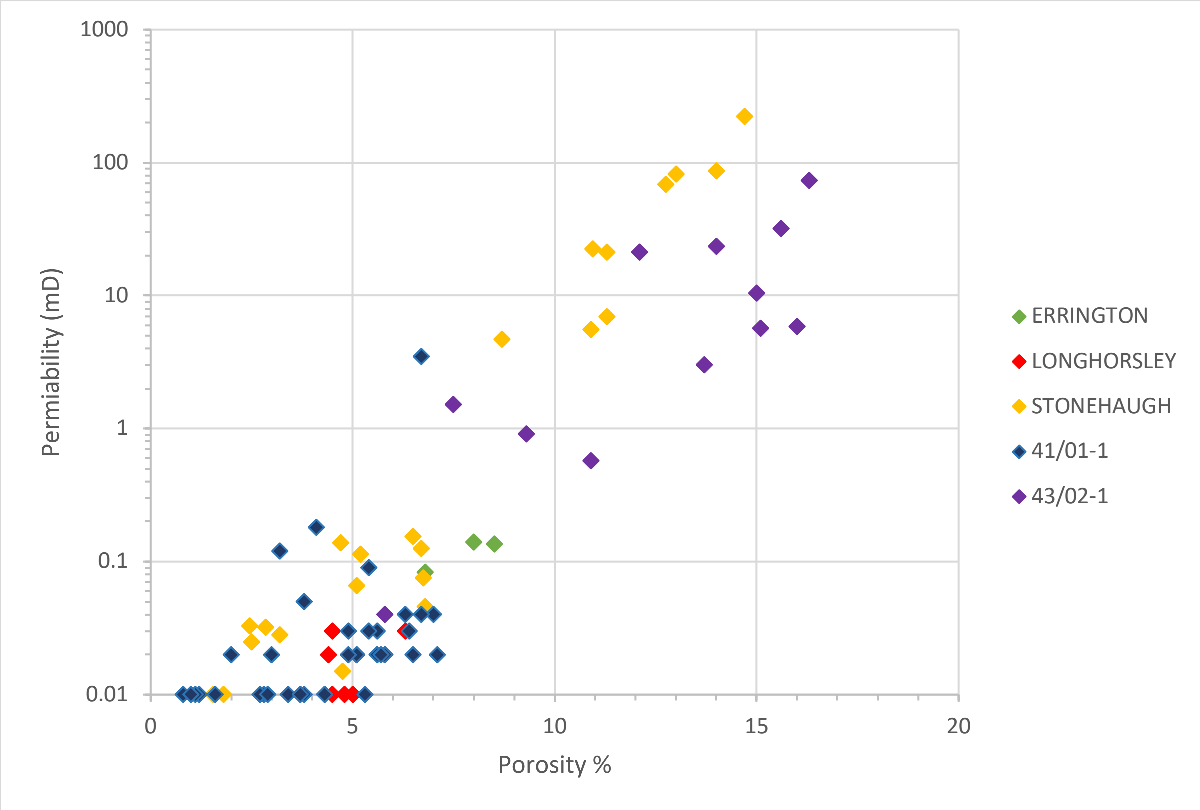

Figure 4.12: Porosity-permeability crossplot for the Fell Sandstone at Errington (green), Longhorsley (red), Stonehaugh (yellow), 41/01-1 (blue) and 43/02-1 (purple).

4.1.4 Interpretation

4.1.4.1 Stratigraphy

The highest log derived net to gross ration, for the Fell Sandstone, is observed within the Longhorsley borehole; the borehole located in closest proximity to the Cheviot High (out of those analysed in this study; ~30km NW). The Fell Sandstone at Longhorsley has a net to gross of 0.7, a value typical of sand rich braided river deposits (Gluyas and Swarbrick, 2004), and is mainly composed of amalgamated, clean channel sands. Moving southwest into the central Northumberland Trough, formation net to gross decreases as the Fell Sandstone transitions into a succession of paralic sandstones, interbedded with increasingly prevalent non-reservoir lithologies. High net to gross ratios, in association with the Cheviot High, are observed within the Fell Sandstone penetrated by the Longframlington and Alnwick boreholes. At Longframlington the Fell Sandstone has a net to gross of 0.95 (Turner *et al.*, 1993) and at Alnwick the formation is composed almost entirely of reservoir lithology (net to gross 0.98 quoted by Turner *et al.*, 1997). The lateral variations in formation net to gross fit the tectono-stratigraphic model proposed by Howell *et al.* (2019) interpreting that the Fell Sandstone was locally influenced by the Cheviot High (Fig. 2.9; Fig. 4.4), which acted to laterally confine the palaeo-river system resulting in increased sediment reworking and a lack of overbank facies preservation between Berwick-upon-Tweed and Longhorsley. Intra-basinal normal faults such as the Antonstown and Sweethope Faults likely exerted a minor local influence on the palaeo-river system (Turner *et al.*, 1993; Howell *et al.,* 2019).

In addition to local confinement, lateral variations in the succession, are controlled by regional subsidence along the Maryport-Stublick-Ninety Fathom Fault system (M-S-NF Fault System). Syn-depositional subsidence is evidenced by the increase in formation thickness towards the basin-bounding fault system with maximum formation thickness observed at Errington 1 (Table 4.1), the borehole located in closest proximity to the M-S-NFF System on the footwall side. The effects of variations in the rate of subsidence would not have been uniformly felt across the Northumberland Trough due to its asymmetric basin profile. Tectonic subsidence would have exerted a progressively weaker control over clastic sediment deposition away from the M-S-NFF System due to the influence of the Cheviot High, an area of comparatively low subsidence (Howell *et al.*, 2019). Within the Northumberland and Solway basins, periods defined by an increasing rate of subsidence would have resulted in increased retrogradation and a reduction in clastic deposition. Conversely periods of decelerating subsidence would have resulted in progradation of the fluvial system (Barret *et al.,* 2018) and an associated increase in clastic deposition.

Localised controls on sediment distribution, along with differential and asymmetric basin subsidence, are reflected in the lateral variation of the formation's wireline log response across onshore borehole sites. Within the Errington, Science Central and Stonehaugh boreholes the Fell Sandstone is shown to be a vertically heterogeneous succession of sandstones, siltstones and shales. At Errington and Science Central in particular, prominent reservoir units that could best facilitate fluid flow are concentrated in the upper part of the formation (Errington Zones A-B; Science Central Zones A-C). Within both boreholes, the lower Fell Sandstone is increasingly interbedded with non-reservoir lithologies (such as clays/shales and silts; Fig. 4.6) which impede fluid flow and compartmentalise the reservoir. Whilst relatively clean sandstones are locally developed, they are often stratigraphically thin and likely not laterally extensive. Estimated sand body width decreases to the south and west (Reynolds, 1999; Gluyas and Swarbrick, 2004) as lateral dispersion of the fluvial system increases and amalgamated channel fills deposits, such as those observed at Bowden Doors and within the Longhorsley succession, become increasingly rare.

In addition, higher API readings for sand bodies within the lower Fell Sandstone successions at Errington and Science Central indicate increased percentages of fine-grained matrix. By contrast, gamma ray readings for stratigraphically thick sand bodies at Stonehaugh have lower gamma ray responses (the lowest out of all onshore boreholes analysed), indicating low clay matrix content. Porosity within these clean sandstones is high (6-11% based on the findings of a petrographic study conducted on samples taken from the Fell Sandstone at Stonehaugh; Corex UK, 2002). Where inferred, the increased abundance of interstitial clay has likely had a deleterious effect on sandstone porosity with sandstones within the lower Fell Sandstone at Errington and Science Central being particularly affected. Potassium feldspars and micas are naturally radioactive and therefore increase gamma ray response.

The abundance of detrital feldspar and micas within the Fell Sandstone is low (Bell, 1978; Turner *et al.*, 1993) so their effect on sandstone gamma ray response is negligible. Sandstone gamma ray response is more likely influenced by the abundance of illite (Rider *et al.*, 1990).

4.1.4.2 Facies variation

Of the three main facies identified, fluvial facies associations, which mainly comprise of thick massive sandstones produced through sandbank collapse and the amalgamation of fluvial channels (Turner *et al.*, 1987; Howell *et al.*, 2019), are associated with the highest porosities. Marine and fluvio-deltaic have a higher abundance of non-reservoir lithologies. As mentioned in the previous section, sand bodies in the lower Fell Sandstone at Errington and Science Central have an increased gamma ray response (Fig. 4.7). The higher clay abundance within these sand bodies is a function of their deposition within a more distal deltaic environment (fluvio-deltaic facies association) where finer grained overbank material is better preserved.

The presence of marine ostracod mudstones and coarsening upwards shale and siltstone sequences within the Fell Sandstone evidence short lived marine incursions which extended as far north as Alnwick (Fig. 4.9) (Turner *et al.*, 1997; Uba *et al.*, 2009). Micritic muds deposited within the associated marine and fluvio-deltaic facies associations are a likely source of calcite cement within North Sea sandstone reservoirs (Worden *et al.*, 2019). Where they occur within the Fell Sandstone, marine and fluvio-deltaic muds may well have acted as an important source of authigenic calcite.

4.1.4.3 Porosity and permeability

Relatively high porosity and permeability is recorded at Easton, Stonehaugh and in well 43/02-1 where petrological studies (Blackbourn, 1990; Corex UK, 2002) have identified well developed secondary pore systems and a lack of authigenic cements such as calcite. By contrast, porosity and permeability within the Longhorsley is considerably lower, based on albeit limited rotary sidewall core data, despite the Fell Sandstone having a higher net to gross (0.7 compared with 0.42 at Stonehaugh and 0.38 at Easton) and net reservoir thickness at this location.

Neutron porosity values for the Longhorsley succession corroborate the results of the sidewall core poroperm data analysis. Figure 4.10 shows that neutron porosities for main paralic sand bodies within the Errington 1 succession are similarly low (approximately 1% lower than at Longhorsley on average). The lateral variation in sandstone porosity between these two boreholes is likely to be the result of varying burial/diagenetic histories, as well as the Errington Borehole's more distal fluvial setting. Although the Fell Sandstone reservoir is now found at similar depths at both sites (1340m at Errington compared to 1321m MD at Longhorsley), asymmetric basin subsidence likely resulted in the Fell Sandstone being buried at a greater depth at Errington; in excess of 3km during maximum Mesozoic burial (ROC, 2005). The Fell Sandstone at Errington thus, would have been subjected to greater pressure-temperature conditions resulting in a greater reduction in pore volume.

No core or wireline log derived permeability data are available for the Fell Sandstone penetrated by the Science Central borehole; however, an overall porosity estimate of <3.5% was inferred using Archie's Law by Younger *et al.* (2016). Average hydraulic conductivity was estimated to be 7×10^{-5} md^{-1} (equivalent to 0.08 mD), assuming an effective aquifer thickness of 234m (Younger *et al.*, 2016). The porosity estimate derived by Younger *et al*. is comparable to the values obtained from Errington 1, falling within the range identified in figure 4.10.

4.1.4.4 Stratigraphic and facies controls on reservoir quality

From wireline log data it can be concluded that stratigraphy and facies association have a strong control over the reservoir quality of the Fell Sandstone. Compartmentalisation and localised depositional influences have resulted in a decrease in overall reservoir quality to the south and west. However, based on the comparison of porosity and permeability data from sites such as Longhorsley and Stonehaugh, it is clear that reservoir quality within the Fell Sandstone has also been influenced by post-depositional factors. Formation porosity is highest at the Stonehaugh Borehole despite the Fell Sandstone having a lower net to gross ratio, owing to its more distal setting away from the influence of the Cheviot High, compared to at Longhorsley. It can therefore evident that in addition to stratigraphy and facies association, the reservoir quality of the Fell Sandstone is influenced by the impact of diagenesis. The Fell Sandstone is buried to a greater depth in the eastern Northumberland Trough and the Solway basin. In these locations increased diagenesis associated with higher temperature and pressure conditions has likely had a more deleterious effect of reservoir quality.

4.1.4.5 Limitations

There is considerable variation in the age of the wells analysed in this study with the oldest onshore well, Stonehaugh, drilled in 1975. All the wells, with the exception of the Errington 1

(2004) and Science Central Deep Geothermal Boreholes (2011), were drilled before the year 2000. As such, there may be variation in the relative accuracy of the data as technology and techniques have changed over time.

The Fell Sandstone is only penetrated by a small number of boreholes where it occurs at depth within the Northumberland Trough. Lateral interpretations of the formations reservoir quality therefore have a degree of uncertainty.

4.2 Thin sections

4.2.1 Bowden Doors outcrop thin sections

4.2.1.1 Detrital composition

At Bowden Doors, quartz (including polycrystalline quartz) constitutes 93% to 99% of the detrital grain mineralogy (95.34% average). The abundance of detrital feldspar grains was low in all samples analysed, varying between 0% and 4% (1.75% average) (Table. 4.2). Examples of partial grain dissolution were visible within a number of thin sections indicating that the abundance of detrital feldspar has decreased over time as a result of dissolution.

Similarly, the abundance of lithic grains such as muscovite was low, between 0.88% and 4.27% (2.91% average) of detrital grain composition (Table. 4.2).

Detrital clay minerals were far less prevalent at Bowden Doors, compared with the borehole samples analysed in this study (Fig. 4.14). All the samples were generally clean sandstones with detrital clay contents of between 4.6% and 10% (7.83% average) (Table. 4.2). Illite is the dominant clay mineral within the samples.

4.2.1.2 Texture and grain contacts

Texture analysis showed that the sandstones were medium to fine grained (twelve samples were classed as medium grained and four classed as fine grained; Fig.4.13). Average grain size across all samples ranged between 0.23mm (sample C) and 0.51mm (sample M). Grain size decreased overall moving up the succession seen at outcrop. Samples taken from the main outcrop were dominantly fine grained (0.25mm grain size) whilst samples taken from the stratigraphically lower second outcrop were dominantly medium grained (0.44mm grain size). Compilation of grain size measurements showed that sixteen samples were well to moderately well sorted (0.414-0.641; F&W). Examples of tangential, long and embayed contacts are visible in all samples. Rarer sutured contacts are also present.

4.2.1.3 Authigenic composition

The main authigenic phases present in thin section were kaolinite, illite and silica cement in the form of quartz overgrowths (Fig. 4.14). Trace amounts of calcite cement were identified in some samples. Overall, the abundance of authigenic quartz cement was low, ranging from 0.33% to 2.67% (1.89% average) (Table. 4.2).

4.2.1.4 Porosity

Intergranular porosity values, obtained through point counting, within the Fell Sandstone were relatively high, ranging from 9.33% to 22.00% (18.07% average) (Table. 4.2). By contrast, porosity values obtained through the JPOR porosity measuring software were considerably lower. The JPOR calculated, average porosity across all Bowden Doors samples was 13.1% (ranging from 6.93% to 24.06%), almost 5% lower than the value obtained from point count data. Pores have good visual connectivity; however, the occlusion of pore necks by clays was occasionally observed. Overall, despite the occlusion of some pore necks by silica cements and clays, the level of pore connectivity was relatively high with 65.5% of pores being at least partially connected. Clay linings appear sporadically within each thin section and some pore space has been completely infilled by authigenic clay (mainly kaolinite). Rarer vuggy pore spaces were also identified. Partial feldspar grain dissolution evidence that the sandstone's initial depositional porosity has been enhanced by the development of secondary pore space. Some microporosity has been visibly retained in pores that have been infilled with authigenic kaolinite however the effect of this is relatively insignificant when compared to the overall macro porosity.

Sample	Grain size	Q	F	L	Carbonate Cement	Quartz Cement	Clay	Porosity
A	Fine	73.30	0.60	0.70	0.00	0.60	4.67	20.00
B	Fine	72.70	0.30	1.00	0.00	1.60	5.30	18.67
C	Medium	68.00	0.70	0.00	0.00	2.20	7.67	19.00
D	Fine	74.60	0.00	0.30	0.00	2.00	5.00	18.00
E	Medium	67.00	0.70	0.00	1.00	1.70	10.33	19.33
F	Medium	66.00	0.70	2.30	0.00	2.00	10.00	19.00
G	Medium	76.70	0.30	0.00	0.00	3.60	10.00	9.33
H	Medium	75.00	0.70	0.30	0.00	0.70	4.30	19.00
I	Medium	74.00	0.70	0.00	0.00	0.30	10.33	14.67
J	Fine	79.00	4.00	0.70	0.00	1.00	3.00	12.33
K	Medium	65.00	2.30	0.70	0.00	2.00	8.00	22.00
L	Medium	79.00	4.00	0.70	0.00	1.00	3.00	12.33
M	Medium	71.00	3.00	0.00	0.00	1.30	5.00	19.67
N	Medium	70.00	2.70	0.30	0.00	2.00	5.00	20.00
O	Medium	70.70	2.00	0.30	0.00	2.00	7.33	17.67
P	Medium	71.70	3.70	1.00	0.00	2.70	4.00	17.00

Table 4.2: Summary of thin section compositions for the Fell Sandstone at Bowden Doors. Values given as percentages. QFL stands for quartz, feldspar and lithic fragments respectively.

