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The climatic, eustatic and tectonic controls on the Mid Carboniferous (Viséan and Namurian) strata of Northumbria, England

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A thesis submitted in partial fulfilment of the degree of Doctor of Philosophy
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No part of this thesis has been previously submitted for a degree in this or any other University. The work described in this thesis is entirely that of the author, except where reference is made to previous published or unpublished work.

Abstract

The Mid Carboniferous (Viséan and Namurian) Yoredale cycles of Northumbria were deposited as a result of glacio-eustatic fluctuations, arising from waxing and waning of Gondwanan ice sheets in the southern hemisphere. Each cycle contains a variety of lithofacies, generally comprising carbonate platform lithofacies deposited during the transgressive systems tract, followed by deltaic or marine shoreline lithofacies, deposited during the highstand, lowstand and falling stage systems tract. There may or may not be a transgressive shoreline lithofacies present at the top of each cycle.

Although there is a general pattern to the composition of each Yoredale cycle, carbonate platform lithofacies are more dominant in the south of the area due to a close proximity to the main marine source to the south-west. Likewise, deltaic and marine shoreline lithofacies are more common in the north of the area due to a close proximity to the main sedimentary source to the north-east.

The duration of each cycle has been calculated as approximately 200,000 years resulting in their classification as fourth-order cycles. Within each Yoredale cycle, the components of a sea-level curve have been identified indicating their formation was directly influenced by fluctuations in relative sea-level. By using Fischer plots, third-order cycles have also been identified and it is inferred that composite eustasy was in operation, resulting from Gondwanan glaciation.

Evidence for climate change is abundant throughout the Mid Carboniferous. By using palaeosoils and lithological evidence for climate change has been recognised. A major arid phase at the Asbian / Brigantian boundary has been identified by the presence of calcretes, red fluvial sediments, a decrease both the amount of coal the amount of fine siliciclastic material within each cycle. This change in climate can be correlated with other areas of similar palaeolatitude indicating that this change was global.

Stable isotope analysis reveals little or no information regarding Mid Carboniferous palaeoclimate and / or palaeoceanography. It has been possible to identify major post-depositional influences on the Mid Carboniferous strata of Northumbria. Both the Weardale Granite and the Whin Sill Complex appear to have generated large amounts of hydrothermal fluids, both during their emplacement and in the case of the Weardale Granite, after emplacement. This has led to the obliteration of the original isotopic composition of the marine limestones.

Tectonic activity associated with the Variscan orogeny began in the Late Devonian, but was still active in Northumbria during the Viséan. The resulting extensional tectonics had a profound affect on sedimentation. During the Viséan, active extension was still ongoing, with the syn-rift phase lasting until the end of the Asbian period. The result of this was a series of E-W trending sedimentary basins with wedge-shaped geometry of sediments. The intervening blocks subsided at a slower rate due to underlying buoyant granite masses compared to the Caledonian basement rock of the basinal areas. Differential subsidence ended in the Namurian and the post rift-phase gradually took over from the start of the Brigantian period onwards. This resulted in uniform deposition, with localised intrabasinal faulting.

The initial objectives for this thesis were to assess not only the effects of climate, eustasy and tectonics on the Mid Carboniferous strata of Northumbria, but also to look at the clastic and carbonate interactions within the classic Yoredale cycles. The vast amount of previously unpublished information that has been obtained from the rocks especially with regards to climate change has meant that the clastic-carbonate interaction study was abandoned. In an area that has been studied for over two centuries due to it mineral wealth it is perhaps surprising to find that there is still much work to be gleaned from such a classic area of British geology.

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Chapter One

1. INTRODUCTION 1

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Chapter 1 – Introduction

1.1 Aims of study

The Viséan and Namurian strata of Northumbria were deposited as rhythmic depositional cycles of mixed siliciclastic and carbonate content commonly referred to as Yoredale cyles. This was a time of major global change from greenhouse to ice house conditions and therefore provides the opportunity to assess the influence of global change on equatorial tropics through the sedimentary record. The proposed causal mechanisms for such a global change vary from changing continental configuration to climate change in association with global changes in CO_2. The cyclic nature of the Northumbrian strata therefore provides the perfect medium to evaluate the role of tectonic, eustatic and climate change on the development of Yoredale cycles, and to provide an insight into the mechanisms and timescales of sedimentary cyclicity in mixed carbonate siliciclastic successions.

Northumbria played a significant part in the Industrial Revolution of the 19th Century due to the large coal reserves present within the Carboniferous strata of the region. This led to a long history of geological research in the area, with work extending as far back as the late 18th Century. In combination with the Carboniferous-hosted mineral-rich veins of the North Pennine Orefield, this has resulted in a prolific history of geological industrial activity in Northumbria. Although the majority of industrial activity has now ceased, many of the quarries and mines that were once active are still accessible or at the very least have valuable literature available on the subsurface of Northumbria.

Despite the wealth of geological research that has been carried out on Northumbria, this has declined in recent years and many recent advances in the world of geological science not been applied to the region. Any studies that have been carried out are generally local studies and do not take the whole of the region into consideration.

Therefore the aims of this study are to:

i) present a comprehensive sedimentological study of the carbonate platform, deltaic and marine shoreline sediments and to present a lithofacies scheme for the whole region.

ii) use sequence stratigraphical analysis to characterise the components of each depositional cycle.

iii) propose a time-scale for each depositional cycle and to identify any further cyclic influences on the strata.

iv) present a detailed pedological study of the palaeosoils present within the strata and to produce a composite palaeosoil classification scheme for the region.

v) identify the evidence for Mid Carboniferous climate change from within the succession.

vi) make a detailed geochemical study of the carbonate platform limestones and compare this with other areas of similar palaeolatitude.

vii) present an overview of the effects that extensional tectonic activity had upon sedimentation throughout the study period.

1.2 Techniques Used

Choice of localities and borehole information

The fieldwork for this study was carried out between October 2000 and June 2003. The close proximity between the field area and the University of Durham meant that fieldwork could be carried out as and when required. The outbreak of the foot-and-mouth epidemic in the early part of 2001 however, meant that the field area was essentially out of bounds for approximately 6 months. Initial help in October 2000 was provided by Maurice Tucker, and again in December 2000 by Brian Turner, when they provided an introduction to the stratigraphy of the Mid Carboniferous of Northumbria and suggested some potential outcrops to study. Any further information about suitable outcrops was derived from the available literature and geological maps.

The choice of locality was determined by the presence of complete depositional cycles. This was necessary in order to correlate depositional cycles between localities. The most complete exposures occur along the Northumberland coastline where the succession is more continuous than further inland. Good continuous successions can also be found along river sections which have also been used in this study. A list of localities used can be seen in Table 1-1.

Outcrop Name	Grid Reference	Chapter/s
Barrasford Quarry	NY 924721	3
Beadnell Coastal Section	Southern limit - headland at Little Rock (NU 240286). Northern limit - Annshead Rocks (NU 230305)	3, 4, 5, 6, 7, 8
Bowlees Beck	NY 906285	3, 4, 5, 6, 7, 8
Brunton Bank Quarry	NY 930698	3
Harthorpe Quarry	NY 866338	3
Haltwhistle Burn	NY 706640	3. 4, 5, 6, 7, 8
Heights Quarry	NY 925390	7
Howick Coastal Section	Southern limit – Longhoughton Steel (NU 272153). Northern limit – Cullernose Point (NU260187).	3, 4, 5, 6, 7, 8
Shaftoe Crags	NZ 051819	8
Spittal / Scremerston Coastal Section	Southern limit – Cheswick Black Rocks (NU 036476). Northern limit – Huds Head (NU 014507)	3, 4, 5, 6, 7, 8
Tipalt Burn	NY 837659	3
Wild Boar Scar	NY 680 325	7

Table 1-1 List of localities including grid references and the main chapters in which they are used

The British Geological Survey (BGS) provided a large amount of borehole data from the study area. All of the information available was studied and those boreholes that presented identifiable depositional cycles were used within this study. A complete list of the boreholes used within this study is presented in Appendix 1.

Sedimentary logging techniques

Field sedimentary logging was carried out on a scale of 1:25. General sedimentary logs included detailed descriptions on bed thickness, lithology, colour, grain-size, degree of sorting, sedimentary structures and fossil content. Appendix 2 presents the detailed sedimentary logs for the study area. Field photographs and field sketches were taken to accompany sedimentary logs. Sandstone samples were collected for provenance analysis and limestone samples were collected for geochemical analysis.

Thin-section descriptions

166 siliciclastic thin sections were studied for this thesis. Thin-sections were looked at in order to assess the detrital grain composition and the possible affects of climate change on sandstone composition. The information obtained from the analysis of these thin-sections is presented in Appendix 3.

Lithofacies approach

There have been many papers produced on the lithofacies of the Mid Carboniferous of Northumbria. Most of these papers however, concentrate solely on either carbonate lithofacies or siliciclastic lithofacies and it is difficult to envisage the complete palaeoenvironment. A comprehensive lithofacies scheme encompassing both the carbonate and siliciclastic lithofacies has been presented. The lithofacies scheme and the depositional model were derived from field observations and thin-sections and are discussed in Chapter 3.

Cycle Analysis

Cycle analysis could only be carried out once all the field observation data and all available borehole data for the area had been collated. Thickness data for all of the cycles used within this study are listed in Appendix 4. Cyclicity was identified by the presence of a marine limestone that could be found directly overlying siliciclastic sediments usually of deltaic or marine shoreline origin, thus marking the beginning of a new cycle. Using the scheme proposed by Coe *et al.* (2003), the sequence stratigraphic components were identified within each cycle. Fischer plots were then constructed to aid in the identification of any trends in cycle thickness.

Palaeosoil Analysis

Palaeosoil analysis was carried out independently of sedimentary logging. Palaeosoil analysis charts were constructed (Appendix 5) to help with the identification of key pedogenic features such as organic activity, relict bedding and coloration. The information gleaned was then compared to classification schemes used by other authors such as Duchaufour (1998) and Retallack (2001), and a comprehensive palaeosoil classification scheme was produced for the study area.

Lithological evidence for climate change

Various methods were used to compile the data to use as evidence for climate change; general colour of the siliciclastic sediments which was obtained from general field observations, the amount of coal within each depositional cycle and the amount of fine versus coarse siliciclastic sediment which were obtained from sedimentary logging data and from borehole data.

Stable Isotope Analysis

Oxygen and carbon stable isotopes were analysed from the carbonate platform lithofacies (limestones) from the study area to identify climatic and oceanographic events (oxygen) and to assess levels of productivity (carbon). Samples were collected from the study area in September and October 2003, and stable isotope analysis was carried out at the Natural Environment Research Council (NERC) Isotope Geochemistry Laboratory in November 2003. $\delta^{18}O$ and $\delta^{13}C$ values were collected and plotted as a chemostratigraphic column. These values were compared with values obtained from other Mid Carboniferous regions of similar palaeolatitude. All of the stable isotope results are shown in Appendix 6.

Tectonic Analysis

Sedimentary logging and borehole information was used to construct a complete stratigraphic succession for various parts of the study area. Thickness variations in addition to lithofacies variations were studied to assess the level of tectonic activity. Field observations of post-depositional sedimentary structures such as convoluted bedding, in addition to channel location and orientation were used to identify localised tectonic events.

1.3 Terminology

Several key terms have been used throughout this thesis and it is therefore imperative to clarify the nomenclature used in the subsequent Chapters.

Mid Carboniferous This thesis uses the term Mid Carboniferous to represent the Asbian (Viséan) to Pendleian (Namurian) periods inclusive.

Northumbria The term Northumbria is no longer used in English geographic nomenclature. '*Northumbria*' refers to the ancient Kingdom of Northumbria which encompasses the area presently occupied by counties Northumberland, Tyne & Wear and Durham (Hawkes & Mills 1991). It is this area that is covered by this thesis.

Study area The study area is synonymous with the term '*Northumbria*'.

Depositional cycle A depositional cycle can be defined as '*a sequence of sediments which change their character progressively from one extreme type to another followed by a return to the original type*' (Whitten & Brooks 1972).

Yoredale cycle A Yoredale cycle can be defined as '*a marine limestone, marine shale, unfossiliferous shale, sandy shale / shaly sandstone / 'grey beds' (interbedded shales, siltstone and sandstone), sandstone, ganister or underclay, and then coal*' (Dunham 1950). The average thickness of each Yoredale cycle is approximately 30m.

Cycle The term *cycle* has been used in preference to the term *cyclothem*. There are a number of reasons for this, the first being that the term cyclothems is associated with the classic Upper Carboniferous depositional cycles and the cycles seen within this study are vary from those found solely within the Upper Carboniferous. Secondly, by using then term cycle, reference is made to the process used to deposit such a package of rock as opposed to referring solely to the sediments within.

1.4 Outline of thesis

Chapter one: Brief introduction to the thesis, aims of the study, methodology and explanation of some of the terminology used within.

Chapter two: Brief introduction to the Carboniferous world. Global palaeogeography, plate tectonic setting, Gondwanan glaciation and associated climate changes, and the biostratigraphic, dating and lithostratigraphic terms for the Mid Carboniferous.

Chapter three: Description and interpretation of the lithofacies identified in the study area.

Chapter four: Sequence stratigraphic analysis of the study area, calculation of cycle duration, and analysis and interpretation of cycle thickness. Discussion of the relative sea-level fluctuations in the Mid Carboniferous, and possible causes of cyclicity within the study area.

Chapter five: Description and interpretation of palaeosoil facies identified within the study area. A palaeosoil classification scheme has been proposed. Discussion of palaeoclimate information revealed by palaeosoil analysis.

Chapter six: Lithological evidence for climate change. The colour of siliciclastic sediments, the amount of coal within each depositional cycle and the amount of fine versus coarse siliciclastic sediments are presented and interpreted. Evidence is combined with climate data from palaeosoil interpretation, and from palaeoclimate from elsewhere in the British Isles Mid Carboniferous and further afield.

Chapter seven: Stable isotope geochemistry of marine limestones. $\delta^{18}O$ and $\delta^{13}C$ values are plotted from whole rock limestones and brachiopod samples. Comparison is made with other Mid Carboniferous analysis. Discussion of isotopic values of limestones and brachiopods from the study area.

Chapter eight: A summary of the affects that tectonic activity had upon sedimentation. An overview of the variations in succession thickness and lithofacies encountered. Localised tectonic activity is summarised by investigating the occurrence of post-depositional sedimentary structures and fault-controlled fluvial channels.

Chapter nine: Brief discussion and summary of conclusions.

Appendix one: List and location of all boreholes referred to within this thesis.

Appendix two: Detailed sedimentary logs. Logs are drawn on a 1:50 scale.

Appendix three: Tabulation of sandstone thin-section compositional analysis.

Appendix four: Tabulation of cycle-thickness data.

Appendix five: Palaeosoil identification criteria.

Appendix six: Tabulation of stable isotope geochemical values.

Chapter Two

2. THE CARBONIFEROUS SETTING: TECTONISM, PALAEOGEOGRAPHY, CLIMATE AND STRATIGRAPHY 8

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Chapter 2 – The Carboniferous Setting: Tectonism, Palaeogeography, Climate and Stratigraphy

2.1 Introduction

The aim of this chapter is to outline the global and regional context in which sedimentation occurred in Northumbria during the Carboniferous period. During the Lower to Mid Carboniferous sedimentation, as in many other areas, was often strongly 'cyclic' in nature as mentioned in Section 1.1. Tectonics, sediment supply and eustasy are all variously inferred to have influenced cyclic sedimentation and published data on each of these factors is summarised in turn. The global plate tectonic setting is reviewed (Section 2.2), prior to evaluating the tectonic framework of NW Europe (Section 2.3) and then Northern England (Section 2.4). The palaeogeography of Northern England is reviewed in Section 2.5, which is followed by an evaluation of the palaeoclimatic evolution of the Late Palaeozoic (Section 2.7) and the contributing factors to climate change during this time including continental configuration (Section 2.8) and Late Palaeozoic glaciation (Section 2.9). In the final section of this chapter (Section 2.11), the biostratigraphy and lithostratigraphy of Western Europe and in Northern England are introduced.

2.2 Carboniferous global plate tectonic configuration

The Carboniferous was a time of major plate tectonic activity due to the amalgamation of the two major continental areas, Laurasia and Gondwana, resulting in the formation of the supercontinent Pangaea. During the Carboniferous, Britain comprised part of the southern part of the Laurasian continent and was situated to the north of the resulting area of plate tectonic convergence (Figure 2-1). The tectonic evolution of Britain during the Carboniferous was strongly influenced by orogenic activity centred on the collision zone.

It is inferred that the formation of Pangaea was not due to a single collisional event, but rather to a series of amalgamation phases during the Palaeozoic. During the Lower Palaeozoic, Laurasia and Gondwana were separated by the Rheic Ocean which was closed by the Mid Devonian due to the northward motion of the Armorican terrane away from Gondwana (Leeder 1988). Such an event heralded the onset of the Hercynian orogenic cycle which was to continue from the Devonian until the early

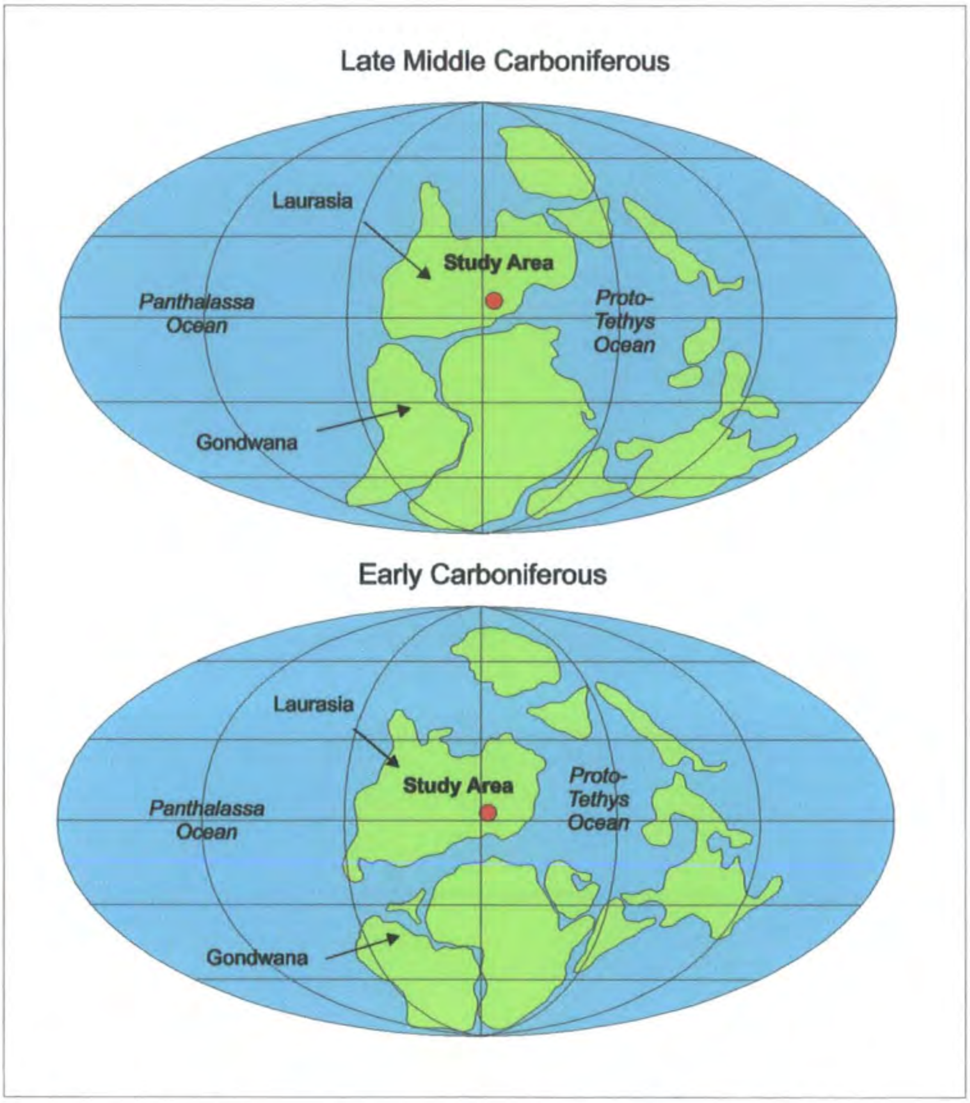

Figure 2-1 Palaeogeographic reconstruction of continental configuration during the Carboniferous. After, Grossman (1994).

Permian and led to the formation of the Variscan fold belt of Europe during the Late Viséan to Late Westphalian (e.g. Ziegler 1982). A further ocean, the Proto-Tethys existed between Laurasia and Gondwana during the Devonian and Carboniferous (Figure 2-1), thought to have been some 20° to 30° latitude in width (Leeder 1988). Progressive closure of this ocean led to the evolution of the Hercynides resulting in a collision orogenic belt of Himalayan proportions (Leeder 1988). Devonian evolution of the southern margin of Laurasia was dominated by the development of an arc trench system as a result of northwards subduction of the Proto-Tethys Ocean, which led to the development of an extensive back-arc rift system in western and central Europe, which remained active until the Late Viséan (Ziegler 1982).

2.3 Regional Tectonic Framework of NW Europe

The main tectonic events of Carboniferous north-west Europe were initiated by the formation of the Hercynides collision-type orogenic belt, well-developed in the Iberian-Armorican-Massif Central region (Leeder 1987). The formation of back-arc basins, or basins that were located on the overriding plate behind the island arc at a subduction zone, resulted in crustal extension of the northern foreland in the Late Devonian and was a consequence of northwards subduction of the Proto-Tethys Ocean leading to north-south tension (Haszeldine 1989). The resulting stretching and thinning of the lithosphere led to subsequent extensional basin formation (Figure 2-2) such as the basins of Northern England (Bott 1984).

2.4 Lower Carboniferous extensional province of Northern Britain

Carboniferous subsidence in Northern England is attributed to the stretching and thinning of the lithosphere in response to subduction to the south (Bott 1984). In northern England the extensional province is found some 500km north of the main Rheno-Hercynian back-arc and is somewhat younger than the extensional province to the south due to the northwards migration of extension (Fraser & Gawthorpe 1990). The Carboniferous lithosphere north of Northern Britain was subject to stretching processes from Late Devonian times onwards causing regional tension and rifting in areas of less buoyant crust (Leeder 1982). The Late Devonian onset of rifting inititated a series of linked half-grabens that were generated by N-S extension (Figure

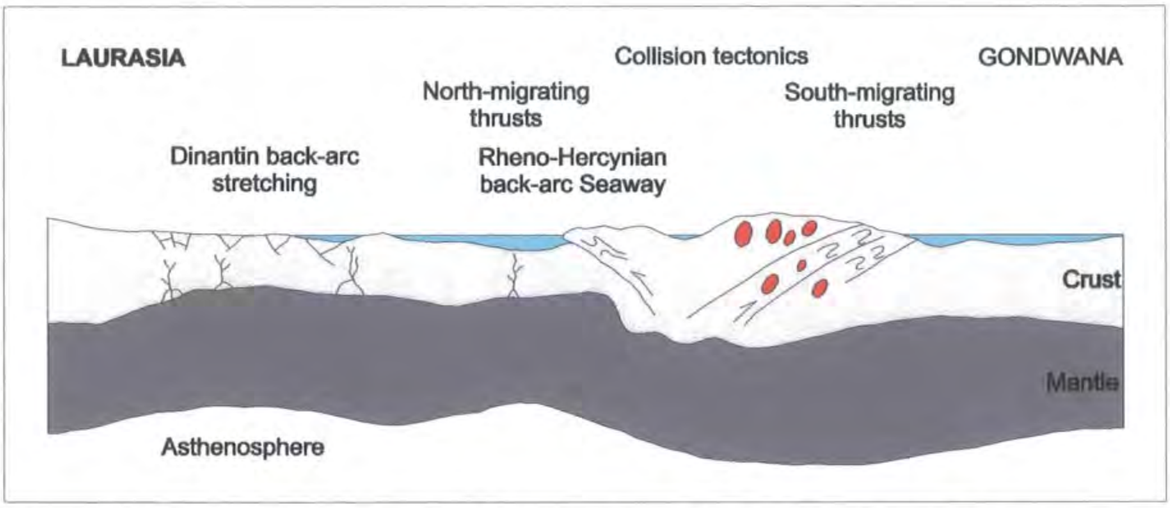

Figure 2-2 Carboniferous extension province showing its relationship to thrust tectonics and the Rheno-Hercynian back-arc basin. From, Leeder (1998).