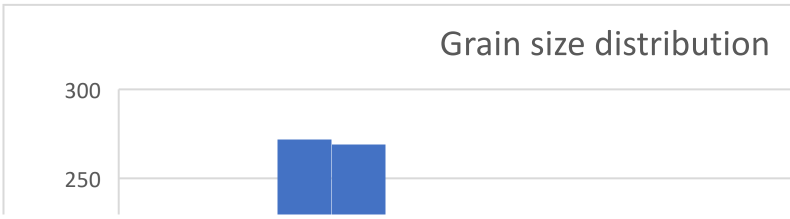

Figure 4.13: Graph showing the grain size distribution within the Fell Sandstone samples taken from Bowden Doors.

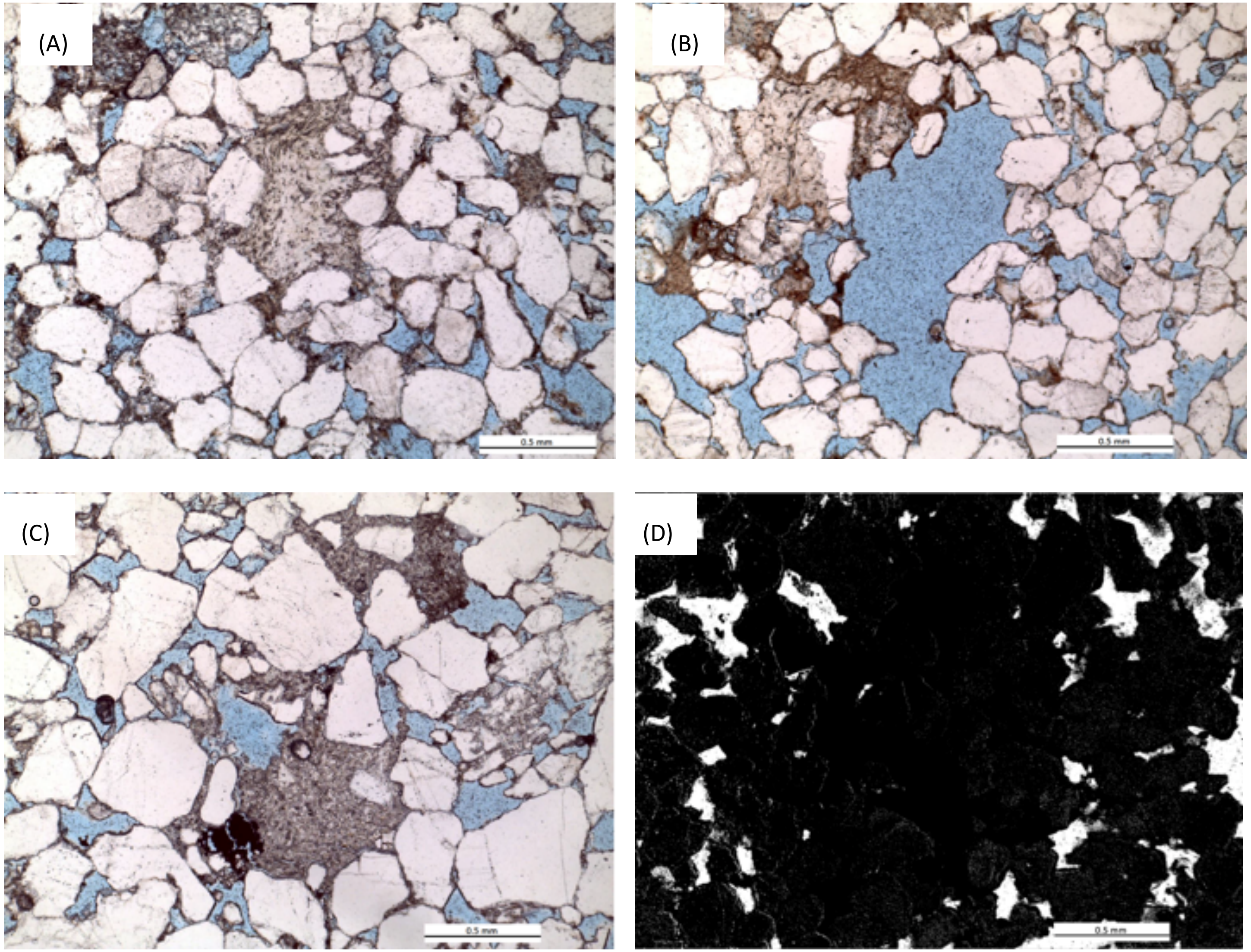

Figure 4.14: Bowden Doors thin section photomicrographs showing A) a vugular/channelized pore, likely created as a result of feldspar dissolution. B) A partially dissolved feldspar grain (centre left), leaving skeletal remnants and microporosity. Secondary pore space (centre) has been partially infilled by authigenic kaolinite, a product of feldspar dissolution. C) Pore space that has been completely infilled by authigenic kaolinite, reducing overall porosity. Long to concavo-convex grain contacts are the dominant forms of grain contact. Overall, kaolinite is patchy and porosity is well preserved. D) A JPOR processed image showing the impact of infilling clay on intergranular porosity.

4.2.2 Science Central Deep Geothermal Borehole thin sections

4.2.2.1 Detrital Composition

The Fell Sandstone at Science Central can be classed as a quartz arenite. Between 91% and 97% of the sandstones detrital grain composition was made up of quartz (94.5% average). Polycrystalline quartz, the abundance of which varies between 0% and 5.7% within the six samples, is included in this (Table 4.3).

The abundance of feldspar within the samples was low, constituting at most 7% of the detrital grain composition (sample 1795m) (feldspar abundance is 2.07% on average for all six samples). In two of the six samples there was no feldspar preserved at all (Table 4.3).

Similarly, the abundance of lithic grains was also low, varying between 1.4% and 5.2% (3.39% average for all six samples) (Table 4.3). Lithic minerals identified include Muscovite, plagioclase, clinopyroxene and chlorite.

Much of the detrital clay has been altered to illite during burial which was the dominant clay mineral within the six samples. It primarily occurred as clay fragments likely derived from the interbedded over-bank deposits rather than channel sand bodies.

Within the top 200m of the formation (between 1420m and 1540m) the abundance of clay was between 13.15% and 18.57% (Table 4.3). Most of the intergranular pore space that wasn't occluded by silica cement was infilled by illitic clay. The abundance of detrital clay increases with depth, making up 51.58% of the bulk composition at the base of the formation (sample 1795m) (Table 4.3). Within the samples taken below 1700m, intergranular space was dominantly filled with clay minerals and the vast majority of uncemented grains had a detrital clay coating. In the thin section sample taken from the base of the formation (1795m), detrital mineral grains made up only 35.08% of the bulk composition as opposed to a maximum of 72.82% at 1540m (Table 4.3).

Trace bioclastic grains, including shell fragments, were visible within clay fragments from 1480m.

4.2.2.2 Texture and grain contacts

Overall, the detrital sediments were very finely grained (mean grain size for all samples is equal to 0.119mm; Fig. 4.15) (Table 4.3) and poorly to moderately well sorted (0.516-1.031 F&W)). Average grain size ranged from 0.086mm (1520m) to 0.15mm (1480m). No overall trend in grain size was identifiable between the six samples, however, the highest average grain size was recorded at the top of a prominent sandstone unit near the top of the formation (Unit B).

4.2.2.3 Authigenic composition

Authigenic quartz cement varied from 5% to 9% (7.58% average) in the top 200m of the Fell Sandstone (samples: 1420m, 1480m, 1520m, 1540m) where it was the dominant cementing mineral (Table 4.3). At this depth the abundance of calcite cement varied between 2.33% and 4.33%, present mainly as bladed authigenic cementing growths but also as microcrystalline carbonate matrix (Table 4.3).

Below 1700m, where the mud content is greater, the abundance of authigenic quartz was considerably lower, between 2% and 3.66% (Table 4.3). At this depth calcite was the dominant authigenic cement, peaking at 18.3% at 1760m depth (10.2% average for samples 1760m, 1780m and 1795m).

The abundance of kaolinite was consistently low, varying between <1% and 2% for each sample (Table 4.3), infilling localised intergranular space, likely secondary pore space created by feldspar dissolution.

4.2.2.4 Drill mud contamination

A number of the thin section samples contained a significant amount of drill mud. The abundance of drill mud peaked at 1420m where it was observed to make up 24.3% of the bulk composition. The abundance of drill mud was considerably lower in samples taken from greater depths, dropping to a low of 1% at 1760m (Table 4.3). Very little drill mud (less than 4%) was present in the samples taken from below 1700m.

Due to sample disaggregation during the process of preparing the thin sections it is likely that the values for drilling mud abundance, obtained through point counting, are overestimated.

4.2.2.5 Porosity

Accurate quantitative estimates for porosity could not be obtained due to the disaggregated nature of the samples. On visual inspection very little porosity was observed. No primary macroporosity has been preserved due to the effects of compaction, high clay content and a post-depositional mineralisation. Similarly, secondary porosity created through feldspar dissolution has been infilled with later mineral cements or authigenic clays, namely kaolinite. Post-depositional microporosity was noted and in some cases visible within pore spaces infilled with kaolinite. Photos analysed using JPOR returned porosity values of between 0.23% and 2.3% (average sample values shown in table 4.3).

Sample depth (m)	Grain size	Q	F	L	Carbonate Cement	Quartz Cement	Clay	Other	JPOR porosity
1420	Very fine	48.21	0.00	2.39	2.79	9.16	13.15	24.30	-
1480	Very fine	55.02	0.87	3.06	5.67	11.35	16.16	7.86	0.65
1520	Very fine	54.43	0.42	1.27	1.70	11.39	18.57	12.24	1.76
1540	Very fine	69.46	2.35	1.01	3.00	5.03	14.09	5.03	-
1760	Very fine	39.80	0.00	2.01	18.00	2.67	36.12	1.00	-
1780	Very fine	46.24	1.08	2.87	4.20	3.85	36.49	3.16	1.21
1795	Very fine	31.93	0.70	2.46	6.67	2.11	51.58	3.51	-

Table 4.3: Summary of thin section compositions for the Fell Sandstone from the Science Central Borehole. Values given as percentages. Photos suitable for JPOR analysis could only be obtained for three of the samples.

Figure 4.15: Graph showing the grain size distribution within the Fell Sandstone samples taken from the Science Central Borehole.

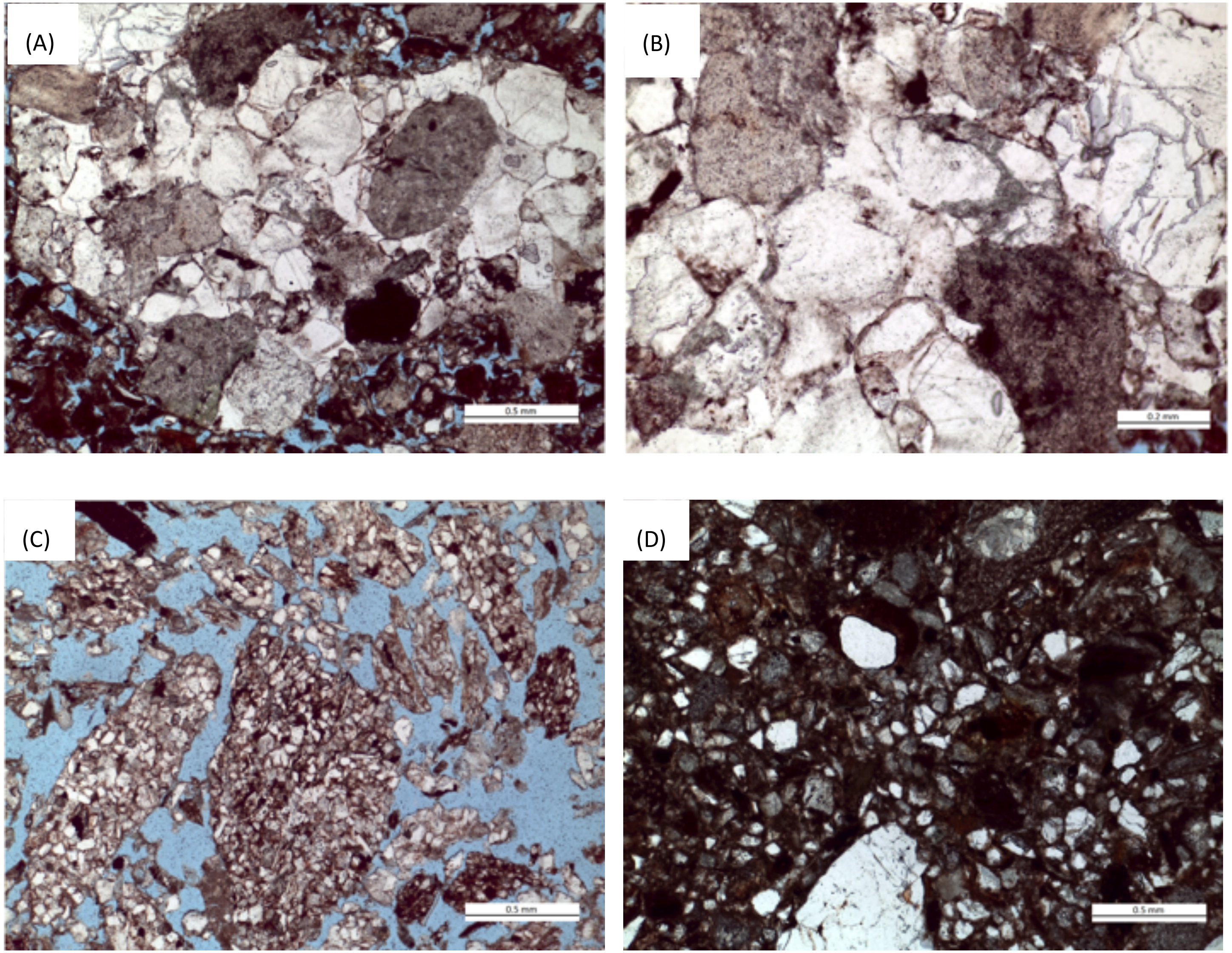

Figure 4.16: Science Central sample photomicrographs. Image A) and B) from 1780m show an intact area of sandstone that has been completely cemented by widespread quartz overgrowth, occluding all porosity. C) A quartzwacke sample from 1520m depth. At this depth average grain size is <1mm (v fine sand). Intergranular space is infilled by detrital clay that has altered to illite. Visible macroporosity is absent although this cannot be quantified here due to sample dissagregation. D) At 1795m depth, the approximate base of the formation, the fell sandstone is mainly composed of illitic clay rather than detrital sand grains.

4.2.3 Errington Borehole thin sections

4.2.3.1 Detrital Composition

The Fell Sandstone at Errington 1 is composed of arenitic sand units interspersed with finer grained clay units. The abundance of quartz varies between 90 and 96% of the total detrital bulk composition (93.48% average). This includes polycrystalline quartz which varies between 0.7 and 4% in abundance (Table 4.4).

Granitic rock fragments composed of: clinopyroxene, identified by its high birefringence, plagioclase feldspar and quartz were identified in three thin section samples (1350m, 1700m and 1900m). These rock fragments were likely derived from the Cheviot Granite or the main Caledonian rock source region to the northeast. Trace zircons were also identified in three of the thin section samples. Muscovite is present, albeit in low abundance (<2%), within all the samples (Table 4.4).

Feldspar was observed in all samples; however, it made up only 3.19% of the detrital bulk composition on average (Table 4.4). Most preserved grains did not show signs of alteration, however, several feldspar grains observed, had undergone partial dissolution. Grains that had been partially altered to kaolinite were also visible. Authigenic kaolinite was identified in all twelve samples evidencing that a proportion of the detrital feldspar originally present within the Fell Sandstone has since undergone dissolution or been altered to kaolinite.

The abundance of clay within the samples fluctuated from 35% to as much as 55% (Table 4.4) meaning that all samples are texturally classed as wackes. The lowest clay abundance, 34.8% was observed in the thin section sample taken at 1950m, near the base of the Fell Sandstone (Table 4.4). The highest clay abundance was recorded in the sample taken at 1850m. Clay constituted 42.5% of the formation on average. Much of the initial detrital clay has since been altered to either authigenic illite or shale.

4.2.3.2 Texture and grain contacts

Modal detrital grain size ranged from that of very fine to fine sand (mean grain size for all thirteen samples is 0.157mm; Table 4.4) with a good to moderate degree of sorting (0.488-0.861 F&W). Grain size generally decreased with depth. Maximum average grain size (0.295mm) was recorded at 1500m depth in the lower of the two prominent sand bodies (Zone B) located near the top of the formation. Many sand grains within the samples were matrix supported due to the high clay content within the formation. The majority of grain contacts that were identified were embayed owing to the prevalence of quartz overgrowth and the effects of mechanical compaction, with abundant long and sutured contacts also identified.

4.2.3.3 Authigenic composition

In all samples, detrital grains were well cemented by a combination of pervasive silica and carbonate cement as well as authigenic illite and kaolinite. Areas of cleaner, more arenitic sandstone were dominated by authigenic quartz cement resulting in a high level of grain embayment and suturing. Authigenic quartz abundance varied between a high of 16% at 1450m, a depth at which overall the sand percentage is above average, to below 1% at 1850m (Table 4.4), which has the lowest sand percentage of all depths analysed (34.3%).

More clay rich sandstone areas were cemented by a combination of bladed to microcrystalline calcite and illitic clay. Localised intergranular areas were infilled with Kaolinite, formed through the alteration of detrital feldspar. The abundance of kaolinite varied between 0.3% and 4.7% and did not change significantly with depth (Table 4.4).

4.2.3.4 Drill mud contamination

Only trace amounts of drilling mud (<1%) were identified at 1750m. No drilling mud was identified in any of the other samples from the Errington 1 borehole (Fig. 4.19).

4.2.3.5 Porosity

Overall reservoir quality was poor with no visible macro porosity. Primary porosity has either been diminished by compaction, evidenced by the high abundance of grain embayment, or infilled by authigenic cementation. Negligible secondary porosity has been generated as secondary pore space created though feldspar dissolution has been infilled with authigenic kaolinite. Authigenic microporosity was visible, under plane polarised light within pores that have been infilled by kaolinite. JPOR analysis returned porosity values between 0% and 1.7% (average sample values shown in table 4.4).

Sample depth (m)	Grain size	Q	F	L	Carbonate Cement	Quartz Cement	Clay	Other	JPOR porosity
1350	Very fine	35.57	1.34	2.01	5.30	2.00	47.32	0.67	0.46
1400	Fine	46.49	3.01	2.01	3.70	4.00	36.12	3.01	0.65
1450	Fine	48.00	1.67	1.33	8.20	5.40	35.33	0.00	-
1500	Medium	42.52	2.33	1.33	4.30	2.60	44.19	1.99	-
1550	Very fine	45.49	1.39	2.08	9.00	2.00	39.24	0.00	0.23
1600	Very fine	37.30	0.33	1.33	7.30	1.70	49.30	2.70	-
1650	Fine	44.33	1.00	2.00	7.60	2.00	42.67	0.00	1.20
1700	Very fine	37.00	0.33	2.33	9.30	0.70	46.80	3.30	-
1750	Fine	51.66	2.33	1.00	7.60	2.40	32.60	2.40	0.24
1800	Fine	45.60	2.33	0.33	5.40	1.40	42.70	2.00	-
1850	Very fine	32.66	0.66	1.00	9.00	0.00	55.30	1.30	0.42
1900	Very fine	40.60	1.33	0.66	8.00	1.00	46.70	1.70	-
1950	Fine	52.33	2.00	1.66	5.40	2.40	34.80	1.30	-

Table 4.4: Summary of thin section compositions for the Fell Sandstone from the Errington 1 borehole. Values given as percentages. Photos suitable for JPOR analysis could only be obtained for six of the samples.

Figure 4.17: Graph showing the grain size distribution within the Fell Sandstone samples taken from the Errington 1 Borehole.

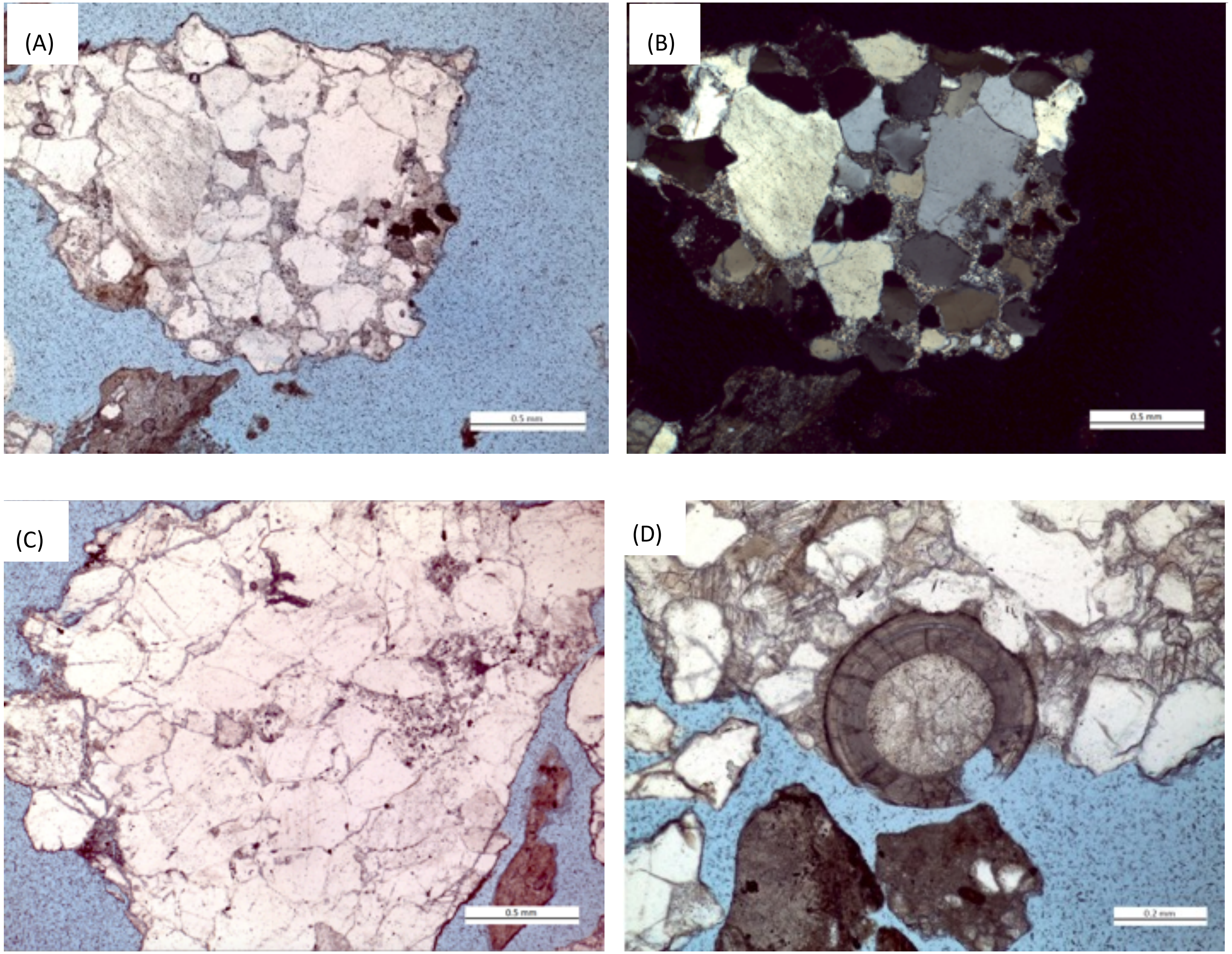

Figure 4.18: Errington photomicrographs. (A) and (B) show a clast of low porosity sandstone, from 1650m depth, in ppl and xpl respectively. Compaction and secondary quartz growth have had a deleterious effect on intergranular porosity. Remnant porosity has been infilled with authigenic kaolinite, leaving only limited microporosity. C) From 1500m depth; intergranular pore space within this sandstone has been completely occluded by pervasive quartz overgrowth. D) Cross-sectional image of a crinoid stem from 1700m depth, indicating deposition in a shallow marine/near shore environment. The surrounding sandstone has been cemented by bladed authigenic calcite growth.

Figure 4.19: Thin section petrography of analysed thin section samples from Bowden Doors, Errington and Science Central. Average compositions for each site are presented as bold lines.

4.2.4 Results of SEM analysis

4.2.4.1 Bowden Doors

Overall reservoir quality was good in both samples analysed. Primary porosity was largely preserved owing to a lack of mineralised cement. Multiple secondary pores were identifiable by the presence of partially dissolved feldspar grains (Fig. 4.20). Authigenic kaolinite, which occurred in patches throughout both samples, was confirmed to be the main pore filling mineral. Individual kaolinite crystals were often present as stacks consisting of multiple pseudoeuhedral crystals. Very long kaolinite stacks, known as vermicules, were commonly visible within larger interstitial spaces (Fig. 4.20). Visible microporosity has been retained within kaolinite infilled pore space. Little authigenic quartz was identified, consistent with observations made during point counting. The development of quartz overgrowth has been limited by the presence of the infilling kaolinite and grain coatings. Other cementing minerals such as calcite were not present in significant abundance.

Grain embayment was common resulting in grains having dominantly concavo-convex contacts. Some potential styolites were observed between some grains (Fig. 4.20), evidencing the occurrence of pressure solution, a form of diffusive mass transfer.

4.2.4.2 Errington

Much of the formation's intergranular porosity (primary and secondary) has been lost through the combined influence of grain compaction and widespread authigenic quartz and calcite precipitation with many quartz grains having fused together into impermeable clusters (Fig. 4.21). All grain contacts were concavo-convex or sutured in nature.

Authigenic calcite cement was identified to be the most abundant cement, commonly infilling any remaining interstitial spaces throughout all three samples analysed (Fig. 4.21). At 1550m depth, remnant intergranular space, not occluded by mineral cement was infilled by a combination of illitic clay and carbonate matrix, consisting of bladed and microcrystalline calcite. Within the cleaner sandstone samples (1400m and 1500m) remnant pore space was manly infilled by bladed authigenic calcite and stacks of authigenic kaolinite (Fig. 4.21). Almost no primary or secondary porosity was preserved within any of the three samples. Pores infilled with Kaolinite have retained limited microporosity however, these interstitial spaces tended to be isolated and there were therefore ineffective. The level of connectivity between these areas of microporosity was difficult to reliably estimate due to disaggregation of the samples, however, overall porosity within the Fell Sandstone at Errington has been greatly reduced.

4.2.4.3 Science Central

Similar to the samples from the Errington borehole, compression and authigenic mineralisation have had a deleterious effect on the porosity of the Fell Sandstone. The vast majority of all intergranular space was infilled with illitic clay, bladed authigenic calcite and kaolinite (albeit it in far less abundance). Authigenic illite, an alteration product of detrital clay, was the most abundant pore infilling mineral at 1760m depth. Within the cleaner sandstone samples from 1480 to 1540 metres depth interstitial porosity was primarily infilled by either bladed calcite cement or authigenic quartz.

Grain suturing and concavo-convex contacts were common within all samples owing to the effects of abundant secondary quartz growth and burial compaction.

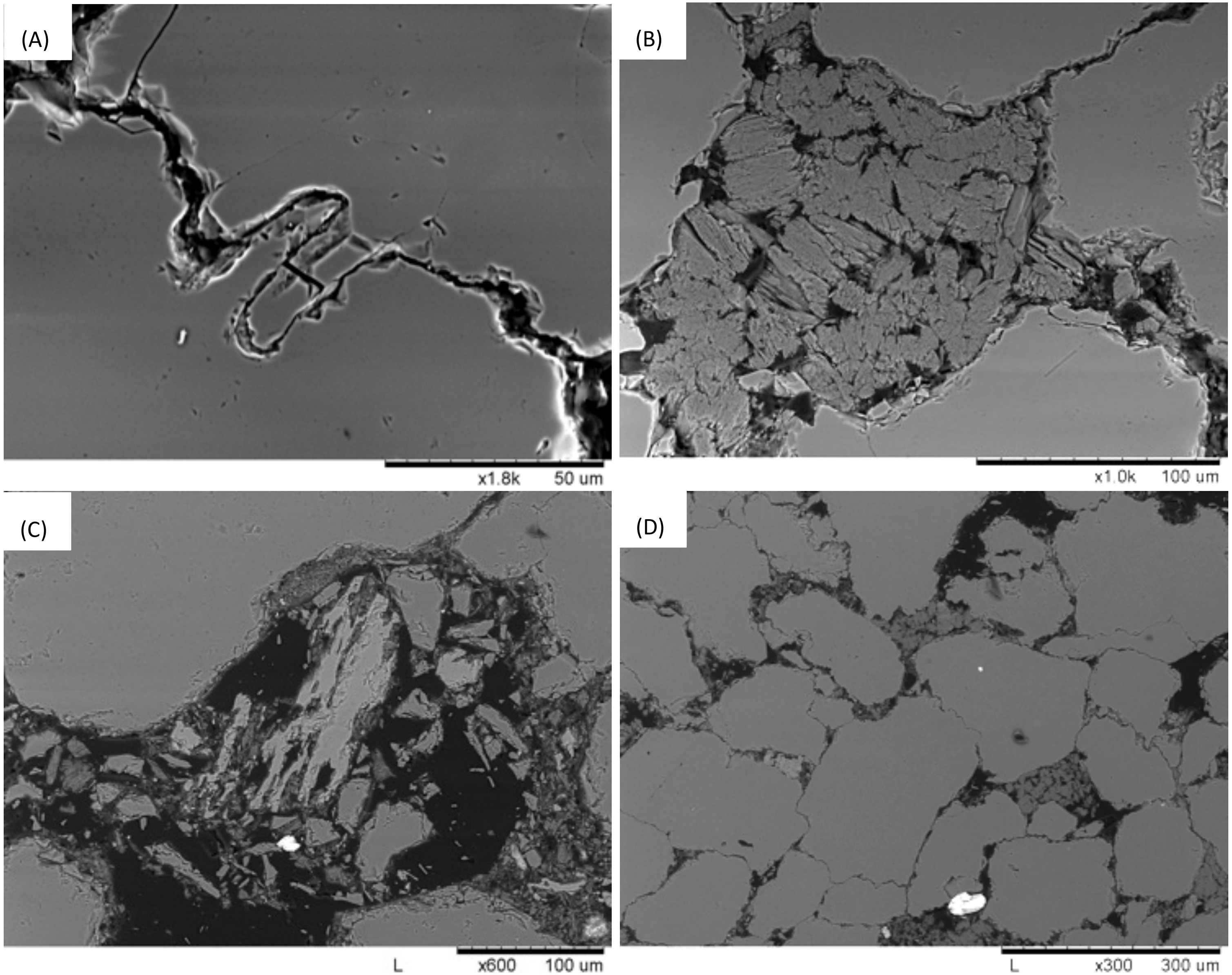

Figure 4.20: Bowden Doors SEM photomicrographs showing A) possible styolitisation along the boundary of two quartz grains. B) Pore filling stacks of authigenic kaolinite. Microporosity is visible between the kaolinite stacks. C) A feldspar grain that has been largely dissolved, leaving only skeletal remnants. The created secondary pore has been preserved, increasing the macroporosity. Some authigenic kaolinite can be seen lining the pore. D) The effect of authigenic kaolinite growth on intergranular porosity. Patches of infilling kaolinite are visible in a number of pores however, significant microporosity is retained within these interstitial spaces. Compaction and overgrowth have created sutured and concavo-convex grain contacts, reducing overall macroporosity.