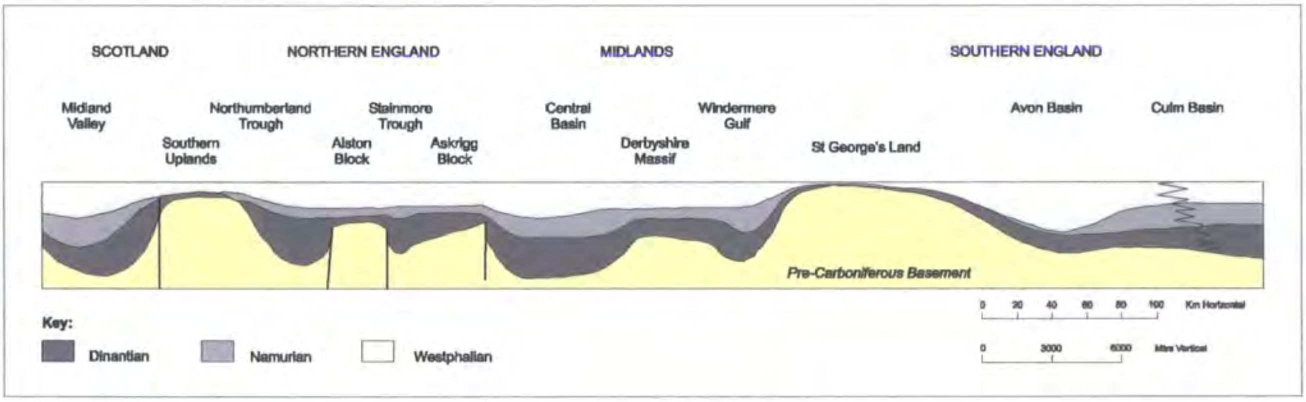

Figure 2-3 Section from north - south across Britain during the Dinantian to Westphalian. From, Johnson (1982).

2-3; Fraser & Gawthorpe 1990). Caledonian inheritance in the underlying basement rocks of Northern England controlled the location of such half-grabens with the presence of a major Caledonian crustal shear zone thought to be the Iapetus Suture Zone (Figure 2-4) discovered beneath northern England (Chadwick & Holliday 1991). Caledonian inheritance combined with the Hercynian plate cycle produced a complex series of extensional basins (Fraser *et al.* 1990).

The extensional province of Northern England is characterised by a series of E-W trough-like sedimentary basins alternating with raised block areas with basin formation initiated in Late Devonian / Early Carboniferous times (Turner *et al.* 1995). This led to the formation of the Tweed Basin, Northumberland Trough, Carlisle Basin and the Stainmore Trough with the Northumberland Trough being further subdivided into the Solway Basin to the west and the Northumberland Basin to the east (Figure 2-5: Turner 1995). Caledonian granite batholiths in the upper crust beneath northern England led to the structural stability of blocks during tectonically active periods due to the buoyancy of the low-density granite masses (Bott 1987; Fraser et al. 1990) creating a series of intervening blocks (Figure 2-6). Fault-related differential subsidence continued through to the end of the Dinantian and was gradually replaced in the Early Namurian by regionally extensive post-rift, predominantly unfaulted thermal subsidence (Turner 1995) with both basins and blocks subsiding at approximately the same rate (Bott 1987). The Tweed Basin existed as a separate basin until this stage, when regional subsidence occurred and the Tweed Basin and Northumberland Basin merged into a single basin (Turner 1995). Some fault reactivation, however, did occur during the Early Namurian (Fraser & Gawthorpe 1990). This is further discussed in Section 8.6.

2.4.1 Syn-Rift Sedimentation

Syn-rift sedimentation continued intermittently from the Late Devonian up until the Late Brigantian (Fraser & Gawthorpe 1990). The main phases of syn-rift sedimentation were from Late Devonian to Early Tournaisian, Late Chadian to early Arundian, Mid to Late Asbian and during the Brigantian (Gawthorpe *et al.* 1989), while phases of tectonic activity were punctuated by intervals of relative tectonic quiescence (Gawthorpe *et al.* 1989). In the Northumberland and Tweed Basins early syn-rift was dominated by influxes of mature siliciclastic detritus from the Southern

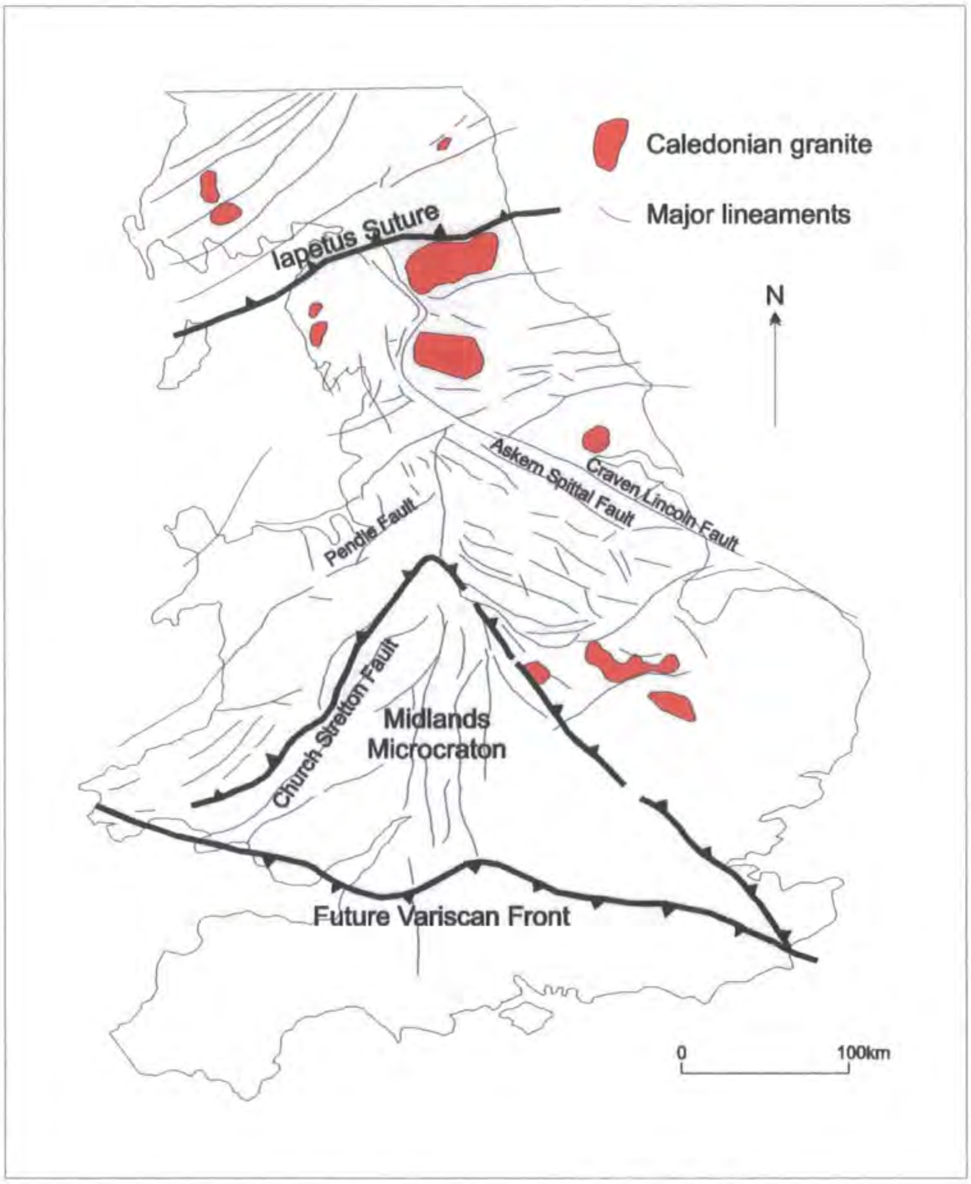

Figure 2-4 Caledonian tectonic inheritance of England and Wales. From, Fraser & Gawthorpe (1990).

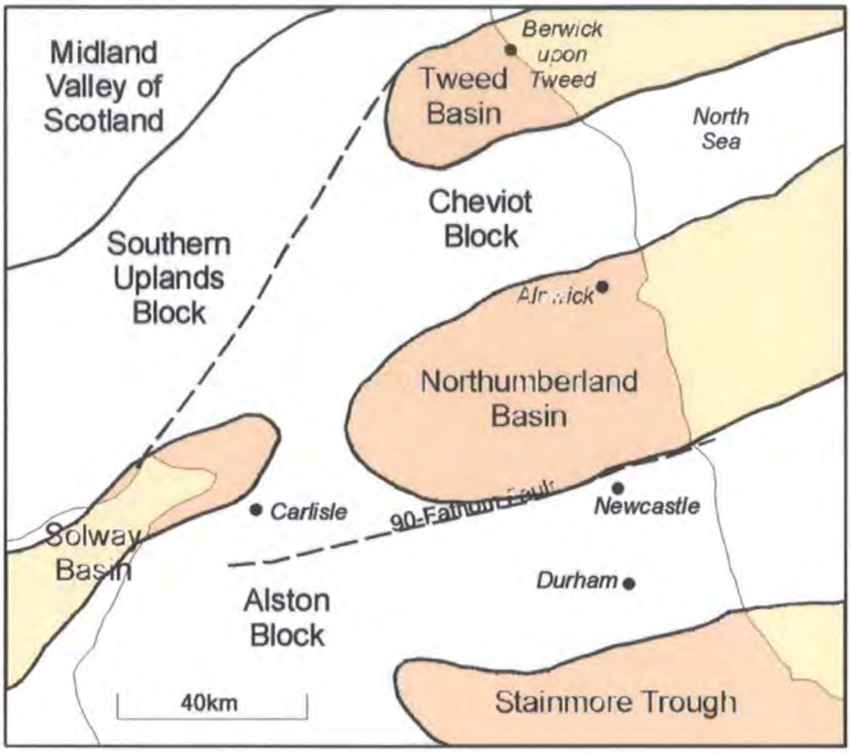

Figure 2-5 Cartoon structural map of northern England. Modified from, Johnson (1995).

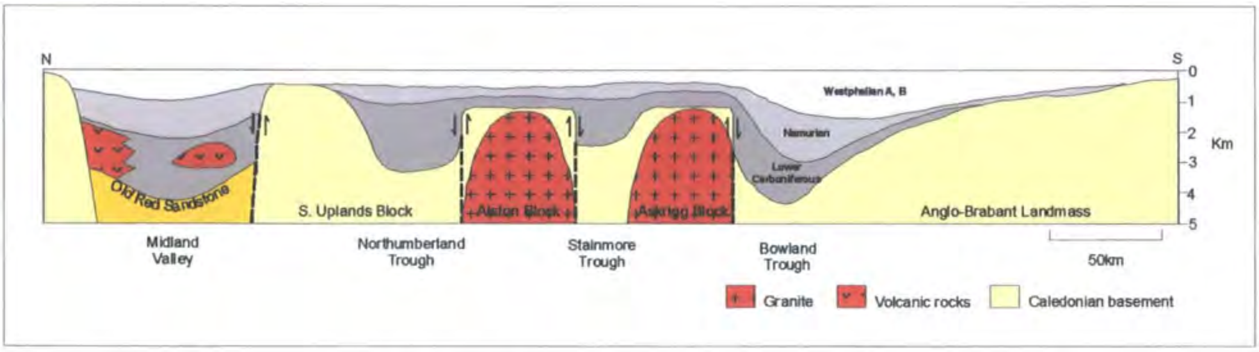

Figure 2-6 Schematic section showing tectonic structure of northern England. Lower Carboniferous sediments represent syn-rift sequence, whilst Namurian - Westphalian sediments represent post-rift sequence. From, Leeder (1982).

Uplands hanging-wall source areas, which was followed by the diachronous advance of a major axial braided Pennine fluvial system from the north-east in Arundian and Holkerian times with major syn-depositional controls on alluvial architecture (Gawthorpe *et al.* 1990). During the Asbian, Yoredale cycles were developed in the south-west with abnormal thicknesses of the dominant siliciclastic delta facies as discussed in Section 8.3.1.2, followed by deltaic cycles over most of the area in the Late Asbian. Northern England was dominated by two syn-rift depositional systems; clastic fluvio-deltaics and carbonate platforms (Fraser & Gawthorpe 1990). Clastic deltas were confined to the north of the region whereas to the south, sediment-starved basins ensured that carbonates accumulated on platform areas (Fraser & Gawthorpe 1990). In tectonically active areas, there were major influxes of siliciclastic sediments due to rejuvenation of source areas or structurally-controlled changes in sediment transport; these effects were most apparent in areas closer to the source and are often recorded as progradation of fluvio-deltaic facies (Gawthorpe *et al.* 1989). In more distal areas, the only evidence of increased siliciclastic input is from the increases in terrestrial mud and the cessation of carbonate production due to inundation of the hanging wall and subaerial emergence of hanging walls (Gawthorpe *et al.* 1989). In general, tectonic subsidence exceeded the rate of sediment supply to basins (Fraser & Gawthorpe 1990) and differential subsidence lead to the thickening of sediments within basinal areas and thinning over blocks (Figure 2-6; Johnson 1995). The Alston Block itself remained a topographic barrier to sedimentation throughout the syn-rift phase in the Early Dinantian (Vanstone 2001).

2.4.2 Post-Rift Sedimentation

Post-rift sedimentation spanned the Late Brigantian to Late Westphalian C times (Fraser *et al.* 1990). The main feature of this phase was a switch from deposition within isolated fault-bounded half-grabens during the syn-rift phase to unconfined deposition during the Namurian to Westphalian post-rift phase as discussed later in Sections 8.3.1.3 and 8.3.1.4 (Vanstone 2001). Progradation of the Pennine fluvio-delatic system occurred, probably triggered by an increase in climatic humidity within the hinterlands of the basin during the Namurian (Cliff *et al.* 1991), as sediment supply overtook subsidence for the first time (Fraser & Gawthorpe 1990). The presence of marine limestones was highly reduced in the Namurian and was eventually replaced by marine mudrocks in the higher parts of the succession (Leeder *et al.* 1989), resulting from the choking of carbonate platforms by siliciclastic material as the progradation of the fluvio-detaic system continued southwards (Fraser *et al.* 1990). Deposition as a whole was uniform as Yoredale cyclicity dominates the succession with a gradual shift of the main depocentre to the south of the area (Figure 2-6; Fraser & Gawthorpe 1990).

2.5 Late Dinantian and Early Namurian sedimentation and palaeogeography

During the Late Dinantian and Early Namurian the sourcelands for the Pennine river and delta system were somewhere in the region of the present day northern North Sea (Cliff *et al.* 1991), and the main marine influence to the areas came from the south-west of the region in the Craven Basin (Figure 2-7; George *et al.* 1976). These features governed the sedimentation throughout the Dinantian with shallow-marine carbonates found to the top of the Asbian on the Alston block, the Northumberland Basin displaying well developed Yoredale cycles composed of river-dominated deltaic clastics and marine carbonates, while the Tweed Basin displayed an increase in importance of delta plains and coal swamps and a decrease of marine limestones throughout the succession as discussed later in Section 8.3.2 (Johnson *et al.* 1995). It should be noted that the lower boundary of the Asbian is considered to be diachronous as the basal limestone in the Tweed Basin is some 100m higher in the succession than that of the Alston Block (Johnson *et al.* 1995).

The presence of structurally positive areas of buoyant granite played a large part in the sedimentation and palaeogeography during the Dinantian and Namurian. These areas formed islands during the Early Carboniferous and were progressively inundated by the sea as the Carboniferous period progressed (Johnson *et al.* 1995). Dinantian successions are thinner over the areas which are underlain by granite as they did not subside at the same rate as the surrounding basins. With a transition to post-rift thermal 'sag' both basins and blocks subsided at the same rate removing any topographic barrier and during the Namurian a more uniform depositional thickness is observed. In the Namurian the river-dominated deltaic portion of the Yoredale cycles locally was replaced by a wave-dominated deltaic portion due to Late Dinantian marine transgressions of the Alston Block (Leeder *et al.* 1989).

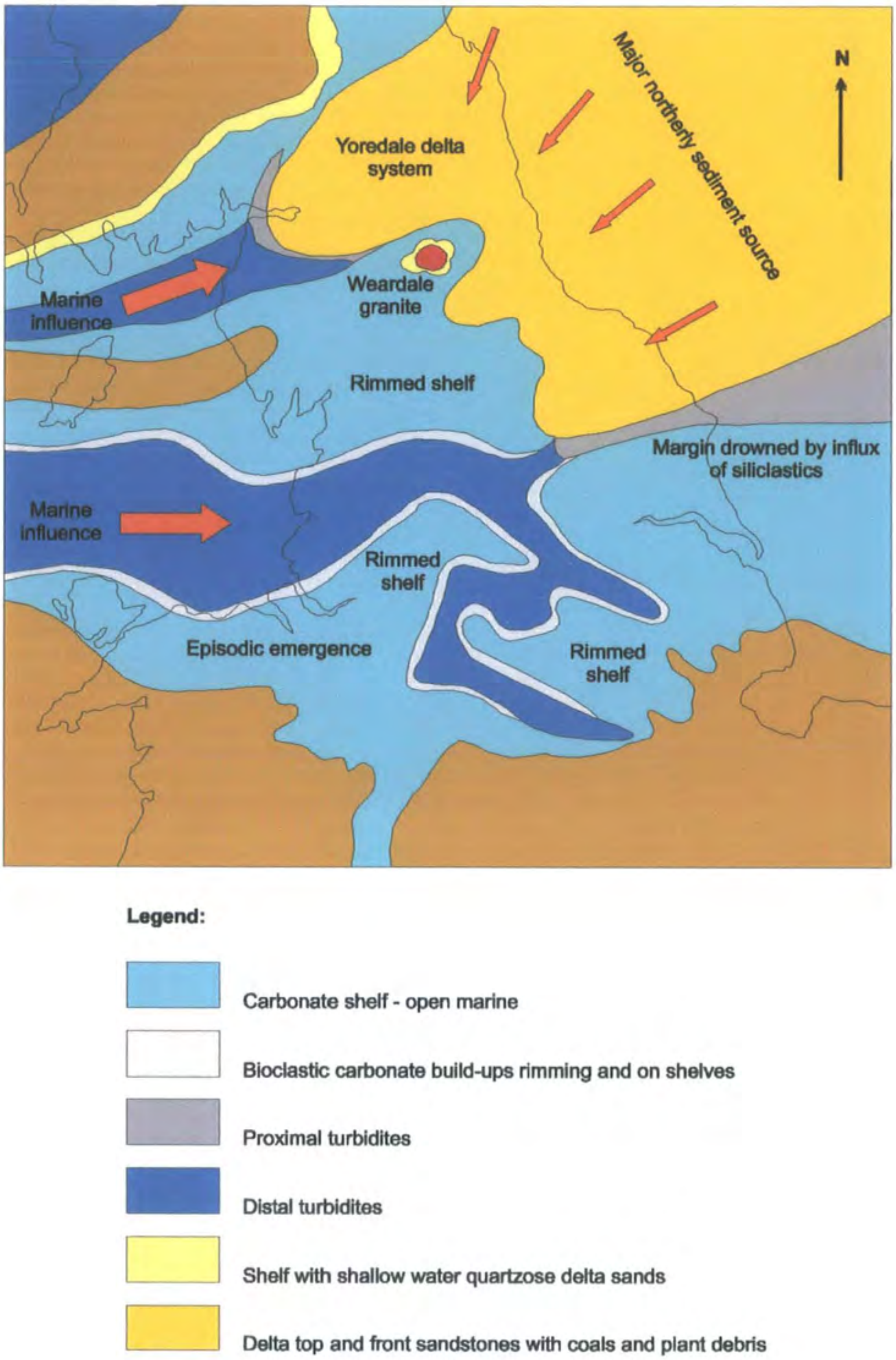

Figure 2-7 Facies map for Late Dinantian to Early Namurian. Adapted from, Fraser & Gawthorpe (1990).

In Early to Mid Dinantian times fluvial-dominated sedimentation was found only in the north-east region of the Tweed Basin but the later Dinantian rivers and delta lobes periodically advanced over the Alston Block as far south as the Askrigg Block, depositing Yoredale cycles. The Namurian therefore saw an overall increased influence of siliciclastic material due to the progradation of the Pennine fluvio-deltaic system southwards. The general progradation of the Pennine river system led to the upwards increase in siliciclastic influence throughout the late Dinantian and Namurian and to the final cessation of carbonate production.

A generalised palaeogeographic map of the Late Dinantian to Early Namurian can be seen in Figure 2-7.

2.6 Summary

The Carboniferous global plate configuration underwent a dramatic change during the Mid Carboniferous resulting in the closure of the Proto-Tethys Ocean and the collision of the two supercontinents of Laurasia and Gondwana. The resulting collision-type orogenic belt led to the formation of back-arc basins in NW Europe as northwards subduction of the Proto-Tethys Ocean got underway. The subsequent stretching and thinning of the lithosphere in response to subduction resulted in the formation of the extensional province of northern England. The outcome of this was the formation of a series of E-W trending sedimentary basins alternating with structurally stable areas or blocks.

Syn-rift sedimentation was dominated by fluvial sediments of the Pennine river and delta system to the north-east and marine carbonate production to the south-west, with the development of Yoredale cycles occurring from the Asbian onwards. The block areas acted as topographical barriers to sedimentation as differential subsidence occurred between the blocks and the basins. During the post-rift phase, differential subsidence came to an end and regional subsidence presided over the area. The removal of topographic barriers assisted the progradation of the Pennine fluvio-deltaic system from the north-east and a gradual cessation of marine carbonate production throughout the region.

2.7 Palaeoclimatic Evolution during the Late Palaeozoic

During the Late Palaeozoic, northern England was located on the southern margin of the supercontinent of Laurasia, within a few degrees of the equator (Wright 1990), 4°S to 13°S during the Lower Carboniferous, and 1°N to 11°N during the Upper Carboniferous (Figure 2-1; Falcon-Lang 2000). The overall climate in south Laurasia was one of dry conditions during the Upper Tournaisian to Mid Viséan, dry to moderately humid during the Upper Viséan with an increasingly more humid climate during the upper-most Viséan to Lower Namurian (Van der Zwan *et al.* 1985).