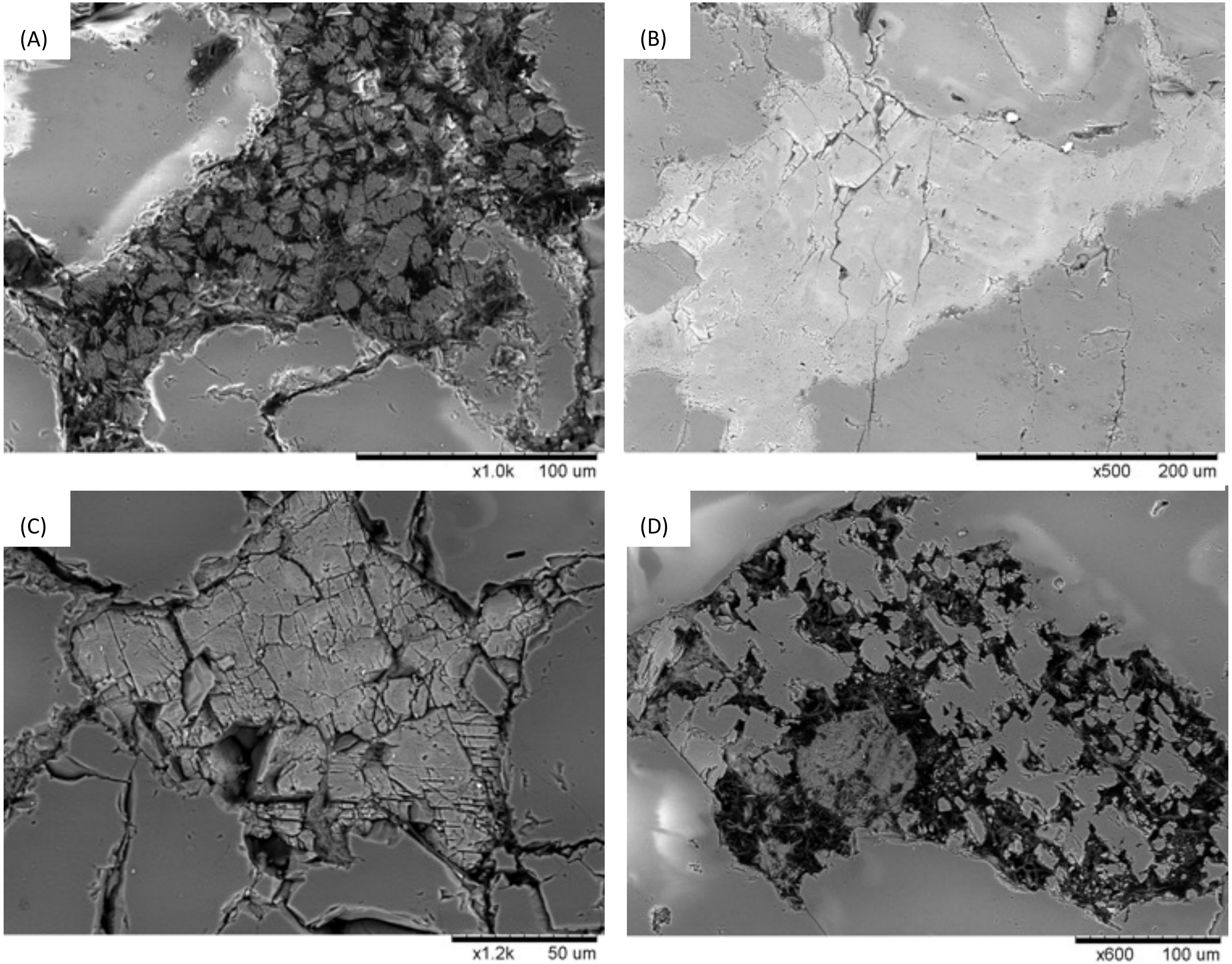

Figure 4.21: Errington SEM photomicrographs showing A) pore infilling stacks of authigenic kaolinite and fibre-like authigenic illite. Large kaolinite vermicules are visble. Microporosity is retained within the pore, between kaolinite stacks. B) and C) Intergranular pores that have been completely infilled by authigenic calcite (sparite), identifiable by its light colouration and cleavage. Authigenic calcite is the most abundant cementing mineral observed at Errington 1. No porosity is preserved. The surrounding quartz grains have been fused by a combination of compaction and secondary quartz growth. D) An area of microporosity, created through the partial dissolution of quartz.

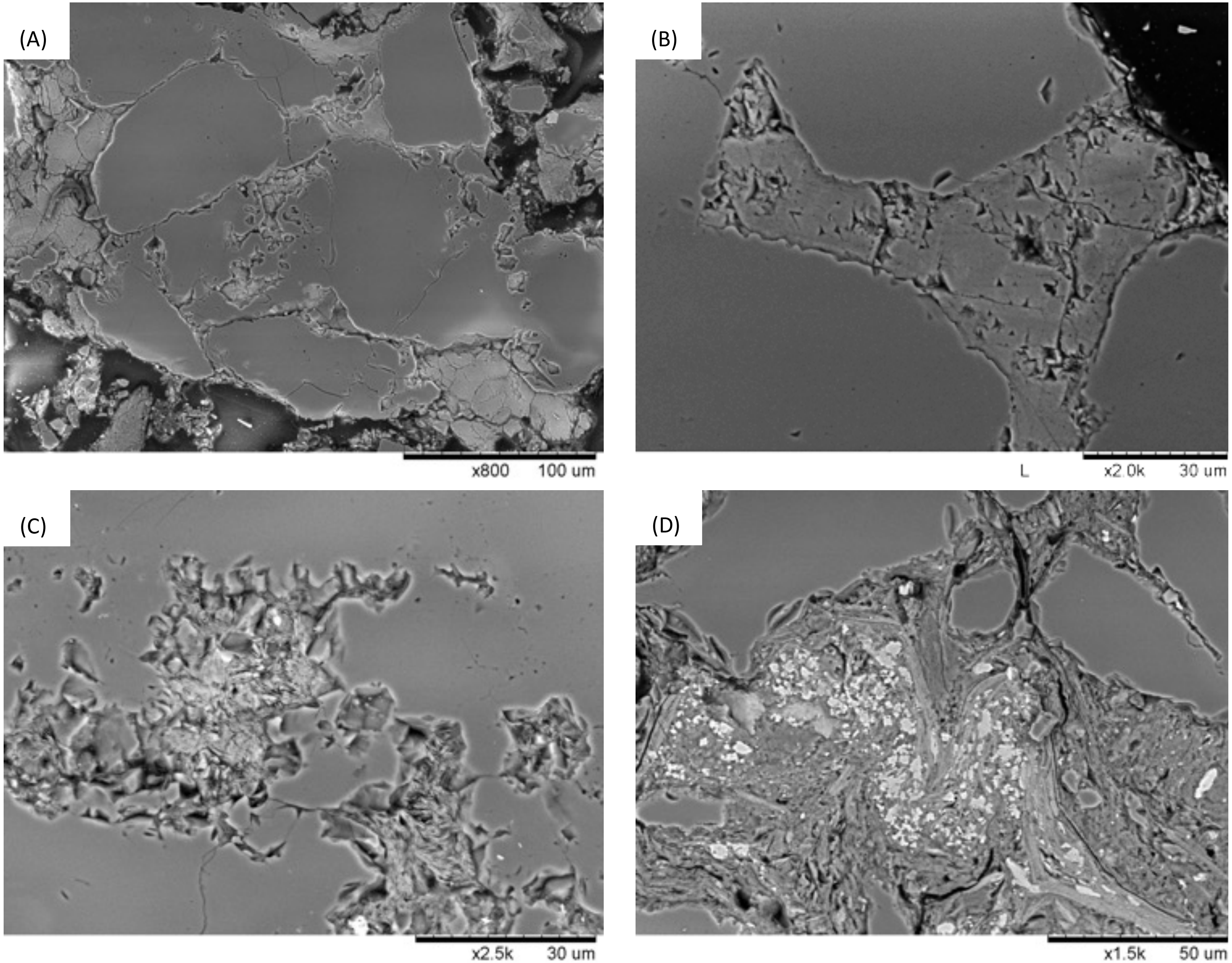

Figure 4.22: Science Central SEM photomicrograph showing A) Sandstone layers have been largely cemented by the growth of bladed, authigenic calcite (sparite). Quartz overgrowth has promoted the formation of concavo-convex and sutured contacts, occluding pore necks. B) An intergranular pore that has been infilled with authigenic calcite (sparite). No microporosity is retained within interstitial spaces infilled by sparite. C) A pore that has been partially infilled by fibrous, authigenic illite. Illite is the most abundant clay mineral observed within the Fell sandstone at Science Central. D) The volume of clay within the formation increases with depth. Samples from a lower depth have a greater abundance of pore infilling illite. Despite this, little microporosity was observed in these areas.

4.2.5 Interpretation

The lithostratigraphy of the Fell Sandstone has long been a subject of academic publication and multiple studies have analysed the petrography of the formation (Hodgson & Gardiner, 1971; Bell, 1978; Turner *et al.*, 1993; Turner *et al.*, 1997; Younger *et al.*, 2016). However, with the exception of the study carried out by Younger *et al.* (2016), these studies have mostly focused on the Fell Sandstone in the Northumberland area, between Berwick-Upon-Tweed and Rothbury, where it is found at outcrop or at burial depths <1km (Alnwick borehole, Longframlington borehole, Stonehaugh borehole). Comparatively little is known about the petrography of the Fell Sandstone in the Central Northumberland and Solway Basins where it is typically buried between 1km and 2km. As such it has previously been unclear as to how burial diagenesis (up to a maximum burial depth of >3km) has affected formation's reservoir quality in these locations.

4.2.5.1 Petrography of Fell Sandstone samples from the Easton, Longhorsley and Stonehaugh boreholes

4.2.5.1.1 Easton

Euhedral quartz overgrowths are widespread within the two Fell Sandstone samples analysed by Blackbourn (1990). Grains were generally closely spaced. Large interstitial areas, where they occur, and pore throats were infilled by stacks of authigenic kaolinite as well as lower quantities of more fibrous illite. Dolomite is occasionally visible but low in abundance (<2.7%). Porosity is limited by quartz overgrowths and pore infilling kaolinite, illite and illite-smectite which occludes much of the intergranular pore space. Between 70.4% and 80.7% of the sample's bulk composition comprised of detrital quartz (including polycrystalline quartz).

To obtain reliable porosity and permeability data, rotary sidewall cores were taken at four separate depths, using a diamond drill bit so as to reduce any alteration to the internal fabric of the rock. All the samples analysed were fine to very fine grained. Porosity, obtained through core analysis, varies between 9.1% and 13.5%.

4.2.5.1.2 Longhorsley

As part of Corex UK's analysis, each sample was point counted (300 points) to obtain quantitative estimates for bulk composition and visible porosity. Thin sections were impregnated with blue epoxy resin to highlight porosity. Samples were also stained with sodium cobaltinitrite and mixed alzarian red-S/potassium ferricyanide acid to help with the identification of K-feldspar and carbonates.

The detrital composition of the Longhorsley samples analysed by Corex UK is equivocal to the sample compositions outlined in this study. The Longhorsley samples are comprised primarily of quartz, the abundance of which varies between 70% and 84% (including up to 3% polycrystalline quartz). The mineralogical composition is relatively consistent across the three samples, all of which plot with over 95% quartz on a QFL plot (Fig. 4.23). K-feldspar is present in all samples, ranging between <1% to 2% (1.5% average) in abundance. Trace muscovite is also visible in all three samples. Trace amounts of plagioclase feldspar are noted in one sample. Much of the original detrital clay has been altered to authigenic illite.

The samples from Longhorsley largely consisted of upper fine to lower medium grained, moderately well sorted sandstone. Concavo-convex and sutured grain contacts were common throughout the samples.

Authigenic quartz overgrowth was observed with abundances of up to 2%. However, Corex UK noted that the true abundance of authigenic quartz may have been disguised due to the high level of grain embayment and suturing. Illite, produced through detrital clay alteration, is the only clay mineral that was observed. Kaolinite is completely absent in all the Longhorsley samples. Calcite (2-4%) and dolomite (up to 4%) micro/pseudospar were observed, both likely being produced through the alteration of micritic mud once present within the samples.

In their study ROC (2002) reported that quantitative estimates for porosity could not be gained from the Longhorsley cutting samples due to their disaggregated nature. Little visible porosity was reported with pore spaces often being filled in with authigenic cements.

4.2.5.1.3 Stonehaugh

All seven samples analysed by Corex UK had an arenitic composition with quartz abundance varying between 70% and 84%. Overall, detrital grains made up between 90 to 97% of the bulk composition. Only trace amounts of K-feldspar were visible in two of the samples. The presence of kaolinite within the samples indicated that any detrital feldspar likely underwent dissolution. Up to 1% muscovite was also visible in all seven samples. Lithic fragments made up between 1% to 3% (1.4% average) of the bulk composition. Heavy minerals, namely zircon and tourmaline are noted in all the samples.

The abundance of detrital clay was reported to be relatively low, between <1% and 3%, with much having been altered to authigenic illite. The detrital grains were generally fine to medium grained and well sorted. Concavo-convex and sutured contacts were the most common types of grain contacts.

Authigenic quartz abundance varies between 1% and 6% (3.2% average). Again, Corex UK noted that the nature of the grain contacts may have disguised the full amount of quartz overgrowth.

The abundance of illite varied considerably within the samples with only trace amounts to none identified within four of the samples. These four samples were found to have consistently higher porosities (6-14%) than the three samples with higher levels of illite (1-4%). The illite present at Stonehaugh is the product of detrital clay alteration and possibly the breakdown of grains (glauconite). The presence of glauconite may indicate a marine input, typical of a deltaic environment. Kaolinite was more abundant within the Fell Sandstone at Stonehaugh than the other locations analysed, varying between 1% and 10% (4.7% average). Authigenic calcite was mostly absent, with only trace amounts in one sample, however, the abundance of ferroan dolomite was higher, varying between 2% and 7% (3.7% average).

The variation in illite abundance and porosity indicates that two types of samples were analysed by ROC. Within the four more porous samples porosity varied between 6% and 14%, as mentioned above. These porosity values likely resulted from the dissolution of liable grains such as feldspar, creating oversized and channelised pores. Continued secondary porosity growth is evidenced by kaolinite overgrowths along pore walls. Pore space within these samples has been only slightly reduced by carbonate cementation. In the other three samples however, only trace porosity was reported. Within these samples only small amounts of secondary porosity were preserved owing to increased compaction and cementation. Overall porosity is seemingly controlled by the level of secondary porosity development with little primary porosity being preserved. The results of the SEM analysis, conducted by Corex UK (2002) further reinforce the findings obtained during point counting.

4.2.5.2 Petrography

The Fell Sandstone is arenitic in composition at all three locations studied (Fig. 4.23). There was little meaningful change in QFL composition between Bowden Doors, Errington and Science Central with the paucity of lithic and feldspathic grains being characteristic of the formation at each site. Indeed, the petrographic findings for the formation's detrital composition were largely consistent with previous lithological/thin section descriptions of the Fell Sandstone (Hodgson, 1978; Turner *et al.*, 1993; Corex UK, 2002), which also ascribe the Fell Sandstone an arenitic detrital grain composition (Fig. 4.23). The lack of any discernible pattern in QFL composition, within the existing dataset, indicates that it does not vary laterally across the Northumberland Trough. However, thin section data, courtesy of the Oil & Gas Authority (Corex UK, 2002), of samples from the Stonehaugh borehole, showed that detrital feldspar was absent at this location. The presence of Kaolinite indicated that this was most likely the result of diagenetic dissolution (Corex UK, 2002). The impacts of liable grain dissolution and its importance, with respect to reservoir quality, is discussed in chapters 4.2.5.3 and 4.2.5.4.

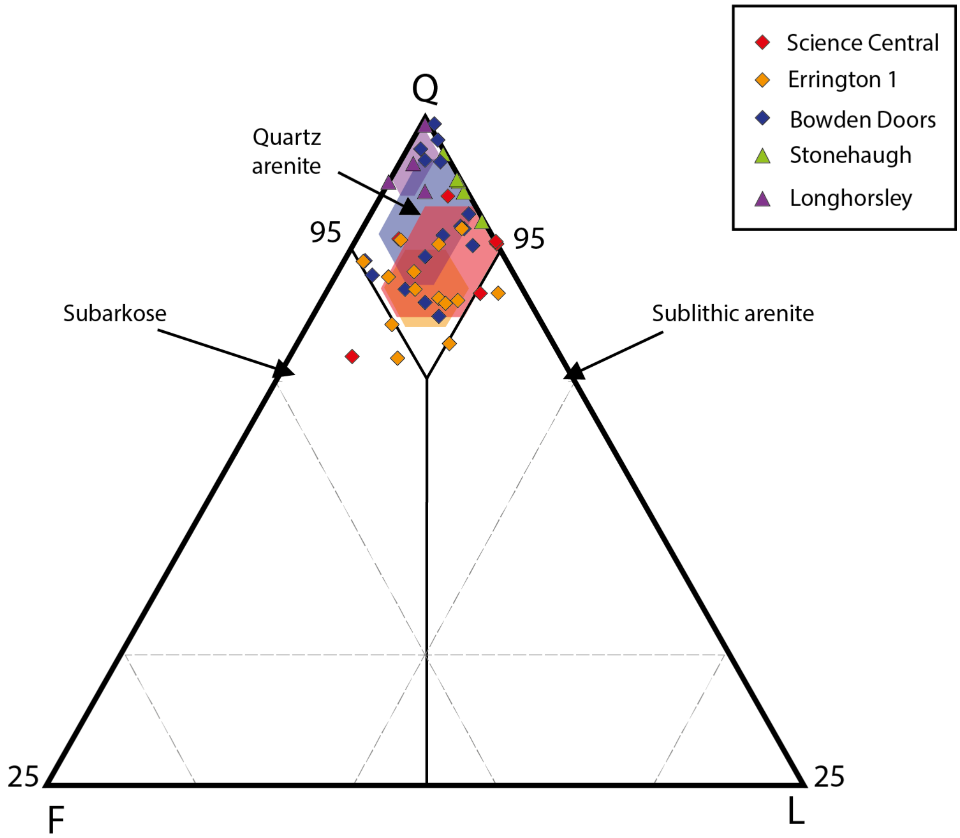

Figure 4.23: QFL (Quartz, Feldspar, Lithics) ternary plot showing compositions of samples from: Bowden Doors, the Errington 1 Borehole, the Science Central Borehole and the Stonehaugh Borehole (obtained through point counting). QFL data from the Longhorsley Borehole and the Stonehaugh borehole, modified from COREX (2002), is also displayed.

Textural analysis of the thin section samples from Bowden Doors, Errington and Science Central revealed a trend of decreasing grain size moving south, away from the Cheviot Hills (Fig. 4.23). Thin sections analysed from Bowden Doors reveal a dominantly medium grained (average grain size ranges from 0.23mm to 0.51mm) sandstone with coarse horizons consisting of grains >0.5mm; consistent with previous grain size measurements of 0.18mm to 0.69mm (0.33mm average), recorded for the Fell Sandstone penetrated by the Shirlawhope Well (Bell, 1978), located 31km southwest. At Errington the Fell Sandstone was dominantly fine grained, with an average grain size of 0.15mm across all thirteen samples. Grain size decreased further still towards Science Central where on average the Fell Sandstone was very fine grained (0.120mm average across all six samples). Overall, average grain size decreased by 0.21mm between Bowden Doors and Science Central, a distance of 70km. Additionally, Bowden Doors samples consistently had a higher degree of sorting (0.414 (well sorted) compared to 0.641 at Science Central (moderately well sorted)). The level of grain size sorting at Science Central ranged from 0.542 (moderately well sorted) to 1.031 (poorly sorted). As stated previously, grain size sorting is the most important depositional control on sandstone porosity (Worden & Burley, 2009). This trend of decreasing grain size in the direction of the Palaeocurrent is reinforced by existing grain size data for the Fell Sandstone. Grain size data, courtesy of Corex UK (2002), revealed that at the Longhorsley 1 borehole, the Fell Sandstone's average grain size was 0.25mm; that of an upper fine to lower medium grained sand, with minimum and maximum grain sizes ranging from that of silt to coarse sand. At Stonehaugh the Fell Sandstone is also described as fine to medium grained, however, the abundance of grains in excess of 0.5mm in lower, compared to at Longhorsley. These lateral trends in grain size and sorting most likely reflect lateral changes in the depositional environment rather than any post-depositional process.

The volume of clay/shale within the sandstone samples also increased to the southwest (Fig. 4.7), away from Bowden Doors, where point counting analysis revealed an average sand % of over 90%, towards Errington and Science Central (point count determined sand percentages of 46.9% and 52.4% respectively). Recent studies have shown that unconfined, aggradational fluvial systems will disperse clastic sediment in a radial pattern (Hartley *et al.*, 2010) resulting in a progressive increase in fine grained material moving downstream (Howell *et al.*, 2019).

The increase in clay abundance, from an average of 7.8% at Bowden Doors to 41.4% at Errington, reinforces the interpretation that sand richness within the Fell Sandstone

Formation was strongly influenced by the Cheviot High. Lateral confinement of the river system, throughout the Chadian to Holkerian, to the east of the Cheviot High promoted the deposition of stacked, sand rich fluvial sand bodies and a reduction in overbank facies preservation. Moving beyond the influence of the Cheviot High into the Central Northumberland Basin the confinement of the Fell River System decreases.

The increase in shale volume and decrease in grainsize sorting indicates that depositional porosity was lower within the Fell Sandstone at Errington and Science Central, compared with at Bowden Doors.

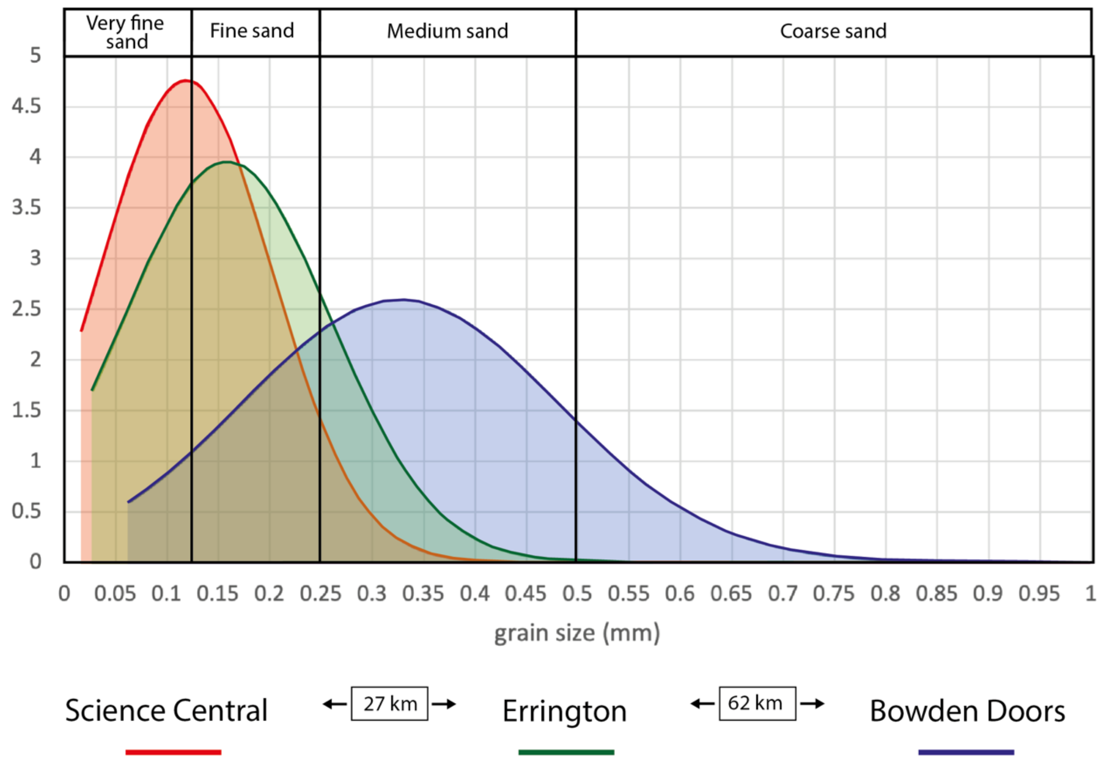

Figure 4.23: Grain size distribution curves, derived from point count data, for the Fell Sandstone at Bowden Doors (blue), Errington (green) and Science Central (red). The data show a trend of decreasing grain size.

4.2.5.3 Authigenic composition and the impact of diagenesis

4.2.5.3.1 Burial compaction and grain packing

The dominance of long to sutured grain contacts at both Science Central and Errington evidence the occurrence of both mechanical and chemical compaction within the Fell Sandstone at these locations. Pressure solution, one of the main mechanisms of chemical compaction, was responsible for the creation of the sutured contacts and micro-styolites observed in thin section. Pressure solution was likely an important source of silica, facilitating the pervasive quartz cementation present within the Errington and Science Central samples.

4.2.5.3.2 Diagenetic alteration and secondary mineralisation

Thin section and SEM analysis of the Fell Sandstone at Stonehaugh and Longhorsley carried out by Corex UK (2002) concluded that good reservoir quality was linked to secondary porosity development. At Stonehaugh in particular, good porosity (6-14%) has been maintained in sandstones where significant secondary pore space has been generated. Within these porous samples the formation of Kaolinite, through the widespread dissolution of K-feldspar has limited the development of quartz overgrowths and pore spaces that have been infilled kaolinite still retain some microporosity. However, Corex (2002) also identified samples where pervasive quartz overgrowth, clays, and carbonate cements have occluded the vast majority of both primary and secondary porosity resulting in poor reservoir quality. Whilst minor secondary pores were observed they were, however, stated to have a negligible impact on overall reservoir quality.

Similarly, poor reservoir quality was interpreted from the results of Corex UK's (2002) analysis of cuttings from Longhorsley. The Fell Sandstone at Longhorsley had a similar detrital composition to the Stonehaugh samples although, unlike at Stonehaugh, detrital feldspar had been preserved (1.5% average). Very little porosity was observed as the majority of primary pore space was observed to be largely infilled by authigenic calcite and quartz. The abundance of illite ranges from 7% to 23% across the three samples, considerably higher than what was observed within the Stonehaugh samples (1-3%). Kaolinite was completely absent in all of the Longhorsley samples. Authigenic calcite (2-4%) and dolomite (up to 4%) micro/pseudospar were interpreted to have both been produced through the alteration of micritic mud once present within the samples.

Kaolinite constituted up to 10% of the Fell Sandstone's bulk composition at Stonehaugh, where detrital feldspar had been completely removed and significant porosity had been generated. At Longhorsley, samples were characterised by a complete absence of kaolinite, indicating that little detrital feldspar dissolution had occurred (ROC, 2002).

Corex UK completed a subsequent petrographic study (Tech 2142) of Fell Sandstone cuttings from the Errington 1 borehole, summarised by ROC (2005, Tech 2139). Samples were selected from Zones A, B and D (Fig 4.3). This study concluded that, similar to the samples from Longhorsley, pore space had been almost entirely infilled by pervasive silica and calcite cement. Secondary pore spaces were rare and often infilled with authigenic clay, commonly creating only ineffective microporosity. Porosity was identified to be best developed in the sandstone units between 1340m and 1400m where it was interpreted that the emplacement of gas had helped in the preservation of primary porosity or assist secondary porosity generation (ROC, 2005). The volume of gas decreased, however, below this interval with negligible amounts present in the basal Fell Sandstone. Again, it was concluded that very little primary porosity has been retained within the Fell Sandstone at Errington and that reservoir quality was controlled by the abundance and subsequent dissolution of feldspar.

The results of the thin section and SEM analysis, conducted on samples from Bowden Doors, Errington and Science Central, largely reinforce the observations made by Corex UK (2002) and ROC (2005, Tech 2139). At both Science Central and Errington, pervasive silica and quartz cementation has had a deleterious effect on porosity, with almost no intergranular pore space observed in any of the samples analysed. Despite the high clay content, observed at both sites, thin section observations revealed that sandstone samples generally had poorly developed clay coatings. Numerous studies (Bloch *et al.,* 2002; Anjos *et al.,* 2003; Taylor *et al.,* 2004) have recognised the importance of clay coatings as a control on quartz cementation. Based on the findings of these studies, sandstones that lack well developed clay coatings are more highly cemented that otherwise identical sandstones that do poses well developed clay coatings (Taylor *et al.,* 2010). This is further evidenced in the Fell Sandstone as authigenic quartz was concentrated within cleaner sandstones and was less pervasive in sandstone samples with greater mud volume.

As mentioned previously, the paucity of K-feldspar is characteristic of the Fell Sandstone Formation, either as a result of dissolution or an inherent lack of feldspar within the clastic sediment source. The abundance of kaolinite was low at Errington, Longhorsley and Science Central locations (2.4%, 0% and 2.7% respectively), when compared with Bowden Doors and Stonehaugh, indicating that comparatively little feldspar dissolution had taken place. Consequently, this indicates that the abundance of detrital feldspar was low at the time of deposition. This is likely the reason why little secondary porosity was observed within the Errington, Longhorsley and Science Central samples. Whilst occasional kaolinite infilled pores, with visible microporosity, were identified within some samples from the Errington borehole during SEM analysis, they were often isolated and likely have little impact on overall porosity. Overall, preserved pore space was poorly connected and thus rendered largely ineffective.

Conversely, substantial primary and secondary porosity (14.94% and 2.87% respectively on average) was preserved within the Bowden Doors samples.

The overall abundance of authigenic cements and clay minerals at within the Fell Sandstone at Bowden Doors was consistently lower than that within the formation at Errington and Science Central. Previous investigations (Monro, 1986; Turner *et al.,* 1993) have identified patchy calcite cement (both sparry and microcrystalline) within the Fell Sandstone southwest of Berwick-upon-Tweed (Murton: NT 9670 4890; Thornton Farm Borehole: NT 9498 4766). However, this study identified almost no calcite cement within the samples from Bowden Doors. Meteoric water influx has most likely removed much of calcite cement originally present at within the outcrop. Significant calcite cement was only present within the Fell Sandstone at Errington, Longhorsley, and Science Central (Fig. 4.7) where the formation is buried to a depth greater than 1km. Based on the burial history interpretation by ROC (2005) the Fell Sandstone would have been subjected to a maximum burial depth of approximately 3km, assuming uniform uplift of 1.8km (ROC, 2005) across the three well sites. With geothermal gradients equivalent to the UK average (26^0C/km; Busby, 2010) calculated at Longhorsley and Errington, this indicates that the formation also experienced temperatures in the range of 80^0C to 90^0C, both prior to Variscan uplift and during the late Mesozoic to early Tertiary. These conditions facilitated the pervasive quartz and calcite cementation observed in thin section. Authigenic calcite was likely deposited as micritic or carbonate material that has since undergone neomorphism, altering, forming microcrystalline and sparry precipitates. The widespread distribution of calcite cement was probably the result of dissolution, of carbonate minerals, diffusion and precipitation (Worden *et al.,* 2019).

Barite, derived from the high temperature brines associated with the Ninety Fathom Fault (Younger *et al.,* 2016), was identified in half of the Science Central samples during point counting. However, it is only present in low abundances. Based on the samples analysed, barite cementation is not widespread and does not appear to have significantly impacted the porosity of the Fell Sandstone.

4.2.5.3.3 Effect of meteoric water influx associated with uplift

Uplift diagenesis (telogenesisi) has most likely had no effect on the Fell Sandstone in the eastern Northumberland Basin where it is penetrated by the Errington, Longhorsley and Science Central Boreholes. Any alterations associated with Variscan uplift at the end of the Carboniferous were most likely overprinted by the following period of deep burial, during the Mesozoic.

Conversely, the porosity and permeability at Bowden Doors has been enhanced by meteoric water influx (Bell, 1978) which has enhanced secondary porosity development through the dissolution of feldspar and authigenic calcite cements. Telogenesis typically occurs within the first few meters to tens of metres of the surface and although large volumes can intrude into aquifers over time, its effect can be relatively minor in siliciclastic reservoirs (Worden & Burley, 2009).

4.2.5.4 Implications for reservoir quality

Porosity within a sandstone is affected by depositional factors such as grain size distribution/sorting and diagenetic factors such as grain deformation, secondary mineralisation, cementation, infiltration and liable grain dissolution (Bell, 1978).

The reservoir quality of the Fell Sandstone varies considerably across the Northumberland Trough. Good reservoir quality was observed at Bowden Doors (9% - 22% porosity) and the Stonehaugh Borehole (9-14% porosity) where feldspar dissolution has resulted in the creation of oversized channelised pores, enhancing porosity. These porosity values were broadly in line with formation porosity ranges quoted by Hodgson and Gardiner (1971) and Bell (1978). Secondly, detrital grain coatings and the formation of kaolinite prior to pervasive cementation has limited late-stage secondary mineralisation at these two locations.

By contrast, the reservoir quality of Fell Sandstone, within the Errington, Longhorsley and Science Central boreholes, was generally poor. Shale/clay constituted up to 30% of sample volume in these locations with altered illite and carbonaceous matrix infilling much of the intergranular space. Overall, samples from Errington, Science Central, and to a lesser extent Longhorsley, were classified as either muddy quartz arenites or quartzwackes with inherently lower depositional porosity than the comparatively clean sandstones observed at outcrop.