A dramatic change in climate was experienced throughout low latitude areas of Laurasia and has been attributed to two primary factors: the closure of the Proto-Tethys Ocean between Laurasia and Gondwana resulting firstly in the Hercynian orogenic belt and eventually in the amalgamation of Pangaea during the Carboniferous and Permian (e.g. Scotese & McKerrow 1990), and the onset of Late Palaeozoic glaciation in Gondwana (e.g. Wright & Vanstone 2001). This subject is discussed in greater detail in Section 6.9.2.

2.8 Continental Drift and Continental Configuration

During the Lower Carboniferous there was a gradual northwards shift of the whole Laurasian continent (Van der Zwan *et al.* 1985) of between 15 to 20° (Figure 2-1; Leeder 1987). Major climatic belts occur subparallel to the equator at the present day and the assumption can be made that the same was true for the geological record (Figure 2-8; Bless *et al.* 1984); thus if there was a northwards migration of the Laurasian continent then a major change in climatic belt would occur. During the Lower Carboniferous there is a marked shift southwards of the humid climatic zone and the related palaeoequator (Van der Zwan *et al.* 1985). This form of long-term global climate change on a scale of several million years can be attributed to movement of continents and orogenesis (Cecil 1990).

The presence of two large supercontinents had a large impact on climatic patterns; the size of the Gondwanan supercontinent in the southern hemisphere may have exerted a large influence on climate patterns (Moore 1989). There is evidence to suggest that a difference in heat budget due to the larger size of the Gondwana landmass caused an offset of the palaeoclimatic equator by up to 10°N, creating a drier climatic zone over

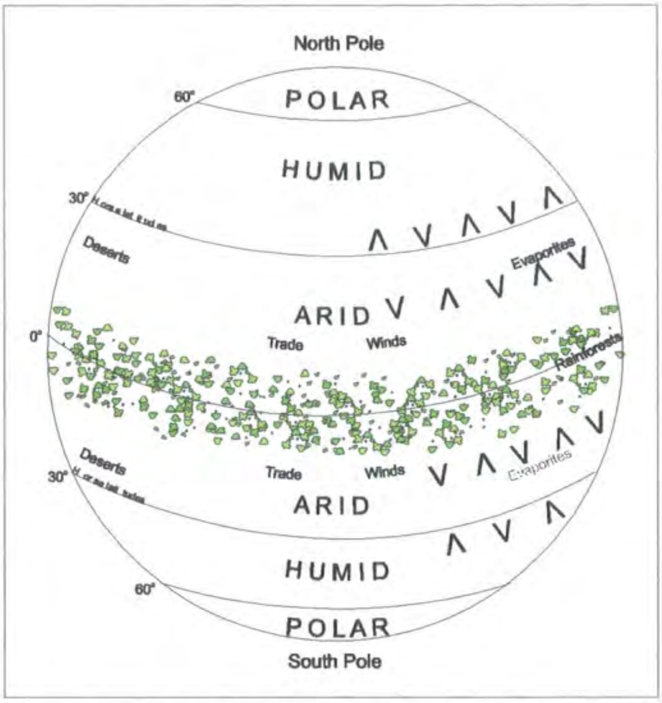

Figure 2-8 Cartoon showing distribution of principal climatic belts around the earth at present day. From, Bless *et al.* (1984).

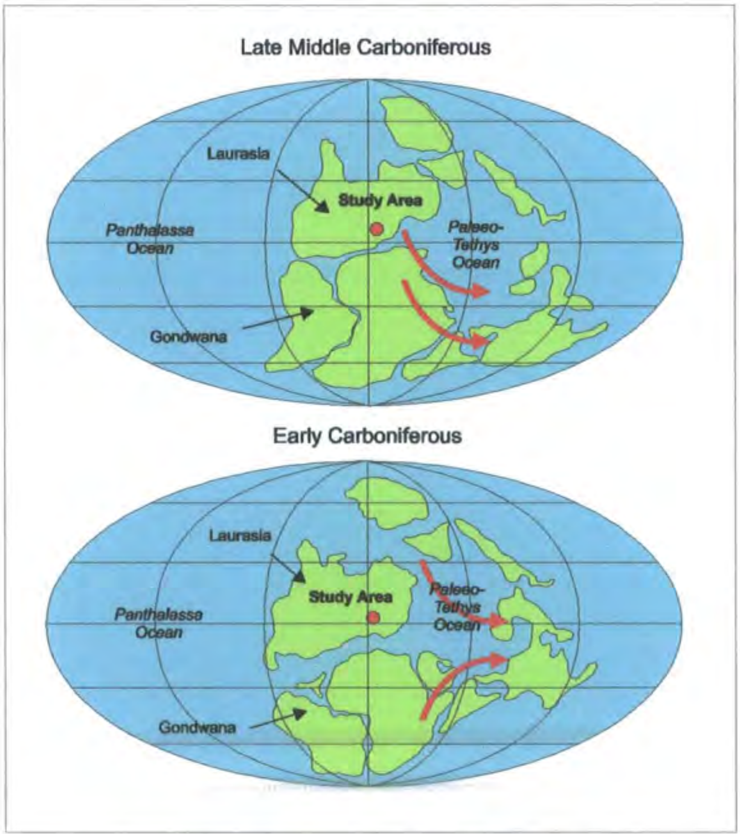

Figure 2-9 Global palaeogeography during the Mid Carboniferous. Arrows indicate atmospheric circulation patterns, monsoonal in Early Carboniferous and zonal in Late Middle Carboniferous. Adapted from, Falcon-Lang (2000).

what is now Western Europe (Wright 1990). This is discussed in greater detail in Section 6.9. The orientation and position of Gondwana in relation to Laurasia, allowed moist air circulation from two major oceans and would have contributed to the onset of the Late Palaeozoic glaciation (Crowell 1978). The closure of the equatorial seaway between Laurasia and Gondwana would have caused major changes in oceanic circulation, resulting in warming of higher latitude areas, but possibly leading to an increase in precipitation over Gondwana (Wright & Vanstone 2001). Such an event is thought to have helped bring an end to the Late Palaeozoic glaciation (Crowell 1978).

2.8.1 Monsoonal Circulation

The continental configuration during the Lower Carboniferous contributed to a monsoonal climate pattern throughout southern Laurasia. There is evidence from palaeoequatorial regions of a semi-arid climate with seasonal rainfall indicative of monsoonal circulation (Falcon-Lang 2000; Wright & Vanstone 2001). Deflection of rains over northern Gondwana led to aridity over southern Laurasia during the Winter Southern Hemisphere low pressure cell, while during the Summer low pressure cell over Gondwana, equatorial air would have been drawn in, creating a seasonal wet and humid zone over northern Gondwana (Wright 1990). A deflection of this sort may have been facilitated by a region of higher relief to the east of what is now southern Britain (Wright 1990). The seasonal alternation of arid or semi-arid climate with a wet and humid climate is characteristic of modern monsoonal circulation observed today in south-east Asia and is mentioned briefly in Section 6.11.1 (eg. Chao & Chen 2001; Dettman *et al.* 2001). The closure of the equatorial seaway between Laurasia and Gondwana during the Mid to Late Viséan heralded an end to monsoonal circulation and the inception of more static wet and humid climatic zones (Figure 2-9; Falcon-Lang 2000).

2.9 Late Palaeozoic Glaciation

Evidence for a major glaciation in Gondwana during the Late Palaeozoic can be found throughout each of the Gondwanan continents including South America, Antarctica, Africa, India and Australia (Crowell 1978). Onset of glaciation is thought to have occurred in western South America and southern Africa in the Mid to Late Viséan (Wright & Vanstone 2001) although it may have begun as early as the Late Devonian

(Caputo & Crowell 1985). The last record of the glaciation can be found in the Mid-Permian sediments of Australia (Crowell 1978).

Several mechanisms have been proposed for the onset of the glaciation; uplift in Australia and South America may have acted as a loci for glaciation to occur (Powell & Veevers 1987), changes in atmospheric CO_2 combined with geographical and insolation changes may have created conditions conducive to glaciation (Crowley & Baum 1992) or as previously mentioned, the closure of the equatorial seaway between Laurasia and Gondwana during the Mid to Late Viséan would have caused major oceanic circulation changes (Rowley *et al.* 1985, Raymond *et al.* 1989, Smith & Read 2000, Wright & Vanstone 2001).

There is evidence to suggest that major uplift of mountain areas has acted as a trigger for Alpine glaciation in the Late Tertiary to Quaternary (Hay *et al.* 1997). Thus uplift in the Carboniferous Australian continent of Gondwana could have acted as a causal mechanism for glacial onset.

Expanding vegetation of the Devono-Carboniferous led to the development of increased levels of oxygen which would have placed a demand upon atmospheric CO_2 (Moore 1983). CO_2 is an important variable responsible for a large climate change (Crowley *et al.* 1987; Fleming 1998), as a greenhouse gas with radiation absorbing properties, any change in CO_2 levels, could bring about major climate change (Berner 1990).

The position of continents at high latitude sites, over one or both of the poles and a continental arrangement over the earth as a whole so that latitudinal oceanic circulation is inhibited could result in glaciation (Crowell 1978). The easily evaporated oceanic water is deflected polewards by the land barrier and so 'snowy centres' can develop in the subpolar regions (Crowell 1978).

2.9.1 The ice-house world tropical climate

The development of a major glaciation affects global climate patterns including the climate in low latitude or tropical regions. Over continents, surface albedo during an ice-house period is higher due to extensive ice sheets, snow and very little vegetation, resulting in largely reduced surface temperatures (Manabe & Hahn 1977). An overall reduction in surface run-off over tropical areas is also experienced due to reduced precipitation, and although evaporation is also reduced overall, the reduction in evaporation in tropical regions is not as great as in those areas of higher latitudes (Manabe & Hahn 1977). The effect this has is that during an ice-house period a more arid climate is experienced.

2.9.2 Fluctuations in Late Palaeozoic eustatic sea-level

Mid Carboniferous sedimentation in areas of low palaeolatitude is characterised by rhythmic sedimentation which has been attributed to changes in eustatic sea-level. Eustatic sea-level changes during the Carboniferous have been well documented by various authors, most notably by Ross & Ross (1987) where a series of 3rd order sea-level cycles are documented (Figure 2-10). Mid Carboniferous cyclic sedimentation at low palaeolatitudes is on a smaller-scale than this as 4th order sea-level changes appear to be the cause of cyclicity (Section 4.3.1.2). Eustatic fluctuations were common throughout the tropical regions during the Carboniferous, and examples can be found in Mid Continent United States Kansas-Type cycles, Central Appalachian Basin Cycles, Northern Britain Yoredale-Type Cycles and also those found in southern Britain and elsewhere in western Europe (Maynard & Leeder 1992; Guion *et al.* 2002).

The approximate duration of each cycle is 0.1 to 1.2 Ma which is likely to be associated with repeated glaciation and deglaciation in Gondwana. This subject is discussed further in Section 4.3.1. Such fluctuations in sea-level are believed by most authors to be a direct result of the waxing and waning of Late Palaeozoic ice centres in Gondwana due to changes in solar insolation, resulting in the removal and addition respectively of oceanic water (e.g. Wanless & Shepherd 1946; Crowell 1978; Heckel 1994). Similar glacio-eustatic sea-level changes have also been recorded in Late Quaternary strata (Carreno *et al.* 1999; Masari & Rio 2002). There has been some objection to this theory however by Isbell *et al.* (2003) who stipulate that the Gondwanan ice sheets were not the primary cause of sea-level changes linked to Late Palaeozoic cycles. These issues will be discussed further in Section 4.4.2.

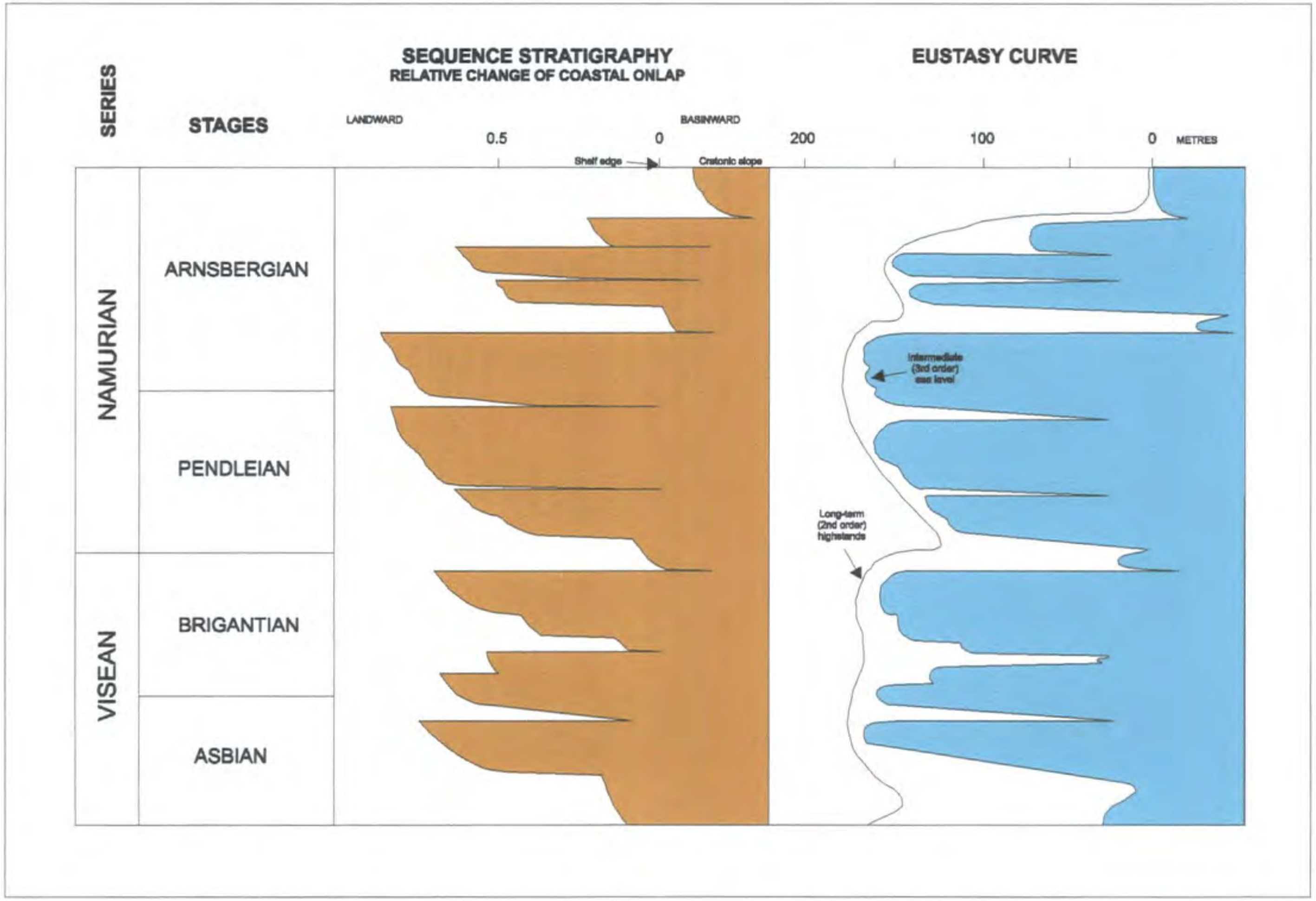

Figure 2-10 Mid Carboniferous sequence stratigraphy and sea-level curve. Adapted from, Ross & Ross (1987).

Glacio-eustasy began abruptly in the Early Asbian in Britian which would imply that some threshold was crossed that triggered a shift in the behaviour of the Gondwanan ice sheets (Wright & Vanstone 2001). This is discussed further in Section 4.4.3.1. Perhaps they grew sufficiently large to trigger decametre-scale sea-level oscillations and also to become sensitised to changes in solar insolation (Wright & Vanstone 2001).

2.10 Summary

Changes in climate during the Carboniferous were brought about by 2 major global changes: the changing continental configuration and the onset of the Late Palaeozoic glaciation in the southern hemisphere.

The palaeolatitude of northern Britain changed considerably between the Lower Carboniferous and the Upper Carboniferous. This was a direct result of the gradual northwards shift of the whole Laurasian continent and would have led to changing climatic belts from relatively arid climatic conditions with monsoonal conditions in the Lower Carboniferous to a more humid climate in the Upper Carboniferous.

The onset of a major glaciation during the Mid to Late Viséan resulted in major changes in the Mid Carboniferous climate and sea-level. This led to a predominantly arid climate in the palaeotropics which has also been observed in tropical areas during the last glacial maximum. A change in monsoonal circulation may also have been generated by the onset of a major glaciation in the southern hemisphere as a much more restricted area would have been affected by monsoonal conditions during this period. The closure of the Proto-Tethys ocean from the Mid to Late Viséan onwards would have resulted in major changes in oceanic circulation and caused warming in high latitudes and ultimately, the demise of the Late Palaeozoic glaciation.

2.11 Bio- and lithostratigraphy

The Lower Carboniferous coral-brachiopod zones proposed by Vaughan (1905) and Garwood (1913) are commonly used for the correlation of the Lower Carboniferous strata of Southern Britain. However, the thick marine limestone bands present in Southern Britain are lacking in Northern Britain so other biostratigraphic correlation methods have had to be used. Foraminifera, conodont zones and palynology have proved more fruitful in correlation of sequences across the area (Armstrong & Purnell 1993) with suitable ammonoid zones also being available for the immediate base and at the top of the Viséan (Upper Asbian and Brigantian).

	Western Europe		
C	Y.	G1b	*Cancelloceras cumbriense*
		G1a	*Cancelloceras cancellatum*
Namurian B	Marsdenian	R2c2	*Verneuilites sigma*
		R2c1	*Bilinguites superbilinguis*
		R2b	*Bilinguites matebilinguis*
		R2b	*Bilinguites eometabilinguis*
		R2b	*Bilinguites bilinguis*
		R2a	*Bilinguites gracilis*
	Kinderscoutian	R1c	*Phillipsoceras coreticulatum*
		R1c	*Reticuloceras reticulatum*
		R1b3	*Phillipsoceras stubblefieldi*
		R1b2	*Phillipsoceras nodosum*
		R1b1	*Phillipsoceras eoreticulatum*
		R1a5	*Reticuloceras dubium*
		R1a4	*Reticuloceras todmordensense*
		R1a3	*Reticuloceras subreticulatum*
		R1a2	*Phillipsoceras circumplicatile*
		R1a1	*Hodsonites proteum*
Namurian A	Alportian	H2c2	*Homoceratoides prereticulatus*
		H2c1	*Wallites eostriolatus*
		H2b	*Homoceras undulatum*
		H2a	*Hudsonoceras proteum*
	Chokierian	H1b2	*Isohomoceras sp. nov.*
		H1b1	*Homoceras beyrichianum*
		H1a	*Isohomoceras subglobosum*
	Arnsbergian	E2c2	*Nuculoceras nuculum*
		E2c1	*Nuculoceras stellarum*
		E2b3	*Cravenoceratoides nititoides*
		E2b2	*Cravenoceratoides nitidus*
		E2b1	*Cravenoceratoides edalensia*
		E2a3	*Eumorphoceras yatesae*
		E2a2	*Cravenoceras greasinghamense*
		E2a2	*Eumorphoceras ferrimontanum*
		E2a1	*Cravenoceras cowlingense*
	Pendleian	E1c	*Cravenoceras malhamense*
		E1b2	*Tumulites pseudobilinguis*
		E1b1	*Cravenoceras brandoni*
		E1a	*Edmooroceras medusa*
		E1a	*Edmooroceras bisati*
		E1a	*Edmooroceras tornquisti*
Visean V3C	Brigantian	P2c	*Lyrogoniatites georgiensis*
		P2b	*Lusitanites subcircularis*
		P2a	*Lusitanoceras granosum*
		P1d	*Paraglyphioceras rotundum*
		P1c	*Arnsbergites sphaericostriatus*
		P1b	*Paraglyphioceras striatum*

Figure 2-11 Ammonoid stratigraphy of the Western European Carboniferous. After, Menning *et al.* 1999.

Ammonoid biostratigraphy (goniatites) is available for the whole of the Namurian of western Europe, including the study area. These zones cannot however be used as exact time units due to the significant changes of environment and consequent evolutionary rates of species during the system time range.

In Western Europe, the Carboniferous is divided into two subperiods, the Lower (or Dinantian) and Upper (or Silesian), and 5 stages (from oldest to youngest: Tournaisian, Viséan, Namurian, Westphalian and Stephanian). A table of the classification of Carboniferous rocks is seen in Figure 2-12.

Carboniferous Period

Periods & Subperiods		Epoch	Age
		Permian	Asselian
Carboniferous	Silesian	Stephanian *300.3* ●	Stephanian C
			Stephanian B
			Stephanian A
			Cantabrian
		Westphalian	Westphalian D
		310.7 ●	Westphalian C
			Westphalian B
			Westphalian A
		Namurian	Yeadonian
			Marsdenian
			Kinderscoutian
			Alportian
			Chokierian
		324.6 ●	Arnsbergian
			Pendleian
	Dinantian	Viséan *319* ●	Brigantian
			Asbian
		334 ●	Holkerian
			Arundian
			Chadian
		Tournaisian *352* ●	Ivorian
			Hastarian
		Devonian *354* ●	Famennian

Figure 2-12 Classification of Carboniferous rocks. Partly after Ramsbottom *et al.* 1978 and Harland *et al.* 1982. The figures shown in italics are radiometric ages from Menning *et al.* (1999).

Radiometric ages have been calculated for the Carboniferous by various workers, with the age of the Carboniferous changing greatly since the first of this work was undertaken by Steiger & Jäger (1977). The age of the beginning of the Carboniferous has varied between 368Ma and 352Ma, whilst the age of the end of the Carboniferous has varied between 300Ma and 286Ma. The most recent work on radiometric dating on the Carboniferous has been carried out by Menning *et al.* (1999). It is these dates that have been used in this thesis to calculate the average duration of each Yoredale cycle in Section 4.3.1 (Table 4-2). The majority of dating used by Menning *et al.* (1999) was extracted from volcanic ash layers, using a combination of stratigraphic ages from Belgium, Britain, Spain and France. Menning *et al.* (1999) give the beginning of the Carboniferous at 354Ma, which conflicts with the date provided by Tucker *et al.* (1998) of 362Ma. The duration of the Dinantian period is given as 27.5Ma by Menning *et al.* (1999), with ages from previous authors ranging from 24Ma (Haq & Van Eysinga 1987) to 40Ma (Odin 1982). The duration of the Silesian period is given by Menning *et al.* (1999) as 27.5Ma, with ages ranging from previous authors ranging from 27Ma (Korn & Kullmann 1995) to 47Ma (Harland *et al.* 1982). A summary of the radiometric ages produced by Menning *et al.* (1999) can be seen in Figure 2-12.

The late Viséan (Asbian and Brigantian) and the early Namurian (Pendleian and Arnsbergian) are the main focus of interest in this thesis. Due to the long history of geological research in the area referred to in Section 1.1, lithostratigraphical terms vary greatly. There are also regional variations is lithostratigraphical nomenclature due to the size of the study area. Figure 2-13 presents the history of lithostratigraphical nomenclature in addition to the most recent terms used throughout the area. The combined nomenclature of the North Pennines (North) (Young 1998) and the North Pennines (East) (Mills & Holliday 1998) will be used in this thesis.

Figure 2-13 Lithostratigraphic nomenclature for the Upper Viséan and Lower Namurian of Northumbria. Partly after, Johnson *et al.* 1995.