In addition to depositional factors, pervasive cementation, associated with increased diagenesis, has occluded virtually all intergranular space. Whilst kaolinite was present within the formation at both Errington and Science Central, suggesting that a phase of secondary pore formation did take place, its effect on reservoir quality was relatively insignificant.

4.3 Geothermal Resource calculation

4.3.1 Porosity volume

	Range	Average	Units
Northumberland Basin			
Area	-	1173	km^2
Thickness	381 - 643	512	m
Net: gross	0.42 - >0.7	0.5	fraction
porosity	0.01 - 0.07	0.05	fraction
Temperature	-	40	^0C
South of the S-NF Fault			
Area	-	757	km^2
Thickness	377	377	m
Net: gross	0.47	0.47	fraction
porosity	0.01 - 0.035	0.023	fraction
Temperature	40 - >100	75	^0C

Table 4.5: parameters used to calculate the geothermal resource of the Fell Sandstone in the Northumberland Basin and south of the S-NF Fault system.

Overall, the Fell Sandstone was calculated to have total volume of 2000km^3 (1450km^3 in the Northumberland Basin and 560km^3 south of the S-NF Fault System) with an associated pore volume of 85km^3. Of this approximately 970km^3 was determined to be at temperatures in excess of 40^{0}C (15km^3 in the Northumberland Basin and 3km^3 south of the S-NF Fault System), assuming uniform average porosities (Table 4.5).

4.3.2 Geothermal resource estimation

For the Fell Sandstone in the Northumberland Basin (Area 1) the total thermal energy stored within the brines was estimated at 1.04 EJ (EJ = Exajoules, equal to 10^{18}J). This estimate assumes an overall average temperature of 40^{0}C, the cut-off temperature for low enthalpy geothermal systems, and is therefore a minimum estimate of the inferred geothermal resource.

South of the fault system (Area 2) the total thermal energy stored within the pore filling brines is estimated to be 0.58 EJ. When combined, the Fell Sandstone across the Northumberland Basin and the Alston Block has total thermal energy of 1.62 EJ stored within intergranular pore space.

4.3.3 Interpretation

4.3.3.1 The geothermal potential of the Fell Sandstone

Estimates of inferred geothermal resource have been made for a number of Mesozoic sedimentary basins and Lower Carboniferous limestones in the UK (Rollin *et al.,* 1995; Jackson, 2012; Busby, 2014; Narayan *et al.,* 2021). Such studies have yielded geothermal resource estimates from anywhere between 0.14 EJ (Mississippian limestone located in Kent; Narayan *et al.,* 2021) and 124 EJ (Sherwood Sandstone Group located in the Wessex Basin; Jackson *et al.,* 2012). Geothermal resource assessments on these principal sedimentary basins (Rollin *et al.,* 1995; Jackson, 2012) have focused mainly on the Triassic Sherwood Sandstone Group, which is present over much of southwestern, central and northern England (Ambrose *et al.,* 2014) as well as underlying Permian sandstones. The Sherwood Sandstone Group is primarily composed of porous, quartz rich sandstones interbedded with conglomerates, deposited as part of a large, braided river system, and more localised windblown deposits (Busby, 2014; Ambrose *et al.,* 2014). Underlying the Sherwood Sandstone Group, the Bridgnorth and Collyhurst Sandstone Formations (located in the Worcester and Cheshire Basins respectively; Table 4.6) have also been investigated as potential geothermal resources.

These two formations, made up of Permian age aeolian sandstone deposits, are characterised by a low gamma ray response, reflecting low mud content (Ambrose *et al.,* 2014). Within the Cheshire and Worcester Basins, Permian aquifers are separated from overlying Sherwood aquifers by successions of Upper Permian Limestones, dolostones and evaporates. Burial depths, within the four basins, range from anywhere between 480m (Top Sherwood Sandstone reservoir, Worcester Basin) to in excess of 4km (Collyhurst Sandstone in the Cheshire Basin). Despite these high burial depths, porosity has often been well retained within the Sherwood Sandstone Group at depth (Table 4.6). Good reservoir quality combined with the deep burial of these hot sedimentary aquifers have made for promising estimates of inferred geothermal resources. The Wessex and Cheshire basins in particular show considerable potential as they are higher temperature resources than the other UK basins (Busby *et al.,* 2014) (76.6^{0}C recorded at 1818m in the Wessex Basin; 81^{0}C recorded at 3600m in the Cheshire Basin).

The bottom-hole temperature recorded at the Science Central Borehole is comparable to temperatures recorded in the Wessex Basin. Thin section analysis (Chapter 3.2) has revealed, however, that the Fell Sandstone beneath Newcastle has an average porosity of only 2.3%, significantly lower than values recorded for aquifers in other UK sedimentary Basins (Table 4.6). A number of assumptions had to be made to quantify the heat resource present in the Fell Sandstone, such as water being assumed to be extracted but not replenished and no attempt was made estimate the heat stored within the rock matrix. The heat resource estimated here is therefore likely a conservative one. However, when considering only the heat content of the brines in place, the formation's low intergranular porosity means that the Fell Sandstone is host to only a modest geothermal resource, falling within the lower range of inferred UK heat resources. Additionally, diagenetic cementation and compaction has resulted in low pore connectivity; explaining why estimated hydraulic conductivity at Science Central is six orders of magnitude lower than permeabilities reported for the Formation in the Berwick area (Bell, 1978; Turner *et al.,* 1993; Younger *et al.,* 2016). It is clear that the Fell Sandstone at Science Central is largely reliant on post cementation fracture and reactivated fault networks to facilitate fluid flow.

The Central Northumberland Basin has been inferred as a larger albeit lower temperature resource (40-50^{0}C). Whilst average porosity was slightly higher than estimates from the Science Central Borehole, porosity and permeability within the Northumberland Basin is not high enough to facilitate sufficient fluid flow without fracture enhancement, again falling short of the values quoted for other UK basins (Table 4.6). High porosity and permeability values observed in the Stonehaugh succession were likely localised and at a burial depth of 350m (MD), not at a high enough temperature to contribute to the formation's geothermal potential.

Basin	Aquifer	Max. thickness (m)	Porosity	permeability (mD)	IGR (EJ)
Cheshire	SSG	2000			75 (total)
	CS	200-1200	0.14-0.2	?	17 (exploitable)
Eastern England	SSG	50-500	0.23	250	19.4
Wessex	SSG	300m	up to 0.26	5000	124
Worcester	SSG	>1000	0.2-0.3	780-7800	
	BS	938	0.2	150	10.6
Northumberland	FS	643	<0.05	<0.1	1.6

Table 4.6: Aquifer properties of main potential geothermal HAS prospects. SSG Sherwood Sandstone Group (Triassic); BS Bridgnorth Sandstone (Permian); CS Collyhurst Sandstone (Permian); FS Fell Sandstone (Carboniferous). SSG, CS and BS aquifer thickness and porosity from Busby (2014); permeability data from Jackson (2012). Estimates for total and exploitable geothermal resource in the Cheshire Basin from Hirst et al. (2015).

The Fell Sandstone is found at depths up to and in excess of 3km in the Solway Basin in where it is most likely host to temperatures in excess of 50^{0}C. The Siliciclastic Fell Sandstone is only penetrated by the Easton Borehole in the Solway basin at less than 1km depth. As such, there is little physical evidence regarding the reservoir quality of the formation at depth in the Solway Basin. As shown in Chapter 4.1, formation net to gross is lower in the Solway Basin, compared to the Northumberland Basin, and the Fell Sandstone succession is more heavily interbedded with marine mud and carbonate lithologies. It is therefore likely the Fell Sandstone in the Solway Basin is well cemented and as a result has low overall porosity, similar to the successions analysed at the Errington and Science Central Boreholes. Additionally, paralic sandstone bodies are interpreted to be thinner and more dispersed. Consequently, the Fell Sandstone in the Solway Basin likely has little potential for development as a geothermal resource.

4.3.3.2 Fracture enhancement

As it is penetrated by only a few boreholes, relatively little information is available regarding the impact of fractures on the porosity and permeability of the Fell Sandstone. Open fractures can greatly enhance permeability in sandstone reservoirs and can assist flow through non-reservoir lithologies, reducing compartmentalisation. Test pumping was of commercial boreholes (namely the Dock Road, Fowberry, Murton and Thornton boreholes) was conducted by Hodgson and Gardiner (1978) to obtain figures for the Fell Sandstones aquifer properties. The test of the Thornton Borehole produced a stepped pumping curve, indicating surges in transmissivity relating to water derived from fissures (Lang, 1960). At the time of Hodgson and Gardiner’s investigation the Thornton borehole was one of only four boreholes used for public supply with a yield in the upper range of those recorded. This result indicates that the fissures visible at outcrop also occur at depth and do considerably enhance the aquifer properties of the Fell Sandstone in the area (Hodgson and Gardiner, 1978). In a number of the other main UK sedimentary basin (Table 4.6) faults such as the Bridgemere Fault (Cheshire) and the Inkberrow Fault (Worcester) have been identified as possible structural targets that could provide sufficient flow rates to use as sources of geothermal energy (Jackson, 2012). In their exploration of the geothermal potential of the Fell Sandstone in the Science Central Borehole, Younger *et al.* (2016) concluded that there was potential for significant fluid flow if post-cementation fracturing had occurred during the Cenozoic. The Ninety Fathom Fault also remains as a potential structural target.

Chapter 5: Discussion and implications

5.1 Reservoir quality and geothermal potential

The thin section analysis conducted on the samples obtained from Bowden Doors reinforces previous lithological descriptions of the Fell Sandstone at this location (Bell, 1978; Hodgson, 1978; Turner *et al.,* 1993); those describing a clean, medium to fine grained, quartz rich sandstone with up to 20% porosity. Thin section samples from the Errington and Science Central Boreholes have shown however, that the reservoir quality of the Fell Sandstone both in the Central Northumberland Basin and overlying the Alston Block is considerably lower than at outcrop in Northumberland. Despite the presence of thick and laterally continuous sand bodies, in the Northumberland Basin in particular, average porosity was interpreted to not exceed 5%. At depths where temperatures are high enough for low enthalpy geothermal heating (>40^0C; Busby, 2010) log and thin section analysis has revealed that sandbodies, in the lower Fell Sandstone in particular, are often muddy and compartmentalised by impermeable non-reservoir lithologies.

One of the main aims of this project was to elucidate the factors contributing to the low flow rates recorded, for the Fell Sandstone, at Science Central. Four different explanations for the Fell Sandstone's low transmissivity, outlined in Chapter 1, were considered. The theory that formation's porosity has been reduced by cataclasis is considered unlikely as no evidence of cataclasis was observed in thin section. The low abundance of barite cement within the Science Central samples indicates that barite precipitation from brines is also not the reason behind the Fell Sandstone's low transmissivity. Barite cement may be more pervasive within the more permeable fracture zones associated with major faults however, such cementation does not appear to have precipitated within the formation as a whole. Further investigation, involving the drilling of lateral wells to intersect the Ninety Fathom Fault System, would be required to determine whether barite cementation is more pervasive closer to faults. Considerable amounts of drill mud were identified in samples from the upper part of the Fell Sandstone indicating that contamination of the borehole may have been a contributing factor. However, due to sample disaggregation quantitative estimates of drill mud abundance, obtained during point counting, were likely higher than in reality. Additionally, only small percentages of drill mud were identified within samples from the lower Fell Sandstone. Therefore, whilst the invasion of drill mud may have contributed to the Fell Sandstone's low conductivity, it is not considered to be the main contributing factor. The pervasive cementation and high clay/shale abundance, observed in the Science Central samples supports the explanation that the reservoir quality of the Fell Sandstone in this location, is inherently poorer than at outcrop. This is further supported by the results of the thin section analysis conducted on samples from the Errington borehole which revealed similarly high levels of clay/shale and authigenic cements (both quartz and calcite). This decrease in intrinsic reservoir quality has been interpreted to be due to the more distal setting of the Errington and Science Central boreholes, in relation to the paleo-river system, and the increased diagenetic alteration of the Fell Sandstone at depth at these locations.

Another principal aim was to evaluate the importance of secondary porosity development in influencing overall reservoir quality. A phase of secondary porosity development was evidenced to have occurred at Errington and Science Central however it has had little impact on reservoir quality overall.

5.2 Implications

The failure of the Science Central Borehole highlighted that there is still scope for improving our understanding of the properties, such as transmissivity, of potential deep geothermal sedimentary aquifers (Younger *et al.,* 2016). In the case of the Fell Sandstone, outcrop studies have proven that the formation is transmissive, with high intergranular porosities and open fracture networks in northern Northumberland (Bell, 1978; Younger *et al.,* 1995). Beyond the analysis conducted at Newcastle Science Central (Younger *et al*., 2016), very little academic information, regarding the deep subsurface reservoir quality of the Fell Sandstone, is available. Industry reports are available from only a limited number of onshore petroleum exploration wells in the Northumberland Trough.

This study has been the first to directly compare thin section samples from the Fell Sandstone at outcrop in northern Northumberland to samples taken from the Central Northumberland Basin and beneath Newcastle Science Central, where the formation is found at depths in excess of 1km. The findings of this study demonstrate that previous petrographic studies of the Fell Sandstone at outcrop and in northern Northumberland are not representative of the Fell Sandstone further south in the Central Northumberland Trough.

Away from the S-NF Fault System the relatively low temperature and poor reservoir quality of the Fell Sandstone discounts it as a geothermal resource capable of significant production to warrant development.

High geothermal gradients and temperatures, recorded in the Science Central and Throckley boreholes as well as in nearby collieries such as the Rising Sun and Eccles collieries (Younger *et al.,* 2016), show that there is still the potential for geothermal development if future exploration is able to target the S-NF Fault System. The successful development of the Fell sandstone as a geothermal resource is likely to rely on flow enhancement through fracture networks, such as those seen at the Thornton Borehole (Hodgson & Gardiner, 1971), particularly along larger regional faults. High flow rates have already been proven along the nearby Rising Sun Fault (1.4 million litres per day and 0.82 million litres per day recorded at the Rising Sun and Eccles collieries respectively; Younger *et al.*, 2016), indicating that such development may be possible.

In addition to deep, faulted saline aquifers, there is also the opportunity to supply heat from shallow abandoned coal mines. The majority of the of northeast England's population of 2.6 million (Gluyas *et al*., 2020), occupies areas once mined for coal. Work done by Gluyas *et al.,* (2020) states that with around 266 abandoned mines in Northumberland and County Durham there is the potential to meet a large portion of the areas heat demand (13,600 kWh per annum for each household). There is potential for both the Fell Sandstone, intersected by the Ninety Fathom Fault, and Northumberland and County Durham's abandoned coal mines to be developed as sources of low geothermal heat. The decarbonisation of heating in Northumberland and Durham counties would reduce carbon emissions by 2.5 million tonnes (BEIS, 2019; Gluyas *et al*., 2020).

Chapter 6: Conclusions

Formation net to gross decreases to the south and west as the Fell Sandstone transitions from an amalgamation of braided fluvial channel deposits into a succession of paralic sandstones interbedded with non-reservoir lithologies, deposited as part of a fluvio-deltaic environment. This lateral trend of decreasing net to gross is still interpreted to be largely due to the influence of the Cheviot High laterally confining the palaeo-river system in northern Northumberland. Marine influence is shown to increase to the south and west resulting in increased compartmentalisation of the formation. Micritic muds and carbonate deposits, representing marine and fluvio-deltaic facies associations are identified as the most likely source of the widespread calcite cements observed in thin section.

Sandstone samples from the Errington and Science Central boreholes were found to be heavily cemented by pervasive authigenic calcite and quartz overgrowths. These samples were also found to contain large amounts of interstitial clay/shale when compared to sandstone samples taken from Bowden Doors. Overall, pore filling clay and cements have had a deleterious effect on the porosity and permeability of the Fell Sandstone in the Central Northumberland Trough (Northumberland Basin). It is clear that the high porosities and permeabilities recorded in previous outcrop studies (as well as those recorded as part of this studies analysis of samples from Bowden Doors) are not representative of the subsurface Fell Sandstone in the Northumberland Trough

Secondary porosity is well developed within the Fell Sandstone at Bowden Doors and Stonehaugh, evidenced by partial grain dissolution and the presence kaolinite. A phase of limited secondary porosity development has also occurred within the Fell Sandstone at Errington and Science Central however, it has had little effect on overall reservoir quality.

Secondary pore spaces are generally not connected and are often infilled with kaolinite or later cements.

Only small amounts of Barite were identified in samples from Science Central and it is concluded that its precipitation has not significantly affected reservoir quality the formation beneath Newcastle. Varying amounts of drill mud were present within the samples from Science Central. The invasion of drill mud may have contributed to the poor transmissivity calculated by Younger *et al.* (2016), however, this is considered secondary to the inherently poor reservoir quality of the Fell Sandstone penetrated by the Science Central Borehole.

Whilst the Fell Sandstone beneath Newcastle is host to high temperatures, the results of this study's log and thin section analysis have shown that the Fell Sandstone is ineffective at facilitating substantial fluid flow without the aid of open fracture networks. Calculated porosity readings were considerably lower than values quoted from other sandstone formations in prominent UK sedimentary basins. Significant fluid flow trough fracture networks associated with the Ninety-Fathom Fault still remains as a possible avenue of exploration.

6.1 Future work

Echoing the conclusions of Younger *et al.* (2016), damage zones associated with the Ninety Fathom Fault remain as an avenue for further exploration. Future explorations of the Fell Sandstone should focus on the geothermal appraisal of faults such as the Ninety Fathom Fault where high flow rates could still be found. If flooded mines, fractured deep saline aquifers, such as the Fell Sandstone, and the fractured Weardale Granite can be successfully developed as geothermal resources, it will be possible to completely decarbonise heating in the

Northumberland and Durham Counties (Gluyas *et al.,* 2020), bringing the UK a step closer to net zero emissions.

References:

Aigner, T., Schauer, M., Junghans, W. D., & Reinhardt, L. (1995). Outcrop gamma-ray logging and its applications: examples from the German Triassic. *Sedimentary Geology*, *100*(1–4), 47–61. https://doi.org/10.1016/0037-0738(95)00102-6

Ajdukiewicz, J. M., & Lander, R. H. (2010). Sandstone reservoir quality prediction: The state of the art. *American Association of Petroleum Geologists Bulletin*, *94*(8), 1083–1091. https://doi.org/10.1306/intro060110

Allen, D. J., Brewerton, L. J., Coleby, L. M., Gibbs, B. R., Lewis, M. A., MacDonald, A. M., Wagstaff, S. J., & Williams, A. T. (1997). The physical properties of major aquifers in England and Wales. *British Geological Survey*, *Technical*, 312. http://nora.nerc.ac.uk/13137/

Ambrose, K., Hough, E., Smith, N. J. P., & Warrington, G. (2014). Lithostratigraphy of the Sherwood Sandstone Group of England, Wales and south-west Scotland. *British Geological Survey Research Report RR/14/01, 50*.

Anjos, S. M. C., De Ros, L. F., & Silva, C. M. A. (2003). Chlorite Authigenesis and Porosity Preservation in the Upper Cretaceous Marine Sandstones of the Santos Basin, Offshore Eastern Brazil. In Clay Mineral Cements in Sandstones (pp. 289–316). *Blackwell Publishing Ltd*. https://doi.org/10.1002/9781444304336.ch13

Archie, G. E. (1942). The Electrical Resistivity Log as an Aid in Determining Some Reservoir Characteristics. *Transactions of the AIME*, *146*(01), 54–62. https://doi.org/10.2118/942054-G

Armstrong, H. A., & Purnell, M. A. (1993). Thermal maturation of the Lower Carboniferous strata of the Northumberland Trough and Tweed Basin from conodont colour alteration index (CAI) data. *Proceedings of the Yorkshire Geological Society*, *49*(4), 335–343. https://doi.org/10.1144/pygs.49.4.335

Armstrong, H. A., & Purnell, M. A. (1987). Dinantian conodont biostratigraphy of the Northumberland Trough. *Journal of Micropalaeontology*, *6*(2), 97–112. https://doi.org/10.1144/jm.6.2.97

Arsenikos, S., Quinn, Martyn, F., Pharaoh, T. C., Sankey, M., & Monaghan, A. (2015). *Seismic interpretation and generation of key depth structure surfaces within the Devonian and Carboniferous of the Central North Sea, Quadrants 25 – 44 area.* 66. http://nora.nerc.ac.uk/id/eprint/516758

Arsenikos, S., Quinn, M., Kimbell, G., Williamson, P., Pharaoh, T., Leslie, G., & Monaghan, A. (2018). Structural development of the Devono-Carboniferous plays of the UK North Sea. *Geological Society Special Publication*, *471*(1), 65–90. https://doi.org/10.1144/SP471.3

Barrett, B. J., Hodgson, D. M., Collier, R. E. L., & Dorrell, R. M. (2018). Novel 3D sequence stratigraphic numerical model for syn-rift basins: Analysing architectural responses to eustasy, sedimentation and tectonics. *Marine and Petroleum Geology*, 92(November 2017), 270–284. https://doi.org/10.1016/j.marpetgeo.2017.10.026

Bath, A. H., Darling, W. G., George, I. A., & Milodowski, A. E. (1987). 18O16O and 2H1H changes during progressive hydration of a Zechstein anhydrite formation. *Geochimica et Cosmochimica Acta*, *51*(12), 3113–3118. https://doi.org/10.1016/0016-7037(87)90122-0

Bell, F. G. (1978). Petrographical factors relating to porosity and permeability in the fell sandstone. *Quarterly Journal of Engineering Geology*, *11*(2), 113–126. https://doi.org/10.1144/GSL.QJEG.1978.011.02.01

Bloch, S., Lander, R. H., & Bonnell, L. (2002). Anomalously high porosity and permeability in deeply buried sandstone reservoirs: Origin and predictability. AAPG Bulletin, 86(2), 301–328. https://doi.org/10.1306/61eedabc-173e-11d7-8645000102c1865d

Booth, M. G., Underhill, J. R., Gardiner, A., & McLean, D. (2020). Sedimentary and tectonic controls on Lower Carboniferous (Visean) mixed carbonate–siliciclastic deposition in NE England and the Southern North Sea: implications for reservoir architecture. *Petroleum Geoscience*, *26*(2), 204–231. https://doi.org/10.1144/petgeo2019-101

Booth, M. G., Underhill, J. R., Gardiner, A., & McLean, D. (2020). Sedimentary and tectonic controls on Lower Carboniferous (visean) mixed carbonate-siliciclastic deposition in NE England and the Southern North Sea: Implications for reservoir architecture. *Petroleum Geoscience*, *26*(2), 204–231. https://doi.org/10.1144/petgeo2019-101

Booth, M., Underhill, J. R., Jamieson, R. J., & Brackenridge, R. (2018). *Controls on Lower Carboniferous (Dinantian) Prospectivity in the Mid North Sea High Region**. *11050*.

Brackenridge, R. E., Underhill, J. R., Jamieson, R., & Bell, A. (2020). Structural and stratigraphic evolution of the Mid North Sea High region of the UK Continental Shelf. *Petroleum Geoscience*, *26*(2), 154–173. https://doi.org/10.1144/petgeo2019-076

Bray, R. J., Green, P. F., & Duddy, I. R. (1992). Thermal history reconstruction using apatite fission track analysis and vitrinite reflectance: A case study from the UK East Midlands and Southern North

Sea. *Geological Society Special Publication*, *67*(67), 3–25. https://doi.org/10.1144/GSL.SP.1992.067.01.01

Bridge, J. S. (1993). Description and interpretation of fluvial deposits: a critical perspective. *Sedimentology*, *42*(2), 379–379. https://doi.org/10.1111/j.1365-3091.1995.tb02109.x

Busby, J. (2010). Geothermal prospects in the United Kingdom. *Proceedings of the World Geothermal Congress*, April, 25–29. http://www.geothermal-energy.org/304,iga_geothermal_conference_database.html

Busby, J. (2014). Geothermal energy in sedimentary basins in the UK. *Hydrogeology Journal*, 22(1), 129–141. https://doi.org/10.1007/s10040-013-1054-4

Chadwick, R. A., & Holliday, D. W. (1991). Deep crustal structure and carboniferous basin development within the iapetus convergence zone, northern England. *Journal of the Geological Society*, *148*(1), 41–53. https://doi.org/10.1144/gsjgs.148.1.0041

Chadwick, R. A., Holliday, D. W., Holloway, S., & Hulbert, A. G. (1993). The evolution and hydrocarbon potential of the Northumberland-Solway Basin. *Petroleum Geology Conference Proceedings*, *4*(0), 717–726. https://doi.org/10.1144/0040717

Chuhan, F. A., Kjeldstad, A., Bjørlykke, K., & Høeg, K. (2002). Porosity loss in sand by grain crushing - Experimental evidence and relevance to reservoir quality. *Marine and Petroleum Geology*, 19(1), 39–53. https://doi.org/10.1016/S0264-8172(01)00049-6

Clarke, S. M. (2007). Geology of NY74NE, NW and NY75NE, SW and SE, Alston Cumbria. *GEOLOGY AND LANDSCAPE NORTHERN BRITAIN PROGRAMME OPEN REPORT OR/07/032*. https://doi.org/http://nora.nerc.ac.uk/id/eprint/7886

COLLINSON, J. D., JONES, C. M., BLACKBOURN, G. A., BESLY, B. M., ARCHARD, G. M., & McMAHON, A. H. (1993). Carboniferous depositional systems of the Southern North Sea. *Geological Society, London, Petroleum Geology Conference Series*, *4*(1), 677–687. https://doi.org/10.1144/0040677

COREX. (2003). FINAL Petrographic study of the Fell Sandstone Section of Stonehaugh and Longhorsley 1. TECH 1646.

Davies, R. J., Almond, S., Ward, R. S., Jackson, R. B., Adams, C., Worrall, F., Herringshaw, L. G., Gluyas, J. G., & Whitehead, M. A. (2014). Oil and gas wells and their integrity: Implications for shale and unconventional resource exploitation. *Marine and Petroleum Geology*, *56*, 239–254. https://doi.org/10.1016/j.marpetgeo.2014.03.001

Davies, S. J., Guion, P. D., & Gutteridge, P. (2012). Carboniferous Sedimentation and Volcanism on the Laurussian Margin. In *Geological History of Britain and Ireland* (pp. 231–273). John Wiley & Sons, Ltd. https://doi.org/10.1002/9781118274064.ch14

Davydov, V. I., Korn, D., Schmitz, M. D., Gradstein, F. M., & Hammer, Ø. (2012). The carboniferous period. In *The Geologic Time Scale 2012*. Felix M. Gradstein, James G. Ogg, Mark Schmitz and Gabi Ogg. https://doi.org/10.1016/B978-0-444-59425-9.00023-8

Dean, M. T., Browne, M. A. E., Waters, C. N., & Powell, J. H. (2009). A lithostratigraphical framework for the Carboniferous successions of northern Great Britain (onshore). *British Geological Survey Research Report RR/09/01*, 174.

Ehrenberg, S. N., & Nadeau, P. H. (2005). Sandstone vs. carbonate petroleum reservoirs: A global perspective on porosity-depth and porosity-permeability relationships. *American Association of Petroleum Geologists Bulletin*, *89*(4), 435–445. https://doi.org/10.1306/11230404071

Elliott, T (1975). The Sedimentary history of a delta lobe from a Yoredale (Carboniferous) cyclothem. *Proceedings of the Yorkshire Geological Society, 40(4), 505-536.*

Fawad, M., Mondol, N. H., Jahren, J., & Bjørlykke, K. (2010). Seismic velocities from experimental compaction: New porosity and velocity-depth relations for sands with different textural and mineralogical composition. *Society of Exploration Geophysicists International Exposition and 80th Annual Meeting 2010*, SEG 2010, 1, 2480–2485. https://doi.org/10.1190/1.3513353

Fossen, H., Schultz, R. A., Shipton, Z. K., & Mair, K. (2007). Deformation bands in sandstone: A review. *Journal of the Geological Society*, 164(4), 755–769. https://doi.org/10.1144/0016-76492006-036

Fraser, A. J., & Gawthorpe, R. L. (1990). Tectono-stratigraphic development and hydrocarbon habitat of the Carboniferous in northern England. *Geological Society Special Publication*, *55*(55), 49–86. https://doi.org/10.1144/GSL.SP.1990.055.01.03

Frost, D. V. (1969). THE LOWER LIMESTONE GROUP (VISÉAN) OF THE OTTERBURN DISTRICT, NORTHUMBERLAND. *Proceedings of the Yorkshire Geological Society*, *37*(3), 277–309. https://doi.org/10.1144/pygs.37.3.277

Gluyas, J. G., Adams, C. A., Busby, J. P., Craig, J., Hirst, C., Manning, D. A. C., McCay, A., Narayan, N. S., Robinson, H. L., Watson, S. M., Westaway, R., & Younger, P. L. (2018). Keeping warm: a review of deep geothermal potential of the UK. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, *232*(1), 115–126. https://doi.org/10.1177/0957650917749693

Gluyas, J. G., Adams, C. A., Narayan, N. S., & Hirst, C. M. (2020). *The Geothermal Potential of the Fractured Weardale Granite and Associated Aquifers of County Durham and Adjacent Areas Northern England*.

Hannis, S. (2016). Reservoir evaluation of 3 wells in the Palaeozoic of the Orcadian Basin (UK North Sea): Petrophysical interpretations of clay volume , porosity and Energy and Marine Geoscience Programme. *British Geological Survey Commissioned Report*.

Hartley, A. J., Weissmann, G. S., Nichols, G. J., & Warwick, G. L. (2010). Large distributive fluvial systems: Characteristics, distribution, and controls on development. Journal of Sedimentary Research, 80(2), 167–183. https://doi.org/10.2110/jsr.2010.016

Highley, D. E., Lawrence, D. J. D., Cameron, D. G., Harrison, D. J., Hollowat, S., Lott, G. K., & Bloodworth, A. J. (2000). *Mineral Resource Information for Development Plans Northumberland and Tyne & Wear: Resources and Constraints*.

Hirst, C. M., Gluyas, J. G., Adams, C. A., Mathias, S. A., Bains, S., & Styles, P. (2015). UK Low Enthalpy Geothermal Resources: the Cheshire Basin. *Proceedings World Geothermal Congress 2015*, Melbourne, Australia, 19-25 April 2015 Melbourne, Australia, 19-25 April 2015, 1913(April), 9.

Hirst, C. M., Gluyas, J. G., & Mathias, S. A. (2015). The late field life of the East Midlands Petroleum Province; a new geothermal prospect? *Quarterly Journal of Engineering Geology and Hydrogeology*, *48*(2), 104–114. https://doi.org/10.1144/qjegh2014-072

Hodgson, A. V. (1978). BRAIDED RIVER BEDFORMS AND RELATED SEDIMENTARY STRUCTURES IN THE FELL SANDSTONE GROUP (LOWER CARBONIFEROUS) OF NORTH NORTHUMBERLAND. *Proceedings of the Yorkshire Geological Society*, *41*(4), 509–532. https://doi.org/10.1144/pygs.41.4.509

Hodgson, A. V., & Gardiner, M. D. (1971). An investigation of the aquifer potential of the Fell Sandstone of Northumberland. *Quarterly Journal of Engineering Geology*, *4*(2), 91–109. https://doi.org/10.1144/GSL.QJEG.1971.004.02.01

Holliday, D. W. (1993). Mesozoic cover over northern England: interpretation of apatite fission track data. *Journal of the Geological Society*, *150*(4), 657–660. https://doi.org/10.1144/gsjgs.150.4.0657

Howell, L., Besly, B., Sooriyathasan, S., Egan, S., & Leslie, G. (2020). Seismic and borehole-based mapping of the late Carboniferous succession in the Canonbie Coalfield, SW Scotland:

evidence for a ‘broken’ Variscan foreland? *Scottish Journal of Geology*, sjg2020-007. https://doi.org/10.1144/sjg2020-007

Howell, L., Brown, C. S., & Egan, S. S. (2021). Deep geothermal energy in northern England: Insights from 3D finite difference temperature modelling. *Computers and Geosciences*, *147*(May 2020), 104661. https://doi.org/10.1016/j.cageo.2020.104661

Howell, L., Egan, S., Leslie, G., & Clarke, S. (2019). Structural and geodynamic modelling of the influence of granite bodies during lithospheric extension: Application to the Carboniferous basins of northern England. *Tectonophysics*, *755*(February), 47–63. https://doi.org/10.1016/j.tecto.2019.02.008

Howell, L., Egan, S., Leslie, G., Clarke, S., Mitten, A., & Pringle, J. (2020). The influence of low-density granite bodies on extensional basins. *Geology Today*, *36*(1), 22–26. https://doi.org/10.1111/gto.12297

Howell, L., Mitten, A. J., Egan, S., Clarke, S., & Leslie, G. (2019). *The influence of local low-density basement anomalies on the distribution of fluvio-deltaic sediment in rift basins: the early Carboniferous Fell Sandstone Formation, northern England*.