<table>
<tr><th></th><th></th><th></th><th colspan="2"><i>Fowler (1936)</i></th><th>N. Pennines North
<i>Young (1998) and Frost & Holliday (1980)</i></th><th>N. Pennines West
<i>Arthurton & Wade (1981)</i></th><th>N. N Pennines East
<i>Mills & Holliday (1998)</i></th><th>N. Pennines South
<i>Dunham (1990)</i></th></tr>
<tr><td rowspan="3">Silesian</td><td rowspan="3">Namurian</td><td>Cho</td><td rowspan="2">Millstone Grit</td><td rowspan="2"></td><td rowspan="3">Morpeth Group</td><td rowspan="3">Millstone Grit</td><td>Quarterburn Marine Band</td><td>Quarterburn Marine Band</td></tr>
<tr><td>Arns</td><td rowspan="2">Stainmore Group</td><td rowspan="2">Stainmore Group</td></tr>
<tr><td>Pend</td><td rowspan="3">Carboniferous Limestone Series</td><td>Upper Limestone Group</td></tr>
<tr><td rowspan="2">Dinantian</td><td rowspan="2">Viséan</td><td>Brig</td><td>Middle Limestone Group</td><td>Upper Liddesdale Group</td><td>Upper Alston Group</td><td>Upper Liddesdale Group</td><td>Upper Alston Group</td></tr>
<tr><td>Asbian</td><td>Lower Limestone Group</td><td>Lower Liddesdale Group</td><td>Lower Alston Group</td><td>Lower Liddesdale Group</td><td>Lower Alston Group</td></tr>
</table>

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Chapter 3 – Lithofacies Analysis and Environments of Deposition

3.1 Introduction

The Mid Carboniferous siliciclastic and carbonate rocks of Northern Britain have been studied by many authors (Table 3-1). Although each major lithofacies association has been individually discussed there has been no lithofacies scheme presented to cover both the siliciclastic and carbonate strata. The aim of this chapter will therefore be to synthesise both the information gathered in the field area and from borehole data, and to present a composite lithofacies scheme for the whole area.

Lithofacies Association	Reference
Delta	Martinsen, 1993 Collinson *et al.*, 1990 Martinsen, 1990 Elliott, 1976, 1976b, 1976c, 1975,1974b Collinson, 1968, 1968b Moore, 1959
Marine Shoreline	Percival, 1992 Elliott, 1976
Carbonate Platform	Walkden & Williams, 1991 Brenchley *et al.*, 1990 Gutteridge, 1990 Bridges, 1982

Table 3-1 Previous work published on the Viséan and Namurian siliciclastic and carbonate rocks of Northern Britain with respect to lithofacies description

The purpose of this chapter is to provide a general environmental interpretation for the Viséan and Namurian strata of Northumbria for use in subsequent chapters. Although lithofacies, groups and associations are discussed under their interpretative environmental name, these interpretations were worked out from first principles (see Tables 3-4, 3-5 and 3-6). The associations between each lithofacies are summarised in Table 3-3. For ease of use, the lithofacies are therefore grouped according to environmental associations rather than lithologies. Within each association, lithofacies have been grouped into various major environments, which in turn have been divided into sub-environments as appropriate. The lithofacies associations, groups and individual lithofacies are seen in Table 3-2.

Lithofacies Association	Lithofacies Group	Lithofacies
Delta	Prodelta	Prodelta
	Delta front	Distal mouth-bar
		Proximal mouth-bar
	Delta plain	Low-sinuosity / braided distributary channel
		Meandering distributary channel
		Tidally-influenced distributary channel
		Floodplain deposits
		Interdistributary bay
		Crevasse splay
		Levee deposits
		Palaeosoils
Marine shoreline	Prograding shoreline	Offshore shelf
		Nearshore shelf
		Lower shoreface
		Upper shoreface
	Transgressive shoreline	Tidal channel
		Tidal flat
		Washover fan
		Estuary
Carbonate platform	Carbonate platform	Deep water / low-energy
		Shallowing-upward
		Shallow water (normal)
		Shallow water (low-oxygenation / abnormal salinity)
		Shallow water (anoxic / hypersaline)
	Related lithofacies	Carbonate mud mound / 'knoll-reef'
		Biostromes

Table 3-2 Table of individual lithofacies, lithofacies groups and lithofacies associations within the study area

Table 3-3 Table of lithofacies associations within the study area. Each of the lithofacies has been listed with an x to mark their association with another lithofacies.

Key:

🟨	Delta lithofacies association
🟥	Marine shoreline lithofacies association
🟦	Carbonate platform lithofacies

	D1 – Offshore Shelf	D2 – Distal mouthbar	D3 – Proximal mouthbar	D4 – Braided distributary channel	D5 – Meandering distributary channel	D6 – Tidal distributary channel	D7 – Floodplain deposits	D8 – Interdistributary channel	D9 – Crevasse Splay	D10 – Levee deposits	D11 – Palaeosoils	M1 – Offshore shelf	M2 – Nearshore shelf	M3 – Lower shoreface	M4 – Upper shoreface	M5 – Tidal channel	M6 – Tidal flat	M7 – Washover fan	M8 – Estuary	C1 – Deep water	C2 – Shallowing upward	C3 – Transgressive	C4 – Anoxic / hypersaline	C5 – Low oxygen / abnormal salinity
D1 – Offshore Shelf	▨	×	×					×																
D2 – Distal mouthbar	×	▨	×																					
D3 – Proximal mouthbar	×	×	▨	×	×	×																		
D4 – Braided distributary channel			×	▨			×	×	×		×						×	×	×			×		
D5 – Meandering distributary channel			×		▨		×	×	×		×						×	×	×			×		
D6 – Tidal distributary channel			×			▨		×	×															
D7 – Floodplain deposits				×	×		▨																	
D8 – Interdistributary channel	×			×	×	×		▨		×	×													
D9 – Crevasse Splay				×	×	×			▨															
D10 – Levee deposits								×		▨														
D11 – Palaeosoils				×	×		×				▨				×							×		
M1 – Offshore shelf											×	▨	×											
M2 – Nearshore shelf												×	▨	×										
M3 – Lower shoreface													×	▨	×									
M4 – Upper shoreface											×			×	▨	×								
M5 – Tidal channel																▨	×							
M6 – Tidal flat				×	×											×	▨							
M7 – Washover fan				×	×													▨						
M8 – Estuary				×	×														▨	×				
C1 – Deep water																			×	▨	×	×		
C2 – Shallowing upward																				×	▨	×	×	×
C3 – Transgressive				×	×						×									×	×	▨		
C4 – Anoxic / hypersaline																					×		▨	
C5 – Low oxygen / abnormal salinity																					×			▨

The relative distributions of lithofacies associations and groups, obtained from thickness data in Appendix 2, can be seen in Figures 3-1A and 3-1B respectively.

Figure 3-1A Pie chart to show relative distributions of lithofacies associations within the study area

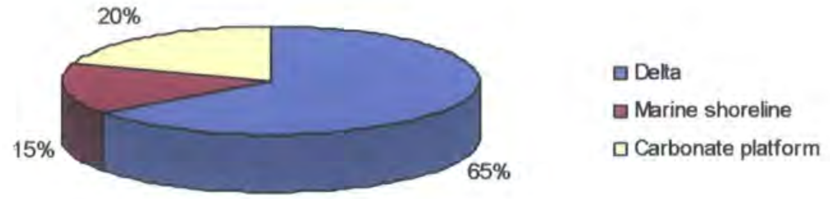
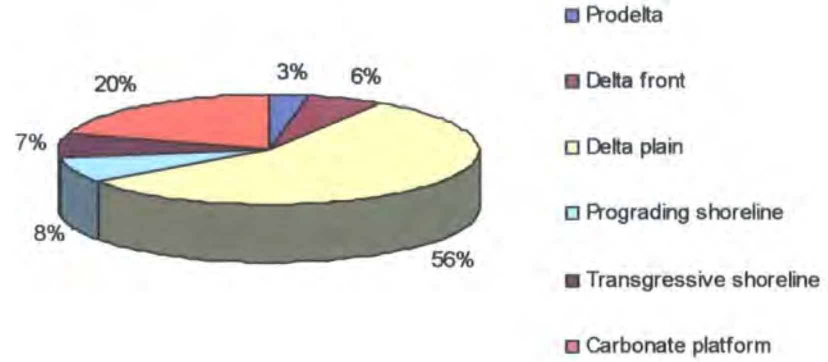


Figure 3-1B Pie chart to show relative distributions of lithofacies groups within the study area



As the purpose of this chapter is to identify environmental associations within the study area as opposed to a complete sedimentological analysis, no attempt has been made to assess the diagenetic features displayed within the succession.

Upper Viséan and Lower Namurian successions were logged from various outcrops throughout Northumbria (Figure 3-2) to provide the observational information needed to produce this lithofacies scheme. Appendix 2 presents detailed sedimentary logs used within this Chapter.

Figure 3-2 Map of study area with location of outcrops (including grid references) used within this Chapter marked.

3.1.1 Cyclicity

Although the cyclic nature of the Mid Carboniferous sediments of Northumbria is discussed thoroughly in Section 4.2, it is necessary to briefly mention the major components of each cycle (Figure 3-3). The average cycle thickness is 30 metres but this can vary greatly throughout the area. The position of each lithofacies within each cycle is imperative to their independent environmental interpretation and the following terms have been used: the base of each cycle is the first 5 to 10 metres and includes carbonates and mudstones. The name of each cycle is determined by the limestone at its base. The mid section of each cycle is made up of various lithologies which generally coarsen-upward, and the upper part of each cycle is sandstone-dominated and can vary from 5 to 20 metres.

3.2 Delta Lithofacies Association

Lithofacies of deltaic origin are the dominant lithofacies within the study area, and represent 65% of the total logged sections as seen in Figure 3-1A. Deltaic lithofacies are well documented from Northern Britain (Table 3-1) where they have been described from the late Early Carboniferous to the end of the Late Carboniferous. Their importance with regards to coal mining throughout the north-east of England has led to an abundance of literature dating back as far as 1809 (Forster 1809).

The deltaic system can be divided into four main depositional environments each of which shall be discussed in turn; prodelta, delta front, lower delta plain and upper delta plain. A table summarising the major components within each lithofacies is shown in Table 3-4.

3.2.1 Prodelta Lithofacies Group

Sediments of the prodelta lithofacies group make up 3% of the entire succession. The prodelta lithofacies group is characterised by laminated mudstones with limited fossil occurrences.

3.2.1.1 D1 Lithofacies – Prodelta

Occurrence and Bed Characteristics

This lithofacies is often poorly exposed. Lateral continuity of this lithofacies is exceptionally good and in some cases can be traced throughout the entire study region.

Table 3-4 Table summarising the major components of each lithofacies and lithofacies group of the delta lithofacies association from the Mid Carboniferous succession of Northumbria.

Lithofacies group and lithofacies	Lithologies	Location within cycle	Unit thickness	Morphology	Lateral continuity	Fossils	Sedimentary structures	Example
Pro-delta Lithofacies Group								
D1 - Pro-delta	Dark-grey to black laminated mudstone. Red on weathered surfaces	Base of cycle: overlies carbonate platform lithofacies, overlain by D3 or D11 lithofacies	0.5 to 4.0cm	Laterally continuous planar beds	100s of kms	Sparse disarticulated crinoids at base of unit. Locally, broken bryozoan, brachiopod and unidentified fossil debris.	Sideritic and calcareous nodules. Friable.	Found at every outcrop
Delta Front Lithofacies Group								
D2 - Distal mouth-bar	Pale- to mid-grey siltstone, lenses of pale-grey fine-grained sandstone	Base of cycles: overlies D1 lithofacies	0.5 to 1.0m	Coarsening-upward unit with planar beds	<50m	Bioturbation common.	Lenses of pale-grey fine-grained sandstone increase upward.	Woodend limestone cycle at Spittal / Scremerston.
D3 - Proximal mouth-bar	Dark-grey shale at base, grading into dark-grey siltstone, grading in to pale-grey to buff fine-grained and medium-grained sandstone	Mid cycle: overlies D2 or D1 lithofacies	4 to 8m	Coarsening-upward unit with planar beds	<50m	Local carbonaceous plant fragments	Planar and trough cross-bedding in siltstone and sandstone components	Four Fathom limestone cycle at Haltwhistle Burn
Delta Plain Lithofacies Group								
D4 - Braided distributary channel	Medium-grained pale-grey to buff sandstone. Coarse-sandstone at base of unit.	Mid to upper cycle: often incises into D4 or D8 lithofacies	6 to 20m	Channel / lens-shaped unit with erosive base	Unknown	Fossilised logs, carbonaceous plant fragments and coal lenses at base.	Planar and trough cross-bedding throughout	Sandbanks limestone cycle at Beadnell
D5 - Meandering distributary channel	Fining upward from pale-grey medium-grained sandstone to medium-grained sandstone	Mid to upper cycle	6 to 20m	Channel / lens-shaped unit with erosive base	Unknown	'Carbonaceous plant fragments at base of unit	Planar and trough cross-bedding and lateral accretion surfaces	Scar limestone cycle at Bowlees Beck
D6 - Tidally-influenced distributary channel	Fining upward from pale-grey medium-grained sandstone to medium-grained sandstone	Mid to upper cycle	1.5 to 20m	Channel / lens-shaped unit with erosive base	Unknown	None visible	Planar and trough cross-bedding. Herringbone cross-beding at top of unit in addition to mud-draped symmetrical ripples.	Acre limestone cycle at Beadnell
D7 - Floodplain deposits	Dark-grey to purple siltstone	Top of cycle	1 to 1.5m	Planar beds	50 to 100m	Abundant carbonaceous plant fragments.	Ripple laminae and siderite nodules common throughout.	Woodend limestone cycle at Spittal
D8 - Interdistributary bay	Dark-grey shale at base, dark- to mid-grey siltstone, silty sandstone and then fine-grained sandstone	Mid to top cycle: overlies D1 lithofacies, commonly incised by distributary channel lithofacies	1 to 4m	Coarsening-upward unit with planar beds	100s of metres	Vertical burrows in siltstone component.	Siderite nodules at base. Ripples, laminae and mudstone lenses common in sandstone.	Oxford limestone cycle at Beadnell
D9 - Crevasse splay	Fine- to medium-grained buff to pale pink sandstone	Top of cycle; interbedded with D8 lithofacies	0.4 to 2.5m	Sheet-like or lens-shaped unit with an erosive base	5m	Local carbonaceous plant fragments. Burrows at top of unit.	Lateral accretion surfaces, asymmetrical ripples	Great limestone cycle at Haltwhistle
D10 - Levee deposits	Fine-grained buff to pale purple sandstone, interbedded with dark- to mid-grey siltstone, mudstone or claystone	Top of cycle; interbedded with D8 lithofacies	0.1 to 0.7m	Thin sandstone beds	2m	Fine carbonaceous rootlets and vertical burrows in sandstone component.		Great limestone cycle at Haltwhistle
D11 - Palaeosoil	Fine-grained siliceous sandstone, siltstone or shale	Very top of cycle	0.2 to 1.2m	Planar beds	Metres to 100s of metres	Carbonaceous plant fragments, fine carbonaceous rootlets, Stigmaria imprints, carbonate nodules, ferric rhizocretions, root mottling.	Some relict bedding / lamination	Found at every outcrop

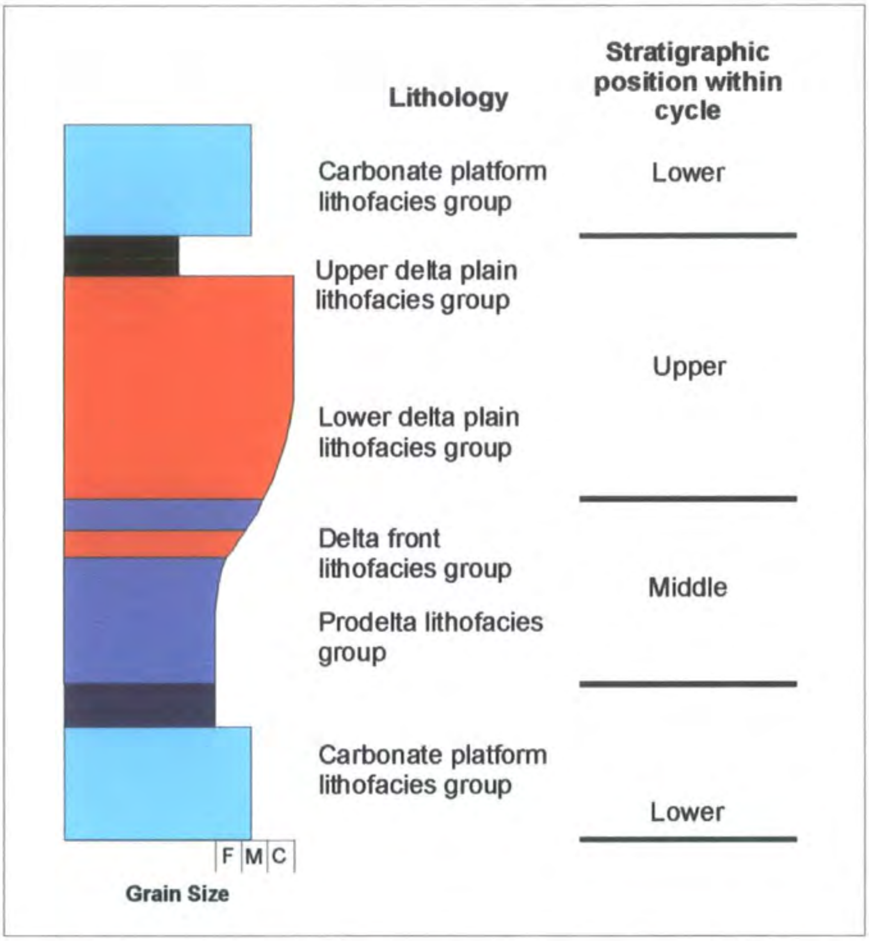


Figure 3-3 Basic cycle diagram displaying major cycle components in relation to their stratigraphic position within each cycle. Grain size indicator key: F=Fine-grained, M=Medium-grained, C=Coarse-grained.

Figure 3-4 Field photograph of early diagenetic siderite nodules within D1 lithofacies. Photograph taken at Spittal coastal section. Lens cap 5cm in diameter for scale.

Examples of this lithofacies have been found at every outcrop studied where it is restricted to the base of each cycle.

The entire unit varies in thickness from 0.5 to 4.0m, although individual planar beds are between 5 and 10mm thick. Early diagenetic nodules are common within the facies and these are mostly composed of siderite (Figure 3-4). Calcareous mudstone nodules are found locally. The shape of nodules is generally elliptical and they range from 3cm to 20cm in length and 5 to 10cm in height; locally nodules are septarian.

This lithofacies is always found above carbonate platform lithofacies (Section 3.4). The overlying sediments are usually of D2 (distal mouth-bar) or D3 (proximal mouth-bar) lithofacies.

Lithological Description

Sediments of the prodelta lithofacies consist of dark-grey to black laminated mudstones which are commonly red on weathered surfaces. Sparse disarticulated crinoids are commonly found towards the base of the unit. Locally, there is a more diverse fossil presence with broken bryozoa, brachiopod and other unidentified fossil debris. Pyrite is found locally within this lithofacies.

Interpretation: Depositional Environment

The thick and extensive mudstone of this lithofacies, in combination with no structures evident of traction currents would suggest that it was deposited in quiet waters out of suspension, well away from the main sediment supply or else when sediment supply was diminished (e.g. Reading & Levell 1996). The quiescent nature of deposition might indicate a deeper water environment; however, in lower energy modern deltas such as the Mahakam Delta in SE Asia, similar deposits are known to accumulate in less then 10m water depth (Allen 1998). The lateral extent of this lithofacies would suggest that similar conditions were in operation throughout the study region for discrete periods of time. The occurrence of crinoids and other stenohaline fossils are indicative of deposition in a marine environment (e.g. Brusatte 2004), at least for the lower part of this lithofacies. At the present day siderite is forming in muds of delta-plain swamps (Pye et al. 1990) and is often associated with brackish water conditions. An influx of meteoric fluid into the marine environment may have resulted in a sulphate reduction zone and resulted in the precipitation of siderite. Sulphate reduction is further substantiated by the lack of pyrite within this lithofacies. The presence of early diagenetic siderite nodules therefore suggests that brackish water conditions may have prevailed, at least periodically (e.g. Shaffer 2002). The conditions of deposition of this lithofacies were probably within a prodelta environment similar to those suggested Vos (1981) from the Devonian of western Libya, and by Hiscott (2003) from the late Quaternary Baram Delta in Borneo.

3.2.1.2Prodelta Lithofacies Group Summary

The prodelta lithofacies group were deposited in the deepest water setting of the deltaic environment, when the sediment source was at its furthest. This lithofacies group signifies the increasing influx of terrestrial material within the delta environment.

3.2.2 Delta Front Lithofacies Group

The delta front group takes up 6% of the Northumbrian succession (Figure 3-1B). The main lithologies coarsen-upward from fine-grained muds and silts, to sand-sized particles. Graphic logs of each lithofacies within the delta front lithofacies group can be seen in Figure 3-5.

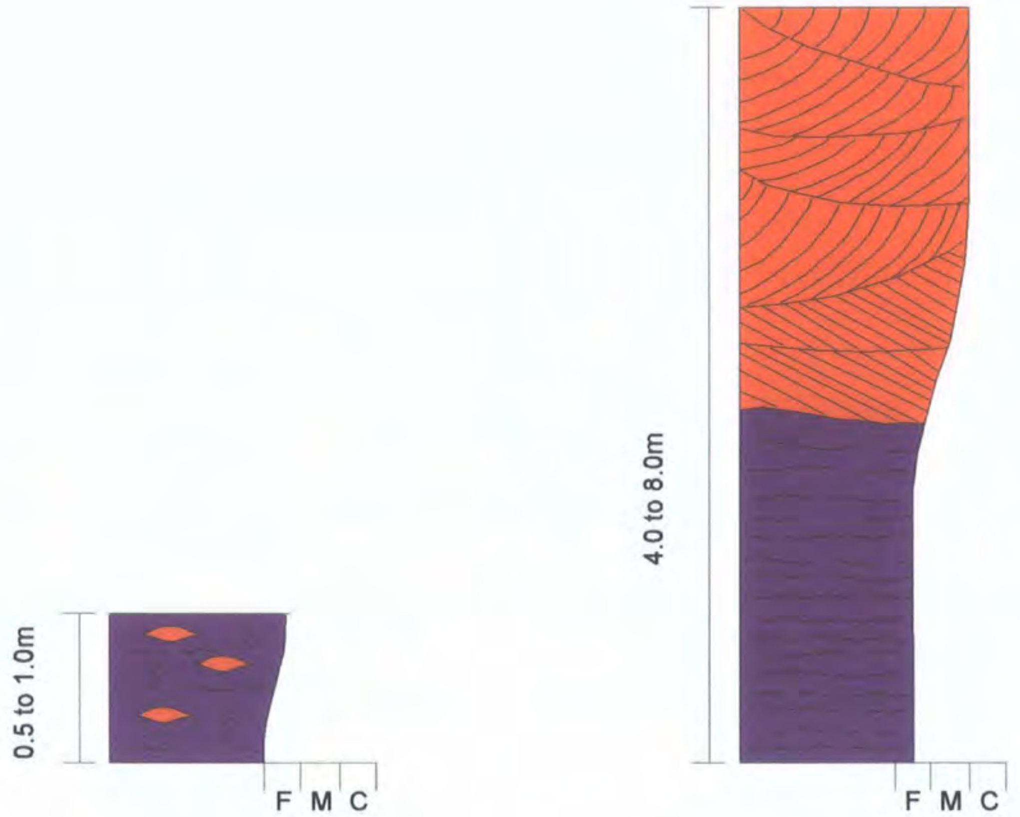
3.2.2.1 D2 Lithofacies – Distal Mouth-Bar

Occurrence and Bed Characteristics

Exposure of this lithofacies is very poor due to the friable nature of the unit. Lateral continuity of exposure is limited to less than 50m. A good example of this lithofacies can be found in the Woodend Limestone cycle (Asbian) at the Spittal / Scremerston coastal section (Grid reference NU 106508) (Ref. D2.1 in Appendix 2).

The entire unit ranges in thickness from 0.5 to 1.0m. Thin, laterally discontinuous planar laminae (0.5 to 2cm in thickness) in addition to lenses of pale-grey sandstone which increase in abundance upward (from 5% to 50%) are the diagnostic features of this lithofacies. The lenses range from 5 to 45cm in length and are between 5 and 15cm in height. Bioturbation in the form of general bed disruption is common throughout this lithofacies.

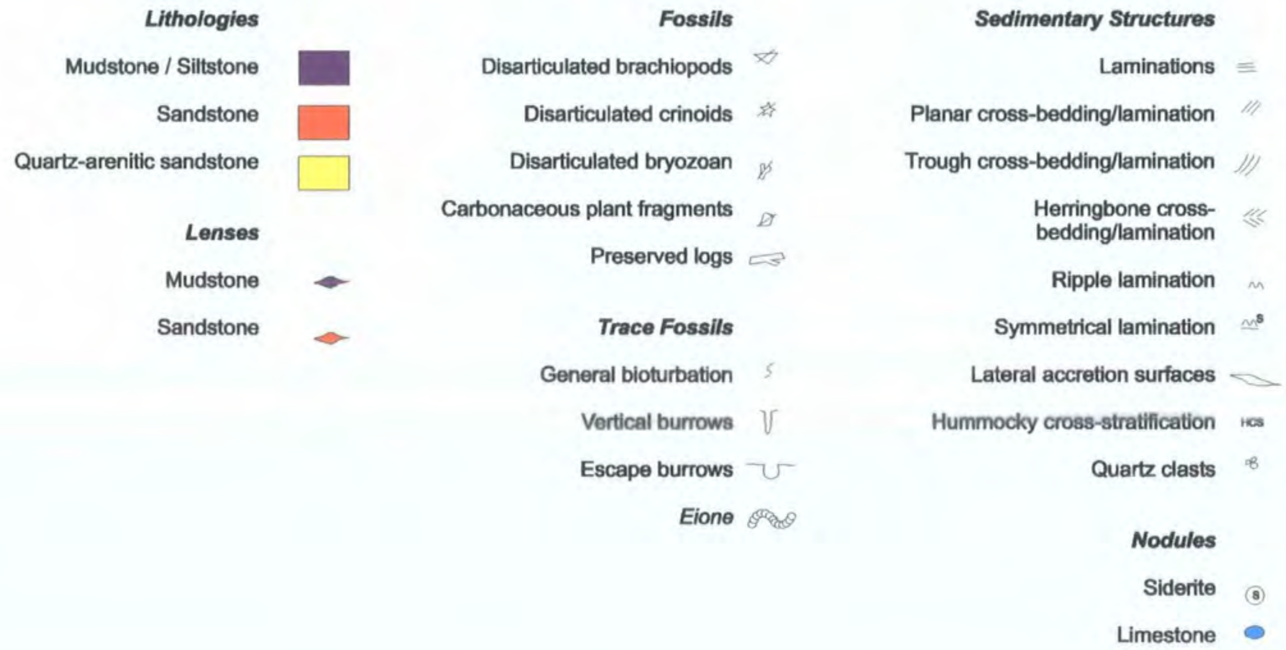
Figure 3-5 Schematic vertical sections of the delta front lithofacies group. D2 lithofacies (distal mouthbar), D3 lithofacies (proximal mouthbar). Grain size indicator is shown along the bottom of each vertical section; F=fine-grained, M=medium-grained and C=coarse-grained. A full key has been provided below and should also be used with Figures 3-8, 3-16 and 3-24.



D2 distal mouthbar lithofacies

D3 proximal mouthbar lithofacies

Key for lithofacies vertical sections



This lithofacies is found gradationally above D1 (prodelta) lithofacies and gradationally below D3 (proximal mouth-bar) lithofacies.

Lithological Description

The primary lithology within this lithofacies is pale- to mid-grey siltstone. Pale-grey fine-grained sandstone makes up the lenticular part of the lithofacies.

Interpretation: Depositional Environment

The thick intervals of mudstone indicate deposition in a predominantly low-energy and relatively deep-water environment; however, siltstone laminae would require a slightly higher-energy due to the coarser grain-size, and lenses of fine-grained sandstone would require higher-energy still. Sediment incursions could be the result of either major floods during which times silt and sand is carried out to the distal mouth-bar and onto the delta slope (e.g. Nakajo *et al.* 2000) or storm events that carried silt and sand into a relatively deep-water environment (e.g. Hips 1998). The upwards increase in grain-size and increased frequency of coarser-grained incursions would suggest an increasingly high-energy environment with progressively closer sediment supply. The depositional environment postulated is one of a distal mouth-bar. This lithofacies bears close affinity to distal mouth-bar sediments described by Elliott (1975) from the Carboniferous of Northern England, and by Wiweko *et al.* (2000) from the Miocene succession in the Kutei Basin of East Kalimantan.

3.2.2.2 D3 Lithofacies – Proximal mouth-bar

Occurrence and Bed Characteristics

This lithofacies is common throughout the study area although the lower part of the unit is often poorly exposed. Lateral continuity is often less than 50 metres. An example of the proximal mouth-bar lithofacies (D3) can be seen in the Four Fathom limestone cycle (Brigantian) at the Haltwhistle Burn river section (Grid reference NY 714659) (Ref. D3.1 in Appendix 2).

This lithofacies consists of a 4.0 to 8.0m coarsening-upwards unit (Figure 3-6). Planar laminae are common within the siltstone component of this unit and cross lamination is common within the lower part of the sandstone unit. Trough and planar cross-

Figure 3-6 Field photograph of coarsening-upward succession at Beadnell. Height of section approximately 5.0m.

Figure 3-7 Base of D4 lithofacies downcutting into underlying D3 lithofacies at Beadnell. Field of view is approximately 4.5m.

bedded sandstones with sets of between 0.3 and 1.0m thick are common in the upper portion of the sandstone. The lithofacies gradationally overlies the D1 (prodelta) or D2 (distal mouth-bar) lithofacies and is commonly cut into by D4, D5, and D6 (distributary channels) lithofacies.

Lithological Description

Units of this lithofacies comprise dark grey siltstone which subsequently passes upwards into pale-grey to buff fine-grained and then medium-grained sandstone. The sandstone is commonly moderately- to well-sorted, and sub-rounded. Locally, there are carbonaceous plant fragments throughout the lithofacies.

Interpretation: Depositional Environment

The overall change in lithology from silt to medium-grained sandstone reflects an overall increase in energy and increasing proximity to sediment source. This is confirmed by the increase in size of sedimentary structure; ranging from planar laminae at the base of the unit, to ripple laminae in the middle of the unit, and planar cross-bedding with sets of up to 1.0m thick at the top of the unit. This succession of sedimentary structures reflects an increasing flow velocity of current upwards (e.g. Tucker 2001). The thickness of the unit, the sedimentary structures found and the association with channelised sandstones of lithofacies D4, D5, and D6 (distributary channels) reflects close affinity to a proximal mouth-bar depositional environment as described from the Eocene deltaic sediments of Texas, USA by Warwick & Hook (1995). In this environment, the flow from distributary channels expands and mixes with seawater to deposit its bedload at the mouth-bar resulting in rapid deposition from currents with a substantial bedload (Elliott 1976).

3.2.2.3 Delta Front Lithofacies Group Summary

The delta front is the region where coarse sediment carried by distributary channels is deposited leading to the formation of mouth-bars; this is an area of active progradation within the deltaic system.

3.2.3 Delta Plain Lithofacies Group

The delta plain lithofacies group contributes 56% to the entire Northumbrian succession (Figure 3-1B) and is the most dominant lithofacies group. Sandstone is the main component, infilling lens-shaped channels although there is a sizeable amount of mudstone and siltstone within the lithofacies group, particularly between channel deposits. Graphic logs of all of the lithofacies within the delta plain lithofacies group are seen in Figure 3-8.

3.2.3.1 D4 Lithofacies – Low Sinuosity/Braided Distributary Channel

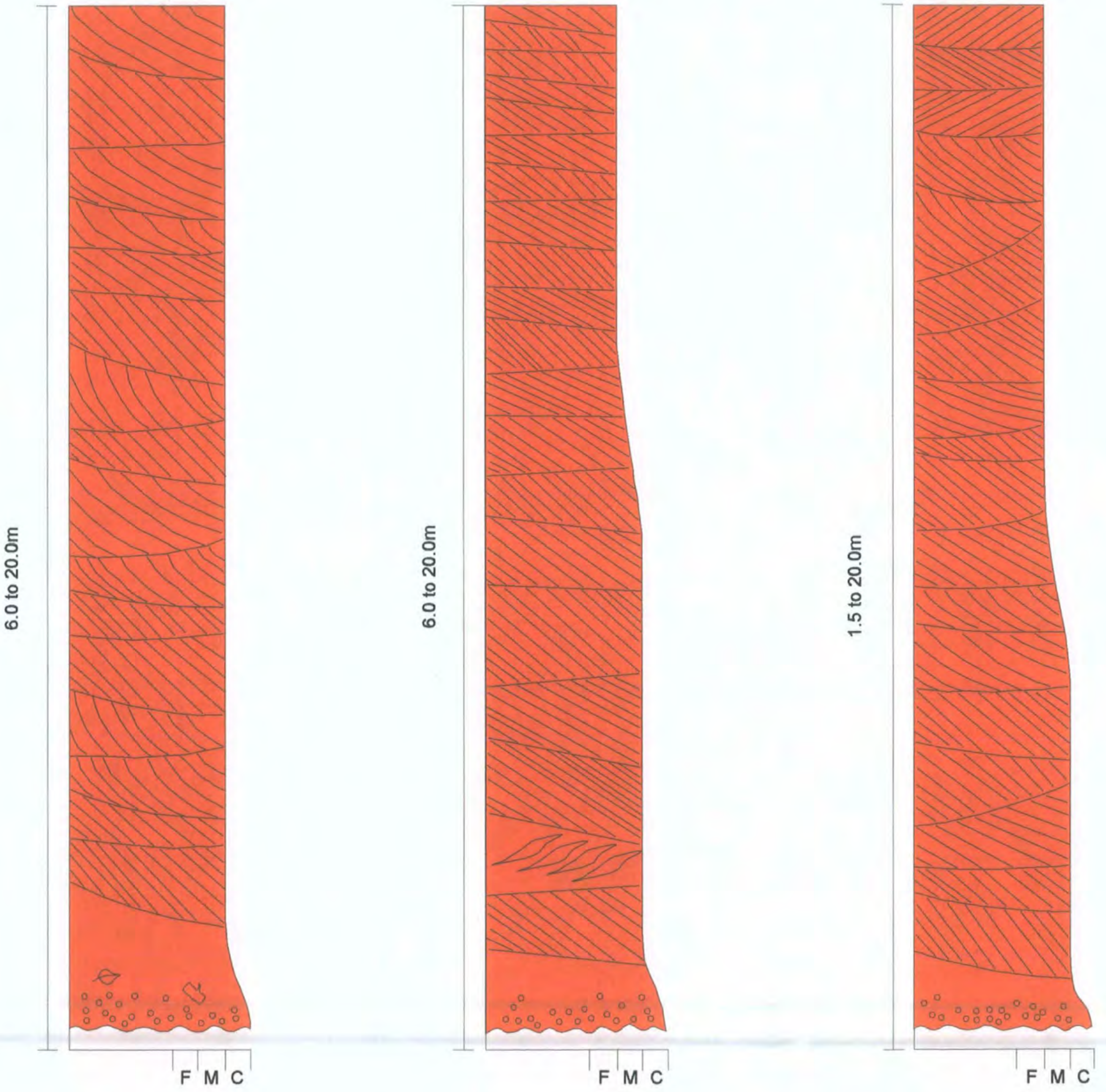
Occurrence and Bed Characteristics

This lithofacies is generally poorly exposed and only partial sections of the inferred sandstone bodies are ever observed, whether it be just the edges if the channel or just the main body of the channel; it is however not restricted to any particular area or time period and are found throughout the study area. The lateral extent is difficult to estimate; due to the channelised nature of the deposits they are difficult to correlate over large areas. This lithofacies is well exposed within the Sandbanks limestone cycle (Brigantian) at the Beadnell coastal section where it is known as the Dunstanburgh Sandstone (Grid reference NU 239287) (Ref. D4.1 in Appendix 2). This lithofacies can also be seen at the Spittal / Scremerston coastal section within the Dun limestone (Asbian) cycle (Grid reference NU 013508) (Ref D4.2 in Appendix 2).

The maximum thickness of this lithofacies ranges from 6 to 20m but due to the channelised nature of the lithofacies this may vary substantially depending on what section of the channel is observed. There are a higher number of thicker channels (those between 15 and 20m thick) within the Late Asbian and Early Brigantian outcrops in the north-east of the study area. Planar cross-bedding is present with the set thickness varying considerably throughout the area from 0.2 to 1.5m, although this remains uniform throughout individual channels. Planar and trough cross-bedding are well displayed throughout. Palaeocurrent directions are towards the south-west and are displayed in Figure 3-9.

The lithofacies generally erosively overlies sediments of D3 (proximal mouth-bar) or D8 lithofacies (interdistributary bay) (Figure 3-7). There is a gradational boundary with the overlying lithofacies which is most commonly that of D11 (palaeosoil) lithofacies. This lithofacies may also be laterally equivalent to D7 lithofacies (floodplain deposits).

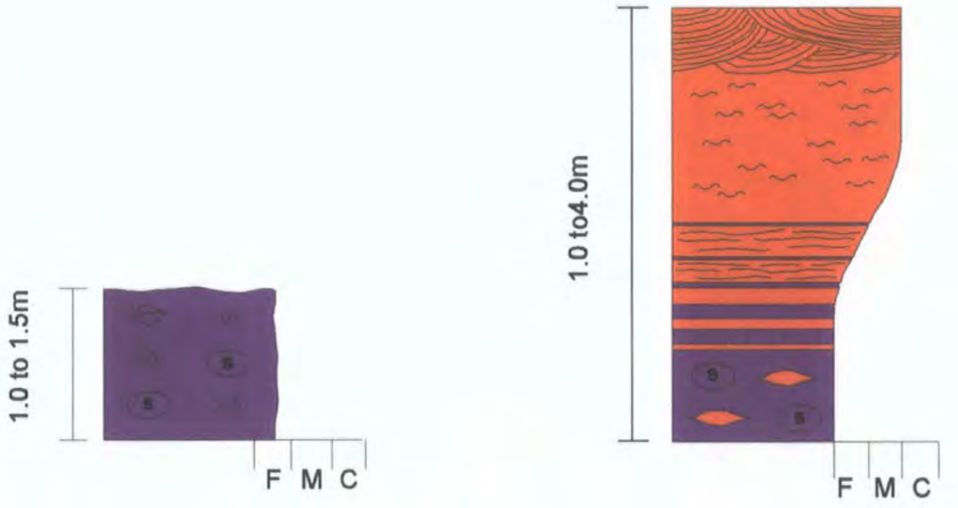
Figure 3-8 Schematic vertical sections of the delta plainlithofacies group. D4 lithofacies (braided distributary channel), D5 lithofacies (meandering distributary channel), D6 lithofacies (tidally-influenced distributary channel), D7 lithofacies (floodplain deposits), D8 lithofacies (interdistributary channel), D9 lithofacies (crevasse splay) and D10 lithofacies (levee deposits). D11 lithofacies (palaeosoils) is not shown as detailed descriptions are given in Chapter 5. Grain size indicator is shown along the bottom of each vertical section; F=fine-grained, M=medium-grained and C=coarse-grained. A full key has been provided with Figure 3-5.



D4 Braided distributary channel lithofacies

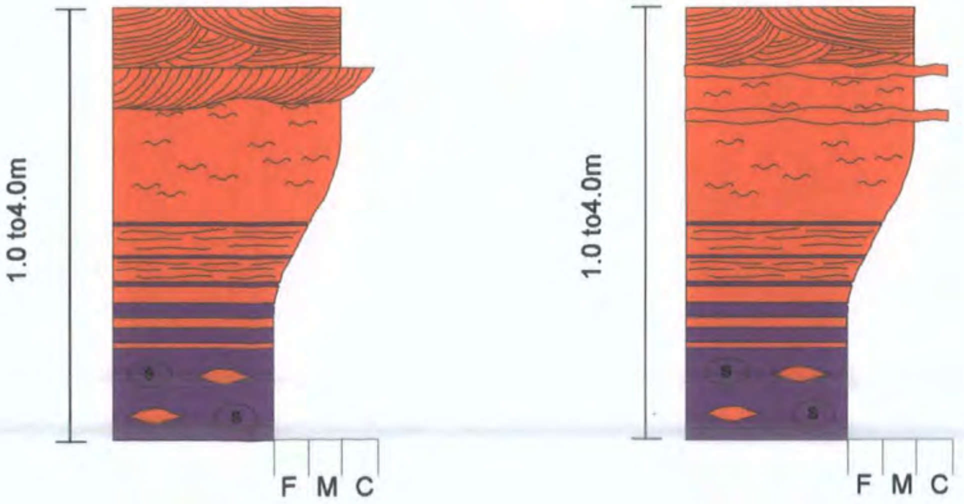
D5 Meandering distributary channel lithofacies

D6 Tidally-influenced distributary channel lithofacies



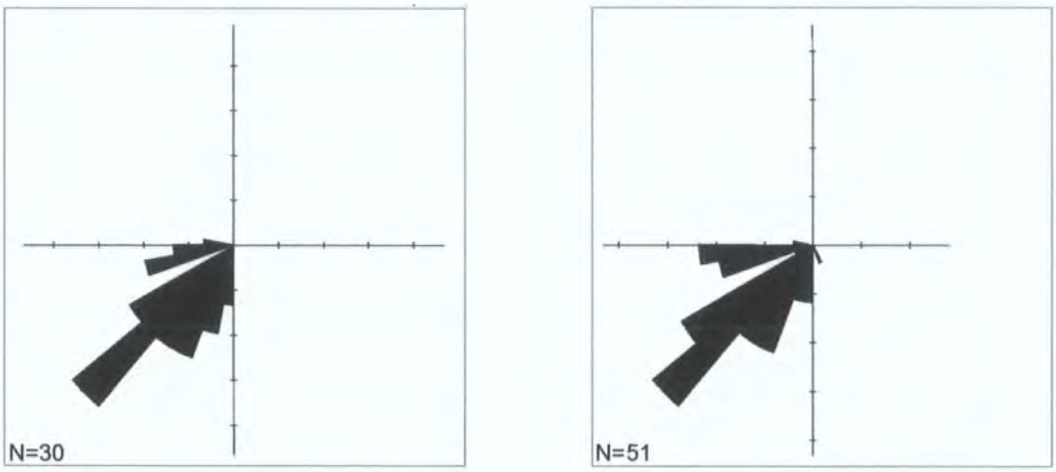
D7 Floodplain deposits lithofacies

D8 Interdistributary bay lithofacies



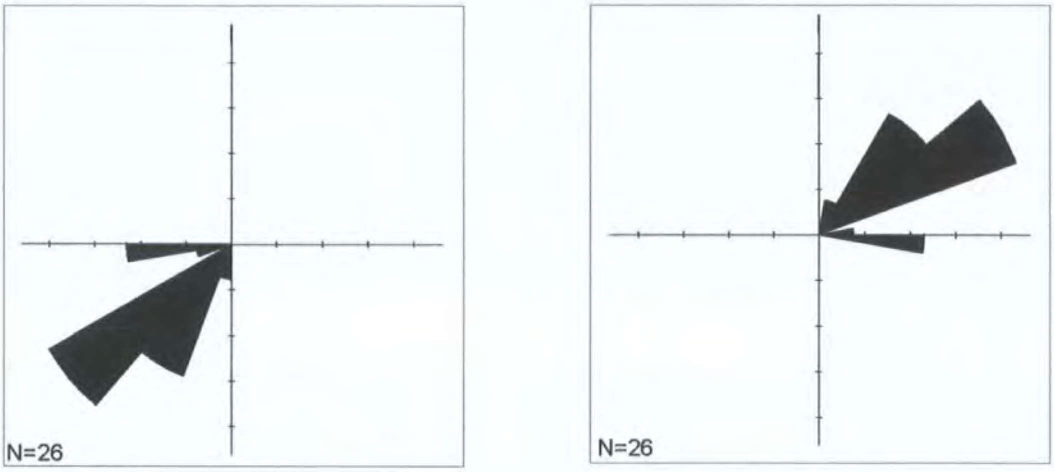
D9 Crevasse splay lithofacies (interbedded with D8 lithofacies)

D10 Levee deposits lithofacies (interbedded with D8 lithofacies)



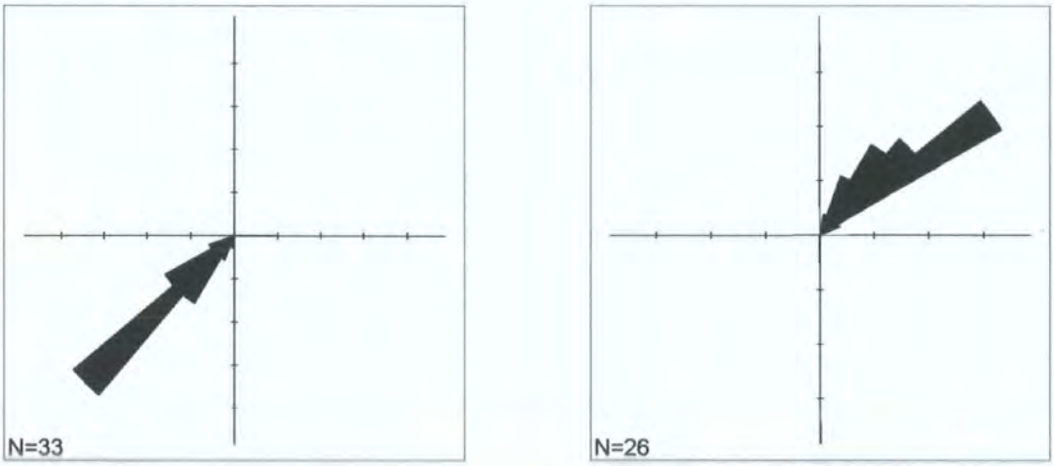
A. D4 Lithofacies (Braided Distributary Channel)

B. D5 Lithofacies (Meandering Distributary Channel)



C. D6 Lithofacies (Tidally-influenced Distributary Channel)

D. D9 Lithofacies (Crevasse Splay)



E. M4 Lithofacies (Upper Shoreface)

F. M7 Lithofacies (Washover Fan)

Figure 3-9 Palaeocurrent directions of various lithofacies within the Mid Carboniferous strata of Northumbria. A: D4 (braided distributary channel), B: D5 (meandering distributary channel), C: D6 (tidally-influenced distributary channel), D: D9 (crevasse splay). E: M4 (upper shoreface) and F: M7 (washover fan).

Figure 3-10 Field photograph of fossilised log at the base of D4 lithofacies at Beadnell. Thickness of log approximately 30cm.

Figure 3-11 Field photograph of carbonaceous plant fragments at base of D4 lithofacies. Photograph taken at Beadnell. Field of view approximately 1.2m.

Lithological Description

The medium-grained sandstone displays a uniform grain-size throughout the entire succession although there is often a basal layer of coarse-grained sandstone containing quartz clasts, 1 to 5mm in diameter. The sandstone is moderately- to well-sorted and is sub-rounded. Fossilised logs, carbonaceous plant fragments and coal lenses are commonly found at the base (Figures 3-10 and 3-11).

Interpretation: Depositional Environment

The restriction of this lithofacies within a channel-shaped unit and the erosive nature of its base have lead to its interpretation as channel and fill deposit. The initial coarseness of sediment at the base of the channel suggest powerful currents (e.g. Collinson 1968) forming a lag deposit (e.g. Miall 1992). Abundant plant debris at the base of the channel would have been swept into the channel during peak flow and would also indicate powerful currents (e.g. Collinson 1968). The cross-bedded sandstone reflects bedload transport. Trough cross-bedding forms by the unidirectional migration of linguoid or lunate bedforms, while planar cross-bedding forms by the migration of straight-crested dunes. All the features indicate deposition within a fluvial channel environment. Based on a lack of a fining-upward grain-size and lateral accretion surfaces, it is suggested that the depositional environment approached that of a low-sinuosity or braided fluvial environment; similar lithofacies are described by Martinius (2000) from the Late Oligocene to Early Miocene from the Lorca Basin, Spain. The location of this lithofacies within the mid to upper section of each cycle, its association with D3 and D8 lithofacies and the size of the sandstone unit, would infer that it was deposited as a distributary channel within the delta plain (e.g. Buttacharya & Walker 1992).

3.2.3.2D5 Lithofacies –Meandering Distributary Channel

Occurrence and Bed Characteristics

This lithofacies is generally poorly exposed and as in Lithofacies D4 (Section 3.2.3.1), only a section of the inferred sandstone body is ever observed. The lateral extent is difficult to estimate as due to the channelised nature of the deposits it is difficult to correlate over large areas. A good example of this lithofacies is seen within the Scar limestone cycle (Brigantian) at Bowlees Beck river section (Grid reference NY 906288) (Ref. D5.1 in Appendix 2) and within the Howick limestone cycle

Figure 3-12 Field photograph of lateral accretion surfaces (marked) within D5 lithofacies. Photograph taken at Howick. Height of notebook is 18cm for scale.

Figure 3-13 Field photograph of planar cross-bedding within D5 lithofacies. Photograph taken at Howick. Height of hammer is 30cm for scale.

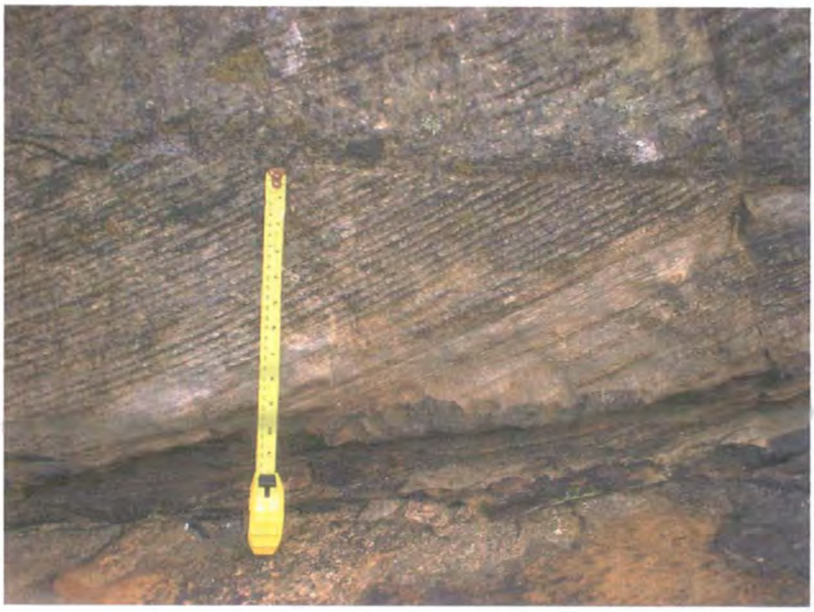


Figure 3-14 Field photograph of planar cross-bedding within D5 lithofacies. Photograph taken at Howick. Length of tape measure is 35cm for scale.

(Pendleian) at the Howick coastal section (Grid reference NU 263174) (Ref. D5.2 in Appendix 2).

D5 lithofacies is of similar thickness to those of the D4 (braided distributary channel) lithofacies (6 to 20m). This lithofacies however includes lateral accretion surfaces (Figure 3-12), planar bedding (Figures 3-13 and 3-14) with a decrease in set size from 1.2m to 0.1m, upwards through the unit. The palaeocurrent direction is towards the south-west (Figure 3-9).

This lithofacies is found erosively downcutting into sediments of D3 (proximal mouth-bar) or D8 (interdistributary bay) lithofacies. There is a gradational boundary with the overlying D11 (palaeosoil) lithofacies.

Lithological Description

This lithofacies is composed of fine- to medium-grained sandstones of varying colours, ranging from buff to pale red. The average composition of the sandstone is 91% quartz, 5% feldspar and 4% lithic fragments, being moderately- to well-sorted and sub-rounded. It displays a fining-upward trend with sandstone varying from medium-grained in the basal part of the channel to fine-grained at the top of the channel. A pebble lag is also found at the base of this lithofacies with coarse-grained sandstone being accompanied by small (1 to 5mm) well-rounded pebbles.

Interpretation: Depositional Environment

D5 lithofacies was deposited as a channel and fill deposit with initial powerful currents and bedload transport throughout (Section 3.2.3.1). Lateral accretion surfaces and upward-fining of the sandstone unit is consistent with deposition within the point bar of a fluvial channel. Deposition laterally infills the channel as it progressively erodes the opposite bank. Deposition of finer sediments occurs in the shallow, lower energy water on the point bar (e.g. Miall 1992 and Collinson 1996). The erosion of the cut bank and the deposition on the point bar lead to a gradual lateral and downcurrent shift in the position of the point bar resulting in lateral accretion surfaces (e.g. Miall 1992). The evidence gathered suggests point bar deposition within a fluvial environment which would be consistent with deposition in a meandering fluvial environment. The occurrence of this lithofacies within the mid part of each cycle and its association with D3 (proximal mouth-bar) or D8 (interdistributary channel) lithofacies indicates that this lithofacies was deposited as a meandering distributary channel within the delta plain.

3.2.3.3D6 Lithofacies – Tidally-Influenced Distributary Channel

Occurrence and Bed Characteristics

This lithofacies is only recognised from two localities which are concentrated in the north-east of the area, at Beadnell and at Spittal / Scremerston. One of the best examples of this lithofacies is within the Acre limestone cycle (Brigantian) at Beadnell coastal section (Grid reference NU 237293) (Ref. D6.1 in Appendix 2). However, they are not temporally restricted. The lateral extent is difficult to estimate; due to the channelised nature of the deposits it is difficult to correlate over large areas.

The total thickness of the lithofacies varies from 1.5m to 20m. Sandstones of this lithofacies exhibit all the features of the D4 and D5 (distributary channels) lithofacies described previously (Sections 3.2.3.1 and 3.2.3.2) but they are characterised by the presence of herringbone cross-bedding in the upper 2m of the lithofacies and locally display mud-draped symmetrical ripples.

The stratigraphic position of this lithofacies within each cycle is the same as those of D4 and D5 (distributary channels) (Sections 3.2.3.1 and 3.2.3.2).

Lithological Description

As the lithology is the same as the distributary channel lithofacies (D4 and D5) see Sections 3.2.3.1 and 3.2.3.2.

Interpretation: Depositional Environment

D6 lithofacies was deposited as channel and fill deposits, formed during transport of sediment as bedload (Section 3.2.3.1). The presence of mudstone drapes over cross-laminae reflects deposition from slack water (e.g. Shanmugam *et al.* 2000). This together with herringbone-cross bedding formed as a result of the reversal of currents, causing dunes and sand waves to change their direction of migration (Tucker 1990) and generally indicates deposition by tidal currents (e.g. Brettle *et al.* 2002). The presence of these two sedimentary structures indicates that tidal currents influenced the deposition of the fluvial channel. This feature is only noted at the top of channelised sandstones and would indicate that channel-fill was complete or near completion when tidal influences were in operation and suggests a period of sediment reworking.

3.2.3.4 D7 Lithofacies – Floodplain Deposits

Occurrence and Bed Characteristics

Outcrops of this lithofacies are limited to the very north-east region of the study area and are only found in the Late Asbian and Early Brigantian outcrops at Spittal / Scremerston. Such deposits can be found within the Woodend limestone cycle (Asbian) at this locality (Grid reference NU 015507) (Ref. D7.1 in Appendix 2). The generally poor quality of outcrop is due to the friability of the rocks. Lateral continuity is difficult to asses due to a lack of information for this area during the Late Asbian and Early Brigantian, but could be up to 50 to 100m.

The thickness of this lithofacies varies from 1.0 to 1.5m thick and commonly contains ripple lamination. Early diagenetic siderite nodules are regularly present within this lithofacies and nodules are generally elliptical and range from 2 to 20cm in diameter.

This lithofacies is commonly cut into by distributary channels (D4 and D5) is overlain by D11 (palaeosoil) lithofacies.

Lithological Description

The fresh surfaces of this lithofacies range from dark-grey to purple-coloured siltstone. Weathered surfaces tend to deeper in colour, being mid-grey to deep purple. Indeterminate carbonaceous plant fragments, ranging from 5mm to 50m in length and 2mm to 15mm in width are common. Plant fragments are abundant throughout the unit and form approximately 10% of the total composition.

Interpretation: Depositional Environment

The fine-grained nature of the sediments within this lithofacies is consistent with deposition out of suspension and once again a relatively quiet environment. Ripple lamination indicates the effects of traction currents (e.g. Shanmugam 1993). Plant fragments are found and although they are not *in situ* this would suggest a proximity to vegetation and that they were likely to be transported into the area by some form of flooding. The abundance of plant material could be due to storm activity which would have provided large amounts of surface runoff carrying large amounts of plant material (e.g. Nokajo *et al.* 2000). It has been postulated that wildfire episodes were common within the Carboniferous period, probably started by lightning strikes or volcanic activity (Scott & Jones 1994). Such fires would have had a dramatic effect on ecosystems causing severe erosion and causing large amounts of charred vegetation to be carried into depositional systems (Scott 2000; Scott *et al.* 2000). Wildfire could have therefore been a causal mechanism for the large amounts of plant material found within the Carboniferous rocks of the study area. The presence of siderite may indicate marsh-like conditions at least periodically (e.g. Moore *et al.* 1992). The various colours of the sediments will be discussed further in Section 6.4, but overall colour variations may indicate differing levels of water table (Retallack 1990). This information, in combination with a close proximity to D4 and D5 distributary channels, would indicate that this lithofacies formed as overbank deposits on a river floodplain; this lithofacies is similar to those described by Leeder (1974), Miall (1992) and Collinson (1996).

3.2.3.5 D8 Lithofacies – Interdistributary Bay

Occurrence and Bed Characteristics

This lithofacies is one of the most common in the study area with examples seen at every locality. A good example of interdistributary bay (D8) lithofacies is within the Oxford limestone cycle (Brigantian) at Beadnell coastal section (Grid reference NU 232302) (Ref. D8.1 in Appendix 2). The lateral extent is limited and cannot be traced for more than a few 100's of metres. A vertical log of D8 lithofacies can be seen in Figure 3-8.

D8 lithofacies forms units 1.0 to 4.0m thick. The basal component of the unit commonly contains early diagenetic siderite nodules and more locally, cross-lamination. Vertical burrows of approximately 5mm in diameter are common in the siltstone component of the unit and bioturbation commonly obscures any lamination. The sandstone component of the unit contains both symmetrical and asymmetrical ripples which are commonly multidirectional. Small lenses of grey mudstone are often found in the sandstone part of the unit. The sandstone is often laminated.

The lithofacies is found overlying the D1 (prodelta) lithofacies and is commonly incised by distributary channels of D4, D5, or D6 lithofacies. This lithofacies can also be laterally correlated with distributary channels.

Lithological Description

Each unit of this lithofacies comprises of dark grey shale at the base, dark to mid-grey siltstone, silty sandstone and then fine-grained sandstone in various colours including buff, pale grey, purple, pale pink and red. The sandstone parts of the unit is moderately sorted and sub-angular to sub-rounded. The average composition of the sandstone is 91% quartz, 3% feldspar and 6% lithic fragments and is often visibly micaceous on lamination surfaces.

Interpretation: Depositional Environment

The general increase in grain-size from shale to fine-grained sandstone and the presence of bedload structures indicates an increase in current velocity related to a decrease in water depth (e.g. Miall 1992) probably in relation to an increased proximity to a sand source (Section 3.2.2.2.) (e.g. Tucker 2001). The presence of both current- (asymmetric) and wave-formed (symmetric) ripples indicates unidirectional currents and bidirectional wave activity respectively, while the formation of trough cross-bedding indicates deposition from three dimensional dunes (i.e. Collinson 1968). The upward change in sedimentary structure from ripples to cross-bedding upwards reflects a shallowing-upward trend associated with increasing energy (Section 3.2.2.2). The heterogeneity of the unit and the presence of high levels of bioturbation indicate fluctuations in deposition allowing time for colonisation to take place, possibly related to tides, storms or river discharge (Taylor *et al.* 2003). The lateral discontinuity of this lithofacies would suggest that the depositional environment was not laterally extensive and occurred in discrete areas. The lateral correlation of this lithofacies with distributary channels of D4 and D5 lithofacies indicates that this lithofacies was geographically bound by distributary channels. The association of this lithofacies with those of the D1 (prodelta) lithofacies and the downcutting of distributary channels of D4 to D6 lithofacies into this unit, and more importantly the fact that this unit can be laterally correlated to distributary channels would indicate that the depositional environment was that of an interdistributary bay (e.g. Qayyum *et al.* 1996). Interdistributary bays are areas between distributary channels within a deltaic environment. Although this lithofacies has affinities with features displayed by other coastal bay lithofacies, there is a lack of glauconite in the sand beds and any features indicative of shoreline processes such as low-angle cross-bedding, and herringbone cross-bedding (e.g. Shanmugam *et al.* 2000). The presence of both small- and medium-scale distributary channels within this environment also suggests an interdistributary bay environment rather than any other type of coastal bay (e.g. Reading & Collinson 1996).

3.2.3.6 D9 Lithofacies – Crevasse Splay

Occurrence and Bed Characteristics

The exposure of this lithofacies is good and can be found at the majority of the outcrops studied. An example of this lithofacies is found within the Great limestone cycle (Pendleian) at Haltwhistle Burn river section (Grid reference NY 714659) (Ref. D9.1 in Appendix 2). The erosive-based small-scale channels / sheets have a limited lateral extent and can be traced at outcrop for a maximum of 5m and no further.

The lithofacies is characterised by a single erosive-based sandstone within either the D8 (interdistributary channel) lithofacies or the D7 (floodplain deposits) lithofacies. Thickness ranges from 0.4 to 2.5m and contains a single set of trough cross-bedding or cross-lamination. This lithofacies may be sheet-like in morphology but is more commonly lens- or channel-shaped and can vary in width from 0.5 to 10m. Locally, lateral accretion surfaces are present. Both burrows and symmetrical ripples are locally found at the top of this lithofacies. Palaeocurrent directions are displayed in Figure 3-9.

This lithofacies is laterally equivalent to any of the distributary channel lithofacies. A graphic log of this lithofacies is seen in Figure 3-8.

Lithological Description

The sandstone within this lithofacies is a fine- to medium-grained, buff to pale pink sandstone. The average composition of the sandstone is 89% quartz, 5% feldspar and 6% lithic fragments. The sandstone is poorly- to moderately-sorted and is sub-angular. Locally, carbonaceous plant fragments are found within the unit.

Interpretation: Depositional Environment

Due to similarities with medium-scale meandering distributary channels (Section 3.2.3.2) this lithofacies has been interpreted to have been deposited associated with a meandering distributary channel environment. As such units are often discrete lenses of sandstone within mudstone / siltstone of D8 (interdistributary channel) lithofacies it would it is implied that such deposits were laid down by density currents. Symmetrical ripples form due to wave-activity indicating reworking. The erosive nature of this lithofacies within D8 (interdistributary channel) or D7 (floodplain deposits) lithofacies, lateral correlation with distributary channels and the palaeocurrent direction that is perpendicular to the regional palaeocurrent direction in addition to the sedimentary features and morphology of the unit would indicate deposition as a crevasse splay deposits. Sheet-sand morphology or discrete lenses of sandstone within mudstones and siltstones are common within crevasse splays where they are deposited as density currents. The ripples found on the surface indicating wave activity is also a common feature of crevasse splays as they are reworked into small sand spits.

3.2.3.7 D10 Lithofacies – Levee Deposits

Occurrence and Bed Characteristics

The occurrence of this lithofacies is common but can only be correlated laterally up to a maximum of 2m. An example of this can be found within the Great limestone cycle (Pendleian) at Haltwhistle Burn river section (Grid reference NY 714569) (Ref. D10.1 in Appendix 2).

This lithofacies is characterised by the presence of numerous thin sandstone beds found interbedded with D8 (interdistributary bay) lithofacies (Figure 3-8). The sandstone beds range in thickness from 0.1 to 0.7m. The thickness and frequency of the sandstone beds increases upward from 10% to 80% within the lithofacies mentioned.

Lithological Description

The main lithology is fine-grained buff to pale purple sandstone which is interbedded gradationally with dark to mid-grey siltstone, shale or claystone. Fine carbonaceous rootlets and vertical burrows are common in the sandstone in the upper half of the lithofacies.

Interpretation: Depositional Environment

The main diagnostic feature of this lithofacies is the interbedded nature which would indicate alternating bedload and suspension transport suggesting fluctuating currents. This is emphasised by the occurrence of vertical burrows which could only be established during times of low sediment supply or current fluctuations. The presence of rootlets *in situ* suggests that plants had sufficient time to colonise the area and as these are only found in the upper half of the unit also indicates decreasing sediment supply and / or a shallowing trend. The very small-scale coarsening-upward nature of the lithofacies suggests an overall increase in current velocity and a decrease in water depth (Section 3.2.2.2). The thickness of the units, the interpreted sedimentary structures and the association of this lithofacies with those of the D8 (interdistributary bay) lithofacies would indicate that this lithofacies probably formed as levee deposits on the flanks of distributary channels; these occur on both the upper and lower delta plain (e.g. Collinson 1996).

3.2.3.8 D11 Lithofacies - Palaeosoils

Occurrence and Bed Characteristics

Sediments of this lithofacies vary greatly throughout the area and are described more thoroughly in Chapter 5.

Thickness of this lithofacies varies from 0.2 to 1.2m. Occurrence of this lithofacies is very common and is found at the top of 95% of all cycles.

Lithological Description

Lithologies range from fine-grained pale grey to buff siliceous sandstone, to mid-grey siltstone, to dark grey shale. This lithofacies contains one or more of the following features: carbonaceous plant fragments, fine carbonaceous rootlets, *Stigmaria* imprints, carbonate nodules, ferric rhizocretions and colour mottling.

Interpretation: Depositional Environment

In situ fine carbonaceous rootlets, *Stigmaria* imprints and ferric rhizoconcretions all indicate the colonisation of plants within this unit and would suggest that this lithofacies was a palaeosoil or 'fossil soil'. The occurrence of this lithofacies at the top of each cycle prior to the deposition of marine limestone would also indicate that it was an exposure surface prior to the onset of a marine transgression although evidence suggests that vertical packages of palaeosoils that underlie a marine limestone may be evidence of a marine transgression. The features displayed in this unit vary significantly both temporally and spatially throughout the study area and are discussed in detail in Chapter 5.

3.2.3.9 Delta Plain Lithofacies Group Summary

The delta plain lithofacies group consists primarily of numerous distributary channels that down-cut into interdistributary bay sediments. The dominant environments of deposition were fluvial with many interfluvial deposits resulting from slack water conditions during overbank conditions. The lateral variation within this depositional environment was immense meaning that the lateral extent of each lithofacies can be very limited. The effects of tides and waves are minimal.

3.2.4 Delta Lithofacies Association Summary

The deltaic succession seen in the Mid Carboniferous of Northern Britain is generally progradational, with active seaward progradation resulting in the prodelta muds being overlain by delta front silts and sands which in turn are overlain by delta plain sediments (Reading & Collinson 1996). This succession is repeated and terminates in a more regressive lithofacies as the entire delta progrades seawards, providing the rate of deposition exceeds the rate of subsidence (Miall 1976). The cessation of delta progradation occurs when a marine transgression floods the delta plain and carbonate platform lithofacies are deposited. The overall interpretation of the Northern Britain deltaic system is that it was deposited as a river-dominated delta (e.g. Elliott 1976) although more recent work has suggested that the role of tides, storms and waves has been highly underestimated (e.g. Reynolds 1992). A full environmental reconstruction of the delta lithofacies association is seen in Figure 3-15.

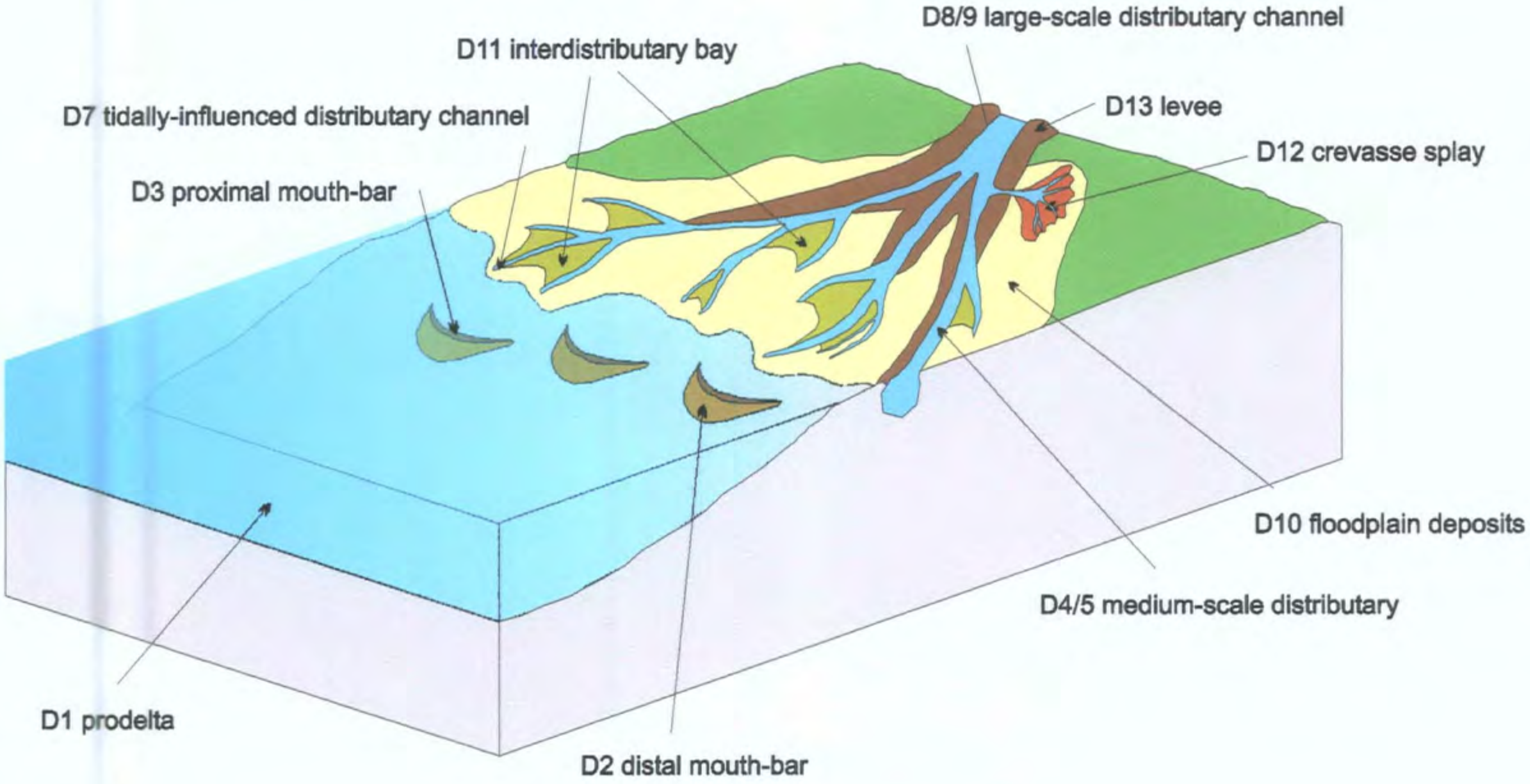


Figure 3-15 Palaeoenvironmental reconstruction of the Mid Carboniferous delta setting. The reconstruction shows the likely depositional environments of the major lithofacies identified in this study.

Table 3-5 Table summarising the major components of each lithofacies and lithofacies group of the marine shoreline lithofacies association from the Mid Carboniferous succession of Northumbria.

acies group and facies	Lithologies	Location within each cycle	Unit thickness	Morphology	Lateral continuity	Fossils	Sedimentary structures	Example
grading Shoreline Lithofacies Group								
- Offshore elf	Dark-grey shale, lenses of fine-grained pale-grey sandstone	Base of cycle: overlies carbonate platform llithofacies, overlain by M2 lithofacies	0.5 to 1.3m	Planar beds	100s of metres to kms	Abundant broken fossil debris: crinoids, bryozoan and brachiopods	Sandstone lenses, symmetrical ripples	Cockleshell limestone cycle at Bowlees
- Nearshore elf	Interbedded pale- to mid-grey quartz arenitic sandstone, silt and shale	Near base of cycle; overlain by M3 lithofacies, underlain by M1 lithofacies	0.9 to 3.5m	Planar beds	Metres to 10s of metres	Bioturbation common	HCS throughout. Local symmetrical ripples and planar cross-bedding.	Cockleshell limestone cycle at Bowlees
- Lower oreface	Interbedded pale-grey quartz arenitic sandstone, silt and shale	Mid cycle	0.8 to 2.0m	Planar beds	Metres to 10s metres	Bioturbation common	Low-angle planar cross-bedding, symmetrical ripples	Sandbanks limestone cycle at Howick
- Upper oreface	Fine- to medium-grained buff and pale-grey sandstone	Top of cycle	1.8 to 2.5m	Planar beds	Metres to 10s of metres	Bioturbation common	Low-angle planar cross-laminae	Little limestone cycle at Haltwhistle
ansgressive Shoreline Lithofacies Group								
- Tidal annel	Pale-grey fine- to medium-grained sandstone	Top of cycle	0.5m	Channel / lens-shaped unit with erosive base	Unknown	Disarticulated Poductid shells not *in situ* at base of unit	Planar and trough cross-bedding and lateral accretion surfaces	Little limestone cycle at Haltwhistle
- Tidal-flat	Alternate beds of fine- to medium-grained quartz arenite and dark-grey shale	Top of cycle; overlain by M5 tidal channel lithofacies	1 to 2m	Planar beds	Metres	Carbonaceous plant fragments locally found at top of unit	Lenticular, flaser and wavy bedding. Wave ripples and herringbone cross-bedding in upper part of unit	Little limestone cycle at Haltwhistle
- Washover	Fine- to medium-grained buff quartz arenite	Top of cycle	0.5 to 1.25m	Planar beds	Metres to 10s of metres	Vertical burrows towards top of unit	Low-angle planar cross-bedding throughout. Symmetrical ripples at top of unit.	Harthorpe ganister (Percival 1992)
- Estuary	Alternating beds of siltstone, medium-grained pale- to mid-grey sandstone, silty-sandtsone and dark-grey shale	Top of cycle	6m	Planar beds	Unknown	Bioturbation and vertical burrows common towards base of unit	Mud-draped symmetrical ripples and shale lenses	Scar limestone cycle at Bowlees

Table 3.6 Table summarising the major components of each lithofacies and lithofacies group of the carbonate platform lithofacies association from the Mid Carboniferous succession of Northumbria.

acies group and facies	Lithologies	Location within each cycle	Unit thickness	Morphology	Lateral continuity	Fossils	Sedimentary structures	Example
arbonate Platform Lithofacies Group								
- Deep water w energy	Fine-grained, dark to very dark-grey lime mudstone / wackestone	Very base of carbonate component of cycle	30 to 170cm	Planar beds	100s of metres to kms	Limited amounts of very small (<3mm) crinoid and brachiopod fragments. Locally larger (up to 20mm) fragments of trilobites and solitary corals. *Rhizocorallium* and *Zoophycos* on bedding surfaces	Laminae, but locally beds may be massive	Majority of outcrops
- Shallowing-ward	Mid- to dark-grey wackestone to packestone	Above C1 lithofacies	10 to 130cm	'Wavy' beds	100s of metres to kms	Fossil fragments concentrated into lenses. Crinoids, brachiopods, bryozoan, solitary corals, tabulate branching corals and trilobites. *Zoophycos*, *Rhizocorallium* and *Planolites* are common	Lenses of fragmented fossils	Majority of outcrops
- ansgressive / allow water	Medium-grained mid-grey bioclastic packstone	Above C1 or C2 lithofacies	60 to 80cm	Planar beds, commonly with erosive base	10s to 100s of metres	Small (<2mm) disarticulated fragments of crinoids, brachiopods and general shell hash	Presence of quartz clasts (3mm) at base of unit	Sandbanks limestone at Beadnell
- Shallow ter / very stricted	Pale-green calcareous jmudstone	Mid cycle	60cm	Single planar bed	100s of metres to kms	Spherical oncoids (diameter 30 to 60mm)	None visible	Woodend limestone cycle at Spittal / Scremerston
- Shallow ter / semi-stricted	Mid-grey wacke / pack / grainstone	Base of cycle	4m	Planar beds	100s of metres to kms	Broken fossil fragments of crinoids, brachiopods, horn corals and bryozoan, often found in clusters. Dark-red 'algal haloes' around bioclastic fragments	None visible	Oxford limestone at Spittal

3.3 MARINE SHORELINE LITHOFACIES ASSOCIATION

Marine shoreline lithofacies association makes up 15% of the entire Northumbrian succession as seen in Figure 3-1A. Marine shoreline deposits of the Mid Carboniferous of Northumbria are described by a handful of authors (e.g. Percival 1992) although their occurrence may have been underestimated. There are two major groups recognised within this lithofacies according to their position within each cycle; the progradational shoreline group and the transgressive shoreline group. A table summarising the major components within each of the lithofacies within this association can be seen in Table 3-5.

3.3.1 Prograding Shoreline Lithofacies Group

Sediments of the prograding shoreline group make up 8% of the entire succession of Northumbria (Figure 3-1B). Lithofacies from this group are found from the base of each cycle and may dominate the siliciclastic component of each cycle until the return of the carbonate lithofacies heralding the beginning of a new cycle. Graphic logs for all of the lithofacies within this group can be seen in Figure 3-16.

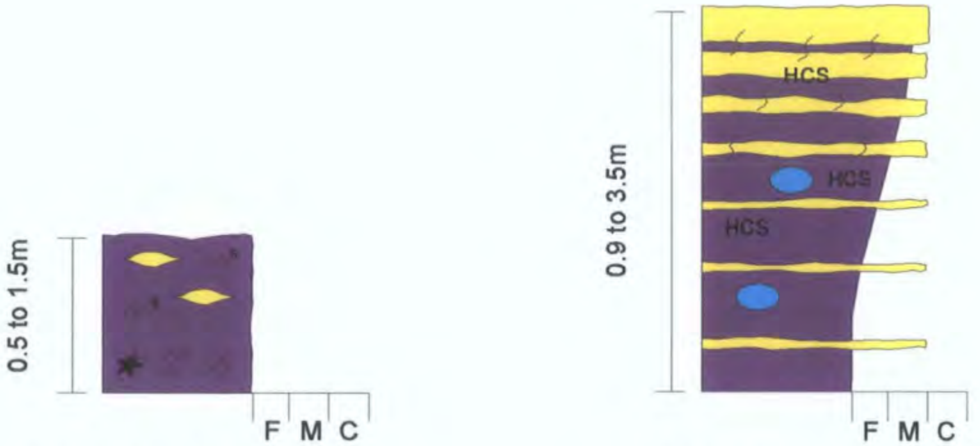
3.3.1.1 M1 Lithofacies – Offshore Shelf

Occurrence and Bed Characteristics

Sediments of this lithofacies are commonly eroded by modern coastal and fluvial processes but they can often be correlated for kms. An example of this lithofacies is seen at the base of the Cockleshell limestone (Brigantian) at Bowlees Beck river section (Grid reference NY 907283) (Ref. M1.1 in Appendix 2).

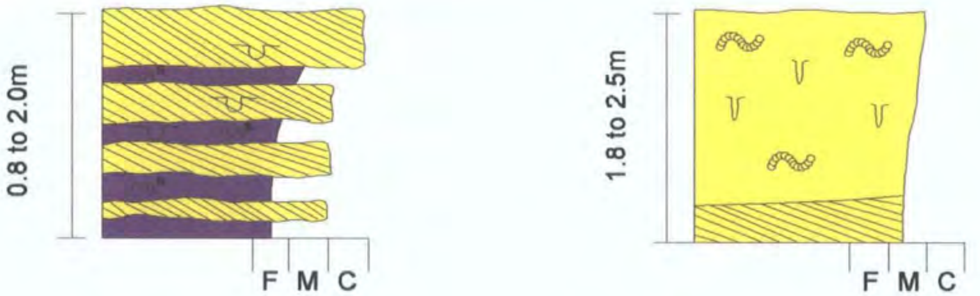
This lithofacies is 0.5 to 1.5m thick. Symmetrical wave lamination (Figure 3-17) is found towards the top of the lithofacies in addition to lenticular bedding, with lenses 10 to 20cm in length and up to 4cm in height.

This lithofacies normally has a sharp and planar boundary with the underlying carbonate lithofacies at the very beginning of the cycle and commonly grade upwards into sediments of the M2 (nearshore shelf) lithofacies.



M1 Offshore shelf lithofacies

M2 Nearshore shelf lithofacies



M3 Lower shoreface lithofacies

M4 Upper shoreface lithofacies

Figure 3-16 Schematic vertical sections of the prograding shoreline lithofacies group. M1 lithofacies (offshore shelf), M2 lithofacies (nearshore shelf), M3 lithofacies (lower shoreface), M4 lithofacies (upper shoreface). Grain size indicator is shown along the bottom of each vertical section; F=fine-grained, M=medium-grained and C=coarse-grained. A full key has been provided with Figure 3-5.

Figure 3-17 Photograph of symmetrical wave lamination in plan view. Photograph taken at Spittal coast section. 'Snowman' is 15cm in height for scale.

Figure 3-18 Photograph of possible hummocky cross-stratification. Photograph taken at Howick coast section. Pen is 8cm for scale.

Lithological Description

The lithology of the M1 lithofacies consists of dark-grey shale containing abundant fine-grained pale-grey sandstone lenses. The base of the lithofacies contains abundant broken fossil debris (<5mm in size) including crinoids, bryozoa, brachiopods and other shelly fragments.

Interpretation: Depositional Environment

The thick laminated mudstone units characteristic of this lithofacies are indicative of deposition in quiet and probably moderately deep waters, well away from the main sediment supply, or during times when supply was diminished (e.g. Witton 1999). The presence of symmetrical ripples in the upper part of the lithofacies, however,

would indicate that quiet conditions were being replaced by higher energy conditions with bidirectional currents dominant, indicating wave- or tide-formed structures (e.g. Shanmugam *et al.* 2000). Lenses of fine-grained sandstone are also indicative of punctuated higher energy influxes of sediment towards the top of the lithofacies (e.g. Chakraborty *et al.* 2003). Marine conditions appear to be prevalent with the presence of marine fossils at least in the lower part of the lithofacies. There is no evidence of brackish water conditions and the gradational boundary with the M2 (nearshore shelf) lithofacies would suggest that this lithofacies remained marine throughout. The nature of the deposits and the association with the overlying lithofacies indicates that the depositional environment was an offshore shelf (e.g. Reading & Collinson 1996).

3.3.1.2M2 Lithofacies – Nearshore Shelf

Occurrence and Bed Characteristics

This is found at all stratigraphic levels and throughout the area. There are several very good outcrops such as that found within the Cockleshell limestone cycle (Brigantian) at Bowlees Beck river section (Grid reference NY 907283) (Ref. M2.1 in Appendix 2). The lithofacies can be correlated for 10s of metres.

Total thickness of this lithofacies ranges from 0.9 to 3.5m. Sandstone beds become thicker (from 2cm to 30cm) and much more abundant upward (25% to 90%) through the local sandstone unit resulting in a coarsening-upwards unit, and they commonly have abrupt bases. Hummocky-cross stratification (Figure 3-18) is seen throughout this lithofacies (with wavelengths of 10cm and wave magnitude of 1 to 2cm) in addition to symmetrical ripples and thin planar cross-bedding. Lenses of mudstone are visible in addition to calcareous nodules which are elliptical in shape and range in diameter from 3cm to 15cm. These decrease in abundance upwards (from 20% to zero).

This lithofacies commonly gradationally overlies M1 (offshore shelf) lithofacies, and grades upwards into M3 (lower shoreface) lithofacies.

Lithological Description

This lithofacies comprises of interbedded pale to mid-grey quartz arenitic sandstone, silt and shale. Indeterminate bioturbation is common especially towards the top of the sequence which greatly disrupts bedding.

Interpretation: Depositional Environment

The typical coarsening-upward nature of this succession and an overall incoming of bedload structures such as ripple-lamination, indicates an increase in current velocity and a decrease in water depth (e.g. Miall 1992). This feature is also indicated by an increase in scale of bedload structures from asymmetrical ripple to trough cross-bedding as discussed in lithofacies D3 (proximal mouth-bar) and D8 (interdistributary bay) (Sections 3.2.2.2 and 3.2.3.5). Symmetrical ripples result from the action of waves on non-cohesive sediment (e.g. Tucker 2001). The alternating laminae described are a result of alternating bedload and suspension transport (e.g. Brettle *et al.* 2002), and the presence of lenticular-bedding indicates fluctuation in sediment supply or level of current activity (Section 3.3.1.1) (e.g. Chakraborty *et al.* 2003) as does the presence of bioturbation at the top of this unit (Section 3.2.3.5), so these would indicate the tide- and wave-influence on the depositional environment. Quartz arenite sandstone also suggests the reworking of sediments consistent with tide and / or wave activity. Hummocky cross-stratification is diagnostic of storm deposition and is consistent with the presence of abrupt bases of the sandstone beds which would also suggest formation due to storm winnowing. The association of this lithofacies with the M1 (offshore shelf) and M3 (lower shoreface) lithofacies, in combination with the interpreted sedimentary structures would suggest a nearshore shelf depositional environment. This lithofacies has close affinity with similar

Figure 3-19 Field photograph of low-angle cross bedding within M3 lithofacies. Photograph taken at Howick. Length of mobile telephone is 10cm for scale.

Figure 3-20 Field photograph of possible escape burrows within M3 lithofacies. Photograph taken at Howick. Lens cap is 5cm in diameter for scale.

depositional environments described by Ahmed & Osman (1999) from the Upper Palaeozoic sequence in southeastern Sinai, Egypt.

3.3.1.3 M3 Lithofacies – Lower Shoreface

Occurrence and Bed Characteristics

This lithofacies is found at various stratigraphic levels and throughout the study area. The best of example of this is seen at the Howick coastal section within the Sandbanks limestone cycle (Brigantian) (Grid reference NU 259185) (Ref. M3.1 in Appendix 2).

The thickness of the entire lithofacies ranges from 0.8 to 2.0m with individual beds being up to 0.5cm. Low-angle (5° to 20°) planar cross-bedding (Figure 3-19), with sets of 20 to 40cm, is the dominant sedimentary structure within the lithofacies although symmetrical ripples are also common.

M3 lithofacies gradationally overlie those of the M2 (nearshore shelf) lithofacies and in turn are gradationally overlain by those of M4 (upper shoreface) lithofacies.

Lithological Description

Interbedded pale grey quartz arenitic sandstone, silt and shale are the dominant lithologies of this lithofacies. Bioturbation in the form of escape burrows (Figure 3-20 is common throughout.

Interpretation: Depositional Environment

The interbedded nature suggests fluctuating currents and periodic influxes of sediment (Section 3.3.1.2), which is also inferred from the occurrence of lenticular bedding. The common occurrence of escape burrows would also suggest periodic sediment influxes. Wave (symmetrical) ripples and low-angle indicates formation in from shoreline processes. This is consistent with the quartz arenitic composition of the sandstone component of the unit, which would have resulted from sediment reworking by either wave or tidal processes (Section 3.3.1.2), a hypothesis supported by the presence of wave-ripples. The features displayed by this lithofacies in addition to its stratigraphic position between M2 (nearshore shelf) and M4 (upper shoreface) lithofacies would suggest that this lithofacies formed in a lower shoreface environment.

3.3.1.4M4 Lithofacies – Upper Shoreface

Occurrence and Bed Characteristics

The lithofacies can be traced laterally for 10s of metres. Outcrops tend to be very good and often form cliffs and crags. Good examples of this lithofacies are seen within the Sandbanks limestone cycle (Brigantian) at Howick coastal section (Grid reference NU 259185) (Ref. M4.1 in Appendix 2) and within the Little limestone cycle (Pendleian) at the Haltwhistle Burn river section (Grid reference NY 710656) (Ref. M4.2 in Appendix 2).

The thickness of the lithofacies ranges from 1.8 to 2.5m and is composed of low-angle (10° to 30°) planar cross-laminated sandstone. Many of the sandstone laminae are draped with mudstone. Palaeocurrent direction is predominantly towards the south-west (Figure 3-9).

Sediments of M4 (upper shoreface) lithofacies are commonly found gradationally overlying the M3 (lower shoreface) lithofacies, and these are commonly overlain by D14 (palaeosoil) lithofacies.

Lithological Description

This lithofacies consists of predominantly fine- to medium-grained buff and pale grey quartz arenites. The sandstone within this lithofacies is well- to very well-sorted and is rounded. Vertical burrows and *Eione* traces (Figures 3-21 and 3-22) are common in the upper part of the lithofacies.

Interpretation: Depositional Environment

Planar cross-bedding is formed by the migration of straight-crested dunes (e.g. Tucker 2001) and the low-angle dip of the foresets indicates the action of shoreline processes (e.g. Scheiber 1994; Collinson 1996). Mud-draped laminae as mentioned previously in Section 3.2.3.4, reflect deposition from slack water during tidal-current reversals (e.g. Shanmugam *et al.* 2000). Quartz arenite composition suggests extensive reworking of sediment which would readily occur in shallow-marine

Figure 3-21 Field photograph of a vertical burrow (marked) within M4 lithofacies. Photograph taken at Howick. Pen is 15cm in length for scale.

Figure 3-22 Field photograph of *Eione* within M4 lithofacies. Photograph taken at Howick. Pen is 15cm in length for scale.

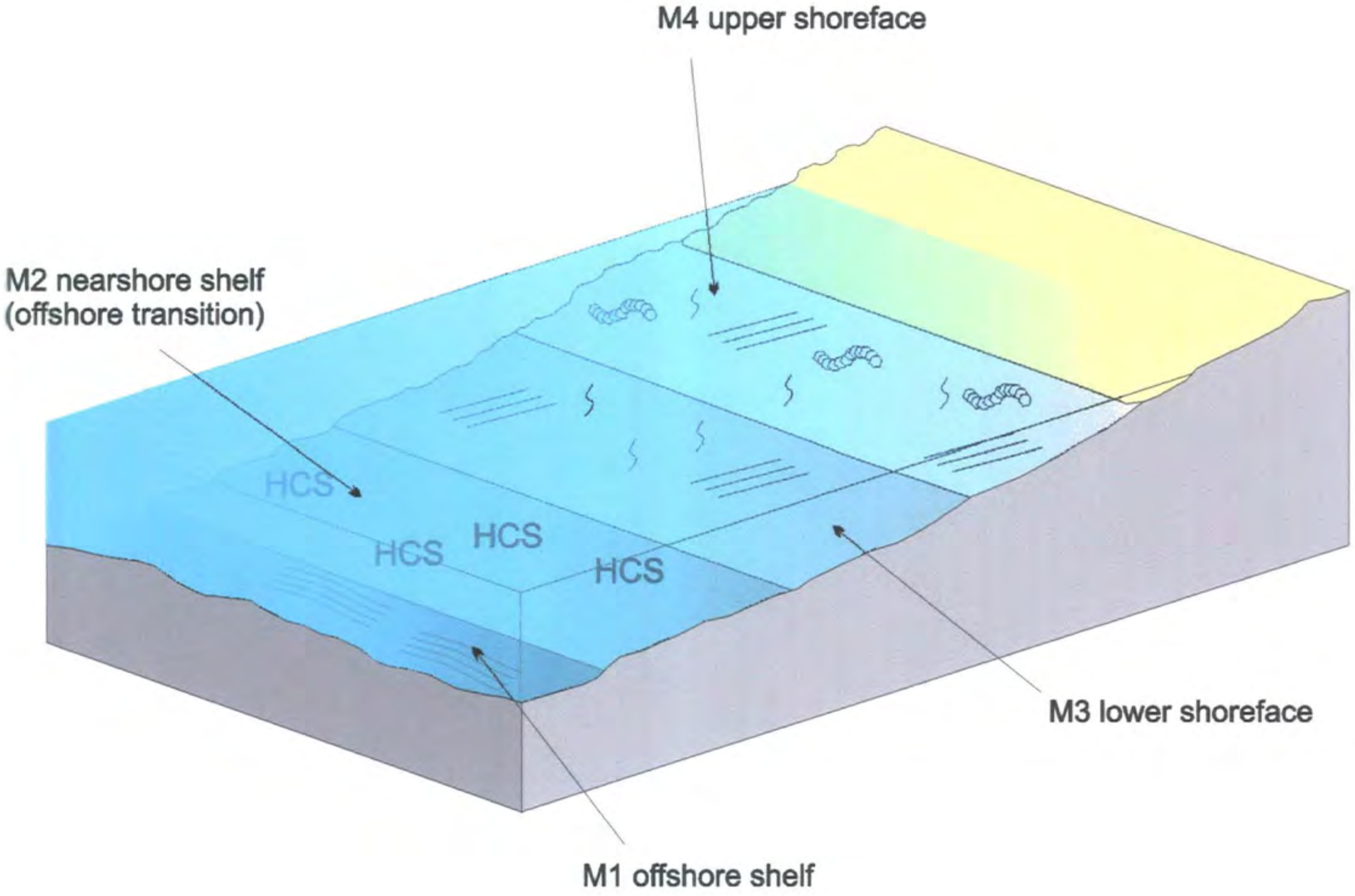


Figure 3-23 Palaeoenvironmental reconstruction of the Mid Carboniferous prograding shoreline setting. The reconstruction shows the likely depositional environments of the major lithofacies identified in this study.

conditions. Vertical burrows such as *Skolithos* are common in shifting substrates which would also reflect reworking of sediments (e.g. Taylor *et al.* 2003). As this lithofacies overlies the M3 (lower shoreface) lithofacies, and in light of all the features described, this lithofacies can be interpreted as forming in an upper shoreface environment. As the palaeocurrent direction is similar to the regional palaeocurrent direction it can be assumed that this lithofacies formed as part of a prograding shoreface. This lithofacies shows affinities with upper shoreface environments described by Elliott (1975) from the study area, and by Payenberg *et al.* (2003) from the Late Cretaceous of Alberta and Montana, USA.

3.3.1.5 Prograding Shoreline Lithofacies Group Summary

Prograding shoreline deposits generally occur as sand spits and beaches which occur at the seaward end of open interdistributary bays and result from wave action on sediment redistributed laterally from adjacent mouth-bars by longshore currents (Reading & Collinson 1996). The occurrence of such deposits overlying platform carbonate lithofacies and their general shallowing-upward would suggest that they formed in a progradational shoreline environment. A full environmental reconstruction of the prograding shoreline lithofacies group is seen in Figure 3-23.

3.3.2 Transgressive Shoreline Lithofacies Group

This lithofacies group represents 7% of the total succession as seen in Figure 3.1A. This group is distinctively different from the prograding shoreline lithofacies group in that it is only found near the top of each cycle. Quartz arenitic sandstones dominate the group but incidental amounts of mud and silt are also found. Graphic logs of all of the lithofacies within this group can be seen in Figure 3-24.

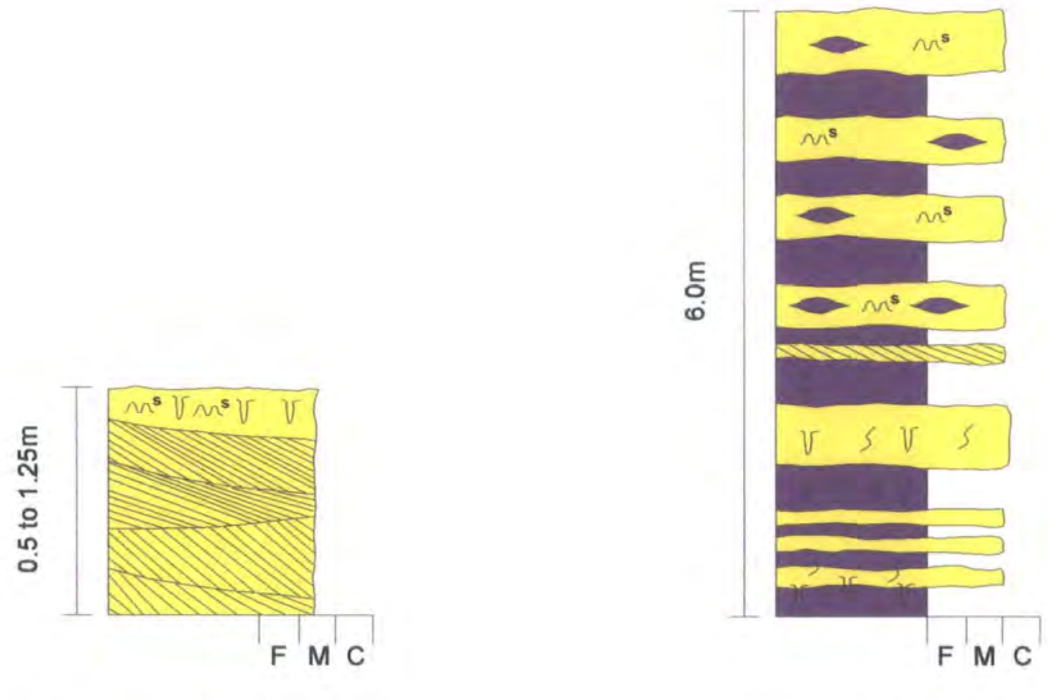
3.3.2.1 M5 Lithofacies – Tidal Channel

Occurrence and Bed Characteristics

This lithofacies is rarely developed, limited to one outcrop within the Little limestone cycle (Pendleian) at the Haltwhistle Burn river section (Grid reference NY 709654) (Ref. M5.1 in Appendix 2). Its lateral extent is unknown.

M5 Tidal channel lithofacies

M6 Tidal flat lithofacies



M7 Washover fan lithofacies

M8 Estuary lithofacies

Figure 3-24 Schematic vertical sections of the transgressive shoreline lithofacies group. M5 lithofacies (tidal channel), M6 lithofacies (tidal flat), M7 lithofacies (washover fan), M8 lithofacies (estuary). Grain size indicator is shown along the bottom of each vertical section; F=fine-grained, M=medium-grained and C=coarse-grained. A full key has been provided with Figure 3-5.

M5 lithofacies consists of a channel-shaped sandstone body of up to 0.5m thickness. Trough cross-beds are found within the unit.

This lithofacies downcuts into the underlying M6 (tidal flat) lithofacies.

Lithological Description

M5 lithofacies is composed of pale-grey, fine- to medium-grained sandstone although on weathered surfaces the sandstone displays a yellow coloration. The average composition of the sandstone is 93% quartz, 4% feldspar and 3% lithic fragments. The sandstone grains are sub-rounded to rounded and is well-sorted. At the base of the unit there is a layer of disarticulated Productid shells, approximately 5cm to 15cm in length, randomly orientated and not *in situ*.

Interpretation: Depositional Environment

The limited thickness (0.5m) of the channel suggests that the channel was formed in only a moderately high-energy environment in comparison to those of the previously described distributary channels which represent areas of high-energy (Sections 3.2.3.1 and 3.2.3.2). The layer of Productid shells at the base of the channel would indicate that there has been some form of marine or near-marine influence at the time of deposition (Beus 1984). The Productid shells are not in life position and are disarticulate which would indicate they have been transported from their source, however, they are not fragmented which would indicate they have not travelled a great distance. These factors and the association with sediments of M6 (tidal flat) lithofacies, would suggest that it was deposited as a tidal channel within a tidal-flat environment (Section 3.3.2.2) (e.g. Dalrymple 1992).

3.3.2.2 M6 Lithofacies – Tidal-flat

Occurrence and Bed Characteristics

This lithofacies has been described from the study area by Elliott (1974), but was rarely found during the study. One example of this lithofacies is within the Little limestone cycle (Pendleian) at the Haltwhistle Burn river section (Grid reference NY 709 655) (Ref. M6.1 in Appendix 2).

This lithofacies is between 1.0 and 2.0m thick. The sandstone component increases upwards from 10% to 90% throughout the unit giving an overall coarsening-upward appearance. Lenticular, wavy and flaser bedding are common throughout with lenses of mud being found within the sand and vice versa. In the upper part of the unit wave ripples and herring bone cross-bedding are common in addition to abundant bioturbation.

This lithofacies is commonly found abruptly overlying those of the distributary channel lithofacies. It is also cut into by the M5 (tidal flat) lithofacies.

Lithological Description

This lithofacies consists of alternate beds of fine- to medium-grained cream or pale grey quartz arenitic sandstone and dark grey shale. The sandstone component of this lithofacies is rounded and well-sorted. Carbonaceous plant fragments are locally found at the top of the unit.

Interpretation: Depositional Environment

The coarsening-upward nature of this unit and an upward increase of bedload structures such as ripple-lamination, indicates an increase in current velocity perhaps associated with a decrease in water depth (Section 3.2.2.2) (e.g. Miall 1992). The alternating beds are a result of deposition from alternating bedload and suspension transport (e.g. Shanmugam *et al.* 2000). The presence of herringbone cross-bedding suggests reversals of current, characteristic of tidal deposits (Section 3.3.1.2) (e.g. Brettle *et al.* 2002). Symmetrical ripples indicate wave activity (Section 3.2.3.3) Flaser-bedding, lenticular-bedding and wavy-bedding are all common throughout this lithofacies and all form as a result of fluctuations in sediment supply or level of current activity, typically found in tidal-flat and delta-front environments (e.g. Tucker 2001). All the sedimentary structures indicate the presence of a shallow-marine, tide- and wave-influenced environment. Additional supporting evidence is the presence of quartz arenite indicating a high-energy shallow-marine environment (Section 3.3.1.2). This feature is also suggested by the presence of bioturbation which could only occur during time of limited sediment supply or level of current activity. All the features listed and the association of this lithofacies with those of the channelised sandstone with shell lag would suggest that this lithofacies formed in a tidal-flat depositional environment, described by Elliott (1974), Dalrymple (1992) and Chokrabarty *et al.* (2003).

3.3.2.3 M7 Lithofacies – Washover Fan

Occurrence and Bed Characteristics

Occurrences of this lithofacies are only seen at 2 outcrops within the study area. They are difficult to detect from borehole data due to the lack of hand specimen and petrological data, so its presence may be underestimated. This lithofacies has been described by Percival (1992) from Weardale (Figure 3-1). The lateral extent of this lithofacies is limited and cannot be correlated more than a few 100 metres away.

The thickness of this lithofacies ranges from 0.5 to 1.25m. Low angle (5° to 20°) planar cross-beds dominate the lithofacies, with each set being approximately 0.3m thick. The palaeocurrent direction is towards the north-east (Figure 3-9). Towards the top of the unit there are abundant symmetrical ripples and vertical burrows.

Sediments of this lithofacies are found near the top of the cycle, overlying distributary channel lithofacies (D4 to D6) or interbedded with tidal flat lithofacies (M6). They are often abruptly overlain by carbonate platform lithofacies.

Lithological Description

This lithofacies is composed of buff-coloured fine- to medium-grained quartz arenite, is well-rounded and very well-sorted. On weathered surfaces the sandstone appears to be pale- to mid-grey in colour.

Interpretation: Depositional Environment

Low-angle planar cross-bedding and symmetrical (wave) ripples indicate that shoreline processes formed this lithofacies. The quartz arenite composition of this lithofacies would suggest some form of sediment reworking (Section 3.3.1.2), which would also indicate shoreline processes. Vertical burrowing within the unit suggests that there must have been at least periodic breaks in sedimentation in order for colonisation to take place. The direction of palaeocurrent in opposition to the regional palaeocurrent direction (Section 3.2.3.1) would be indicative of wave-swash processes. The presence of this lithofacies above distributary channel lithofacies (D4 to D7) at the top of the cycle, in addition to the opposing palaeocurrent direction , would indicate that this lithofacies formed during a transgressive phase of deposition, possible formed by reworking along the margin of the original delta plain. These findings show close affinity with washover fans where flow of material would ‘wash over’ a transgressive barrier island, such as those described by Yang (1999) from the Eocene of Texas, USA. These accumulations may have been the result of storm action leading to periodic deposition and quiescence, allowing time for colonisation (Percival 1992). Transgressive barrier islands often leave little to be preserved in the rock record although they have been described by Percival (1992) from Weardale in the study area. Poor preservation of barrier islands and the associated washover fans may be the reason why this lithofacies is so rare within the study area.

3.3.2.4 M8 Lithofacies - Estuary

Occurrence and Bed Characteristics

The occurrence of this lithofacies is extremely limited and is only noted from the Scar limestone cycle (Brigantian) at the Bowlees Beck river section (Grid reference NY 907285) (Ref. M8.1 in Appendix 2). The lateral extent of the lithofacies is unknown due to a lack of correlatable outcrops or boreholes nearby.

Each bed ranges in thickness from 0.1 to 0.5m. The thickness of the entire lithofacies is approximately 6.0m. Many beds contain planar laminae and the lithology is friable. Symmetrical ripples are common and are frequently draped with fine-grained mudstone. Shale lenses are locally found within the sandstone beds.

Sediments of this lithofacies gradationally overlie distributary channels (D4 and D5 lithofacies) and are in turn overlain by carbonate platform lithofacies from the beginning of the next cycle (Figure 3-25).

Lithological Description

M8 lithofacies consists of alternating beds of siltstone, medium-grained pale to mid-grey sandstone, silty-sandstone and dark-grey shale. Bioturbation and vertical burrows are abundant towards the base of units of this lithofacies.

C2 lithofacies
Five-Yard Limestone (Brigantian)

M8 lithofacies - Estuary

Alternating beds of siltstone, sandstone and shale.

Friable nature of M8 lithofacies has led to severe undercutting beneath overlying Five-Yard Limestone.

Figure 3-25 Field photograph of estuary lithofacies (M8) overlain by Five-Yard limestone (Brigantian). Photograph taken at Summerhills Force, Bowlees Beck. Height of waterfall is approximately 10m.

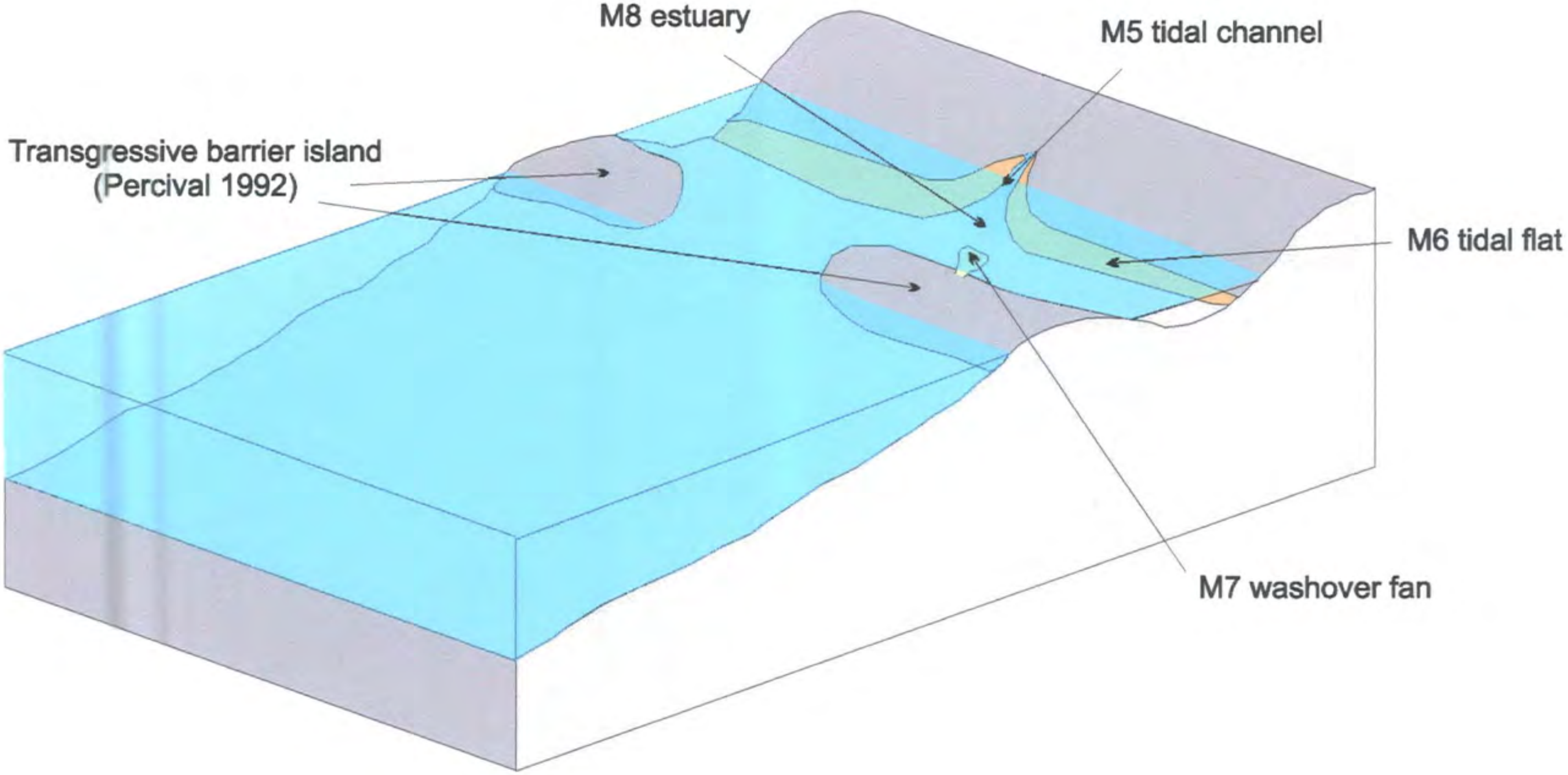


Figure 3-26 Palaeoenvironmental reconstruction of the Mid Carboniferous transgressive shoreline setting. The reconstruction shows the likely depositional environments of the major lithofacies identified in this study.

Interpretation: Depositional Environment

The interbedded nature of the lithofacies indicates alternating bedload and suspension transport suggesting fluctuating currents (Section 3.3.1.2), and this is also indicated by the occurrence of lenticular bedding. Symmetrical ripples are formed as a result of wave action on non-cohesive sediments (e.g. Tucker 2001) and mud-drapes on these ripples reflect deposition from slack water during tidal-current reversals (e.g. Brettle *et al.* 2002). The sedimentary structures noted and the occurrence of this lithofacies on top of distributary channels, immediately prior to the deposition of a marine limestone indicate that this lithofacies formed in an estuarine depositional environment marking the onset of a marine transgression.

3.3.2.5 Transgressive Shoreline Lithofacies Group Summary

Transgressive shoreline sediments have been described by Elliot (1976) and Percival (1992) and have been observed by the author in the study area. The morphology of such deposits takes the form of a transgressive barrier island that becomes gradually drowned as the sea-level rises. The occurrence of such sediments abruptly overlying the upper delta plain and upper lower delta plain sediments suggests that this was a transgressive event. A full environmental reconstruction of the transgressive shoreline lithofacies group can be seen in Figure 3-26.

3.3.3 Marine Shoreline Lithofacies Association Summary

Sandy shorelines in interdeltaic and non-deltaic coastal regions are characterised by elongate shore-parallel sand deposits (e.g. Testa & Bosence 1998). Although the morphology of such deposits is difficult to assess within this study, the presence of marine shoreline lithofacies in general is more common than previously documented.

3.4 CARBONATE PLATFORM LITHOFACIES ASSOCIATION

Carbonate deposition during the Early Carboniferous of Britain was widespread and various carbonate environments were developed. In Northumbria, this lithofacies association makes up 20% of the total succession as shown in Figure 3-1A.

The lithofacies association has been divided into 2 lithofacies groups; the first group consist of 5 lithofacies which have been studied at outcrop, the second group consists of 2 lithofacies which have not been studied at outcrop but are based on descriptions from published literature. A table summarising the major components of the lithofacies found within this association can be seen in Table 3-6. All carbonate platform lithofacies are found at the base of the depositional cycle.

3.4.1 Carbonate Platform Lithofacies Group

The lithofacies within this group range from lime mudstone to grainstone and generally contain marine bioclasts most commonly of crinoids and brachiopods, but coral, bryozoa and trilobites are also found.

3.4.1.1 C1 Lithofacies – Deep water / low energy

Occurrence and Bed Characteristics

This lithofacies is common throughout the study area. It was deposited intermittently throughout the Asbian to Pendleian and generally occurs near the base of the carbonate units. Lateral continuity is excellent and can be traced for 100s of metres, if not kms of outcrop and can be inferred from correlation across the entire study area.

The lithofacies has parallel beds, ranging from 30cm to 170cm. Laminae are common although locally beds may appear to be massive.

Lithological Description

The dominant lithology of this lithofacies is a fine-grained, dark to very dark grey, lime mudstone / wackestone although locally this is developed into packstone beds. There is a limited fossil presence of approximately 2 to 5% evenly distributed within the lithofacies with very small (less than 3mm) crinoid and brachiopod fragments in addition to general shell hash. More locally there are larger fossil fragments (up to 20mm) of trilobites and solitary corals present. The fossil fragments within this lithofacies appear to be unabraded. *Rhizocorallium* and *Zoophycos* are seen on the top of bedding surfaces (Figures 3-27 and 3-28).

Interpretation: Depositional Environment

Mudstone and wackestone are found in low-energy environments without the effects of winnowing (e.g. Sano 1995), this is emphasised by the presence of unabraded bioclasts, although locally developed packstone could reflect periods of higher-energy. The faunal elements present are stenohaline and are indicative of normal marine

Figure 3-27 Field photograph (plan view) of *Rhizocorallium* on limestone surface. Photograph taken at Beadnell. Length of pen is 15cm for scale.

Figure 3-28 Field photograph (plan view) of *Zoophycos* on limestone surface. Photograph taken at Beadnell. Length of pen is 15cm for scale.

salinity (e.g. Beus 1984). The fine-grained nature of this lithofacies infers settling at depths below wave base. In combination with the dark colour, low fossil content and strong bioturbation, dysaerobic conditions were likely (Hips 1998).

The local occurrence of large benthic fossils indicates that there was periodic current activity, but the general muddy matrix indicates low energy conditions and the extensive bioturbation suggests relatively slow sedimentation rates. *Zoophycos* traces are often found on quiet water conditions that are more or less deficient in oxygen, below the storm wave-base (Brett *et al.* 1990). *Rhizocorallium* traces on the other hand are often found in the region between the daily wave-base and storm wave-base (Frey & Pemberton 1985), so the presence of both of these trace fossils could indicate deposition across the storm wave-base. Deposition at depths below significant wave or current activity is likely (e.g. Wright 1986).

3.4.1.2 C2 Lithofacies – Shallowing upward

Occurrence and Bed Characteristics

C2 lithofacies is found in the upper part of the carbonate units.

The lithofacies has beds of varying thickness ranging from 10cm up to 130cm Upper and lower bed surfaces are wavy in morphology, and the lower commonly cuts into the bed below.

This lithofacies is commonly found gradationally overlying the C1 (deep water / low energy) carbonate platform lithofacies.

Lithological Description

The dominant lithology of this lithofacies is a mid to dark grey wackestone to packstone. There are common interbeds of dark grey laminated lime mudstone which are up to 30cm thick. Fossils are common within this lithofacies making up 25% of the total composition, with crinoids, brachiopods, bryozoa, solitary corals, tabulate branching corals and trilobites all being found with some amount of abrasion. The fossils within this lithofacies are larger than those in the underlying C1 lithofacies, with crinoid ossicles being from 2 to 5mm in diameter, brachiopod valves reaching up to 50 to 80mm long and bryozoa fragments being up to 13mm. Fossils are more articulated than the C1 lithofacies with crinoid stems containing up to 20 ossicles being found. Fossil fragments are commonly concentrated into patches of unabraded bioclastic