Huggett, J. M., Selley, R. C., Cocks, L. R. M., Plimer, I. R. (2005). Clays and their diagenesis. *Encyclopedia of Geology 5,* Elsevier, Amsterdam (2005), pp. 61-69.

Ingrams, S., McLean, D., Booth, M., & Bodman, D. J. (2020). Biostratigraphy and paleoecology of Asbian–Brigantian (Mississippian) miospores from Berwick-upon-Tweed, Northumberland, UK: Preliminary results. *Review of Palaeobotany and Palynology*, *276*, 104206. https://doi.org/10.1016/j.revpalbo.2020.104206

Jenkins, A. P., & Torvela, T. (2020). Basin analysis using seismic interpretation as a tool to examine the extent of a basin ore ‘play.’ *Ore Geology Reviews*, 125(February), 103698. https://doi.org/10.1016/j.oregeorev.2020.103698

Johnson, G. A. L. (1984). Subsidence and sedimentation in the Northumberland Trough. In *PROCEEDINGS OF THE YORKSHIRE GEOLOGICAL SOCIETY* (Vol. 45). http://pygs.lyellcollection.org/

Jones, H. K. (2000). Book review: The Physical Properties of Minor Aquifers in England and Wales. *Environmentalist*, *22*(2), 193–194. https://doi.org/10.1023/A:1015318823868

Kearsey, T. I., Millward, D., Ellen, R., Whitbread, K., & Monaghan, A. A. (2018). Revised stratigraphic framework of pre-Westphalian Carboniferous petroleum system elements from the Outer

Moray Firth to the Silverpit Basin, North Sea, UK. *Geological Society Special Publication*, *471*(1), 91–113. https://doi.org/10.1144/SP471.11

Kimbell, G. S., & Williamson, J. P. (2015). *A gravity interpretation of the Central North Sea*. 9–10. http://nora.nerc.ac.uk/id/eprint/516759

Kristensen, L., Hjuler, M. L., Frykman, P., Olivarius, M., Weibel, R., Nielsen, L. H., & Mathiesen, A. (2016). Pre-drilling assessments of average porosity and permeability in the geothermal reservoirs of the Danish area. *Geothermal Energy*, *4*(1). https://doi.org/10.1186/s40517-016-0048-6

Leeder, M. R. (1982). Upper Palaeozoic basins of the British Isles - Caledonide inheritance versus Hercynian plate margin processes. *Journal of the Geological Society*, *139*(4), 479–491. https://doi.org/10.1144/gsjgs.139.4.0479

Lesley, C. A. (1995). *The origin of massive sandstone facies in an ancient braided river deposits*. https://doi.org/http://etheses.dur.ac.uk

Leslie, A. G., Millward, D., Pharaoh, T. C., Monaghan, A., Arsenikos, S., & Quinn, Martyn, F. (2015). *Tectonic synthesis and contextual setting for the Central North Sea and adjacent onshore areas, 21CXRM Palaeozoic Project*. 1–30. http://nora.nerc.ac.uk/id/eprint/516757

Markou, A. (2013). *System Dynamics study of the Fell Sandstone aquifer*. *August*, 1–100.

Martin, C. A. L., & Turner, B. R. (1998). Origins of massive-type sandstones in braided river systems. In *Earth-Science Reviews* (Vol. 44).

Martin, C. A. L. (1995). *The origin of massive sandstone facies in an ancient braided river deposits*. http://etheses.dur.ac.uk

McKerrow, W. S., Mac Niocaill, C., & Dewey, J. F. (2000). The Caledonian Orogeny redefined. *Journal of the Geological Society*, *157*(6), 1149–1154. https://doi.org/10.1144/jgs.157.6.1149

Monaghan, A., Arsenikos, S., Callaghan, E., Ellen, R., Gent, C., Hannis, S., Henderson, A., Leslie, A. G., Johnson, K., Kassyk, M., Kearsey, T., Kim, A., Kimbell, G., Quinn, M., McLean, W., Millward, D., Pharaoh, T. C., Sankey, M., Smith, N., … Williamson, J. P. (2015). *Palaeozoic Petroleum Systems of the Central North Sea/Mid North Sea High*. https://doi.org/http://nora.nerc.ac.uk/id/eprint/516766

Monaghan, A. A., Arsenikos, S., Quinn, M. F., Johnson, K. R., Vincent, C. J., Vane, C. H., Kim, A. W., Uguna, C. N., Hannis, S. D., Gent, C. M. A., Millward, D., Kearsey, T. I., & Williamson, J. P. (2017).

Carboniferous petroleum systems around the Mid North Sea High, UK. *Marine and Petroleum Geology*, *88*, 282–302. https://doi.org/10.1016/j.marpetgeo.2017.08.019

Monro, M. (1986). *Sedimentology of the Carboniferous Fell sandstone group of Northumberland*. Newcastle University.

Myers, K. J., & Bristow, C. S. (1989). Detailed sedimentology and gamma-ray log characteristics of a Namurian deltaic succession II: Gamma-ray logging. *Geological Society Special Publication*, *41*(41), 81–88. https://doi.org/10.1144/GSL.SP.1989.041.01.07

Nance, R. D., Gutiérrez-Alonso, G., Keppie, J. D., Linnemann, U., Murphy, J. B., Quesada, C., Strachan, R. A., & Woodcock, N. H. (2010). Evolution of the Rheic Ocean. *Gondwana Research*, *17*(2–3), 194–222. https://doi.org/10.1016/j.gr.2009.08.001

Narayan, N. S., Adams, C. A., & Gluyas, J. G. (2021). Karstified and fractured Lower Carboniferous (Mississippian) limestones of the UK – A cryptic geothermal reservoir. *Zeitschrift Der Deutschen Gesellschaft Für Geowissenschaften, July*. https://doi.org/10.1127/zdgg/2021/0288

Nemec, W., & Postma. G. (1993). Quaternary alluvial fans in southwestern Crete: sedimentation processes and geomorphic evolution. *Alluvial Sedimentation*, 17, 235-276.

Qu, L. (2016). Investigating the relationship between salinity and specific heat capacity. Investigating the Relationship between Salinity and Specific Heat Capacity, 1–2.

Reynolds, A. D. (1999). Dimensions of paralic sandstone bodies. AAPG Bulletin, 83(2), 211–229.

Ridd, M. F., Walker, D. B., & Jones, J. M. (1970). A DEEP BOREHOLE AT HARTON ON THE MARGIN OF THE NORTHUMBRIAN TROUGH. In *PROCEEDINGS OF THE YORKSHIRE GEOLOGICAL SOCIETY* (Vol. 38, Issue 4). http://pygs.lyellcollection.org/

Rider, M. H. (1990). Gamma-ray log shape used as a facies indicator: Critical analysis of an oversimplified methodology. *Geological Society Special Publication*, *48*(48), 27–37. https://doi.org/10.1144/GSL.SP.1990.048.01.04

Robson, D. A. (1956). A sedimentary study of the Fell Sandstones of the Coquet Valley, Northumberland. *Quarterly Journal of the Geological Society*, *112*(1–4), 241–262. https://doi.org/10.1144/GSL.JGS.1956.112.01-04.12

ROC. (2005). Errington 1 Well Results & Formation Evaluation. TECH 2139. *Available through Oil and Gas Authority release agents*

ROC. (2002). Long Horsley 1 Fell Sandstone Log Analysis. TECH 1620. *Available through Oil and Gas Authority release agents*

Rollin, K. E., Kirby, G. A., & Rowley, W. J. (1995). Atlas of geothermal resources in Europe: UK revision. British Geological Survey, Regional Geophysics Group.

Schmidt, V., & Macdonald, D. A. (1979) The role of secondary porosity in the course of sandstone diagenesis. In *Aspects of Diagenesis.* The Society of Economic Paleontologists and Mineralogists Special Publication, 26, 175-207.

Smith, S. A., & Holliday, D. W. (1991). The sedimentology of the Middle and Upper Border groups (Visean) in the Stonehaugh Borehole, Northumberland. In *PROCEEDINGS OF THE YORKSHIRE GEOLOGICAL SOCIETY* (Vol. 48). http://pygs.lyellcollection.org/

Soltan, R., & Mountney, N. P. (2016). Interpreting complex fluvial channel and barform architecture: Carboniferous Central Pennine Province, northern England. *Sedimentology*, *63*(1), 207–252. https://doi.org/10.1111/sed.12224

Soper, N. J., Strachan, R. A., Holdsworth, R. E., Gayer, R. A., & Greilung, R. O. (1992). Sinistral transpression and the Silurian closure of Iapetus. *Journal - Geological Society (London)*, *149*(6), 871–880. https://doi.org/10.1144/gsjgs.149.6.0871

Southern, S. J., Mountney, N. P., & Pringle, J. K. (2014). The Carboniferous Southern Pennine Basin, UK. *Geology Today*, *30*(2), 71–78. https://doi.org/10.1111/gto.12044

Taylor, T. R., Giles, M. R., Hathon, L. A., Diggs, T. N., Braunsdorf, N. R., Birbiglia, G. V., Kittridge, M. G., MacAulay, C. I., & Espejo, I. S. (2010). Sandstone diagenesis and reservoir quality prediction: Models, myths, and reality. *American Association of Petroleum Geologists Bulletin*, *94*(8), 1093–1132. https://doi.org/10.1306/04211009123

Taylor, T. R., Giles, M. R., Hathon, L. A., Diggs, T. N., Braunsdorf, N. R., Birbiglia, G. V., Kittridge, M. G., MacAulay, C. I., & Espejo, I. S. (2010). Sandstone diagenesis and reservoir quality prediction: Models, myths, and reality. *American Association of Petroleum Geologists Bulletin*, *94*(8), 1093–1132. https://doi.org/10.1306/04211009123

Terrington, R., & Thorpe, S. (2013). Metadata report for the Northumberland and Solway Basin 1: 250 000 geological model. *British Geological Survey Open Report OR/13/049*, 20. https://doi.org/http://nora.nerc.ac.uk/id/eprint/507069

Turner, B. R., Younger, P. L., & Fordham, C. E. (1993). Fell Sandstone Group lithostratigraphy south-west of Berwick-upon-Tweed: Implications for the regional development of the Fell

Sandstone. *Proceedings of the Yorkshire Geological Society*, *49*(4), 269–281. https://doi.org/10.1144/pygs.49.4.269

Turner, B. R., Dewey, C., & Fordham, C. E. (1997). Marine ostracods in the Lower Carboniferous fluviatile Fell Sandstone Group: evidence for base level change and marine flooding of the central graben, Northumberland Basin. In *PROCEEDINGS OF THE YORKSHIRE GEOLOGICAL SOCIETY* (Vol. 51). http://pygs.lyellcollection.org/

TURNER, B. R., & MONRO, M. (1987). Channel formation and migration by mass-flow processes in the Lower Carboniferous fluviatile Fell Sandstone Group, northeast England. *Sedimentology*, *34*(6), 1107–1122. https://doi.org/10.1111/j.1365-3091.1987.tb00595.x

Turner, B. R., & Tester, G. N. (2006). The Table Rocks Sandstone: A fluvial, friction-dominated lobate mouth bar sandbody in the Westphalian B Coal Measures, NE England. *Sedimentary Geology*, *190*(1–4), 97–119. https://doi.org/10.1016/j.sedgeo.2006.05.007

Tzortzis, M., Tsertos, H., Christofides, S., & Christodoulides, G. (2003). Gamma-ray measurements of naturally occurring radioactive samples from Cyprus characteristic geological rocks. *Radiation Measurements*, 37(3), 221–229. https://doi.org/10.1016/S1350-4487(03)00028-3

Uba, C. E., Hasler, C. A., Buatois, L. A., Schmitt, A. K., & Plessen, B. (2009). Isotopic, paleontologic, and ichnologic evidence for late Miocene pulses of marine incursions in the central Andes. *Geology,* 37(9), 827–830. https://doi.org/10.1130/G30014A.1

Vincent, C. J. (2015). *Maturity modelling of selected wells in the Central North Sea*. 193. https://doi.org/http://nora.nerc.ac.uk/id/eprint/516764

Waters, C., Browne, M. A. E., Dean, M. T., & Powell, J. H. (2007). *Lithostratigraphical framework for Carboniferous successions of Great Britain (Onshore)*.

Waters, C. N., Dean, M. T., Jones, N. S., & Somerville, I. D. (2012). Northumberland Trough and Solway Basin. In *Northumberland Trough & Solway Firth text* (Issue 2007).

Waters, C., Millward, D., Thomas, C., (2014). The Millstone Grit Group (Pennsylvanian) of the Northumberland-Solway Basin and Alstone Block of northern England. *Proceedings of the Yorkshire Geological Society*, 60(1), 29-51.

Waters, C. N., Dean, M. T., Jones, N. S., & Somerville, I. D. (2018). Northumberland Trough and Solway Basin. In *A Revised Correlation of Carboniferous Rocks in the British Isles* (Issue 2007, pp. 89–95). https://doi.org/10.1144/sr26.13

Whitbread, K., & Kearsey, T. (2016). Devonian and Carboniferous stratigraphical correlation and interpretation in the Orcadian area, Central North Sea, Quadrants 7-22. *British Geological Survey Comissioned Report*, *CR/16/032*, 74.

Worden, R. H., Armitage, P. J., Butcher, A. R., Churchill, J. M., Csoma, A. E., Hollis, C., Lander, R. H., & Omma, J. E. (2018). Petroleum reservoir quality prediction: Overview and contrasting approaches from sandstone and carbonate communities. *Geological Society Special Publication*, *435*(1), 1–31. https://doi.org/10.1144/SP435.21

Worden, R. H., & Burley, S. D. (2009). Sandstone Diagenesis: The Evolution of Sand to Stone. In *Sandstone Diagenesis*. https://doi.org/10.1002/9781444304459.ch

Wright, V. P., & Vanstone, S. D. (2001). Onset of late Palaeozoic glacio-eustasy and the evolving climates of low latitude areas: A synthesis of current understanding. *Journal of the Geological Society*, *158*(4), 579–582. https://doi.org/10.1144/jgs.158.4.579

Wüstefeld, P., Hilse, U., Koehrer, B., Adelmann, D., & Hilgers, C. (2017). Critical evaluation of an Upper Carboniferous tight gas sandstone reservoir analog: Diagenesis and petrophysical aspects. *Marine and Petroleum Geology*, *86*, 689–710. https://doi.org/10.1016/j.marpetgeo.2017.05.034

Younger, P. L. (1992). The hydrogeological use of thin sections: inexpensive estimates of groundwater flow and transport parameters. *Quarterly Journal of Engineering Geology*, *25*(2), 159–164. https://doi.org/10.1144/gsl.qjeg.1992.025.02.09

Younger, P. L. (2010). *Putting Deep Geothermal Resources at the Heart of City Centre Regeneration Newcastle Science City and the Ninety Fathom Fault: Submission to the Deep Geothermal Challenge Fund of the Department of Energy and Climate Change*. *October*.

Younger, P. L., & Manning, D. A. C. (2010). Hyper-permeable granite: Lessons from test-pumping in the Eastgate Geothermal Borehole, Weardale, UK. *Quarterly Journal of Engineering Geology and Hydrogeology*, *43*(1), 5–10. https://doi.org/10.1144/1470-9236/08-085

Younger, P. L., Gluyas, J. G., & Stephens, W. E. (2012). Development of deep geothermal energy resources in the UK. *Proceedings of the Institution of Civil Engineers - Energy*, *165*(1), 19–32. https://doi.org/10.1680/ener.11.00009

Younger, P. L. (2014). Hydrogeological challenges in a low-carbon economy. *Quarterly Journal of Engineering Geology and Hydrogeology*, *47*(1), 7–28. https://doi.org/10.1144/qjegh2013-063

Younger, P. L., Manning, D. A. C., Millward, D., Busby, J. P., Jones, C. R. C., & Gluyas, J. G. (2016). Geothermal exploration in the Fell Sandstone Formation (Mississippian) beneath the city centre of Newcastle upon Tyne, UK: The Newcastle Science Central Deep Geothermal Borehole. *Quarterly Journal of Engineering Geology and Hydrogeology*, *49*(4), 350–363. https://doi.org/10.1144/qjegh2016-053

Zhang, Y., Pe-Piper, G., & Piper, D. J. W. (2015). How sandstone porosity and permeability vary with diagenetic minerals in the Scotian Basin, offshore eastern Canada: Implications for reservoir quality. *Marine and Petroleum Geology*, *63*, 28–45. https://doi.org/10.1016/j.marpetgeo.2015.02.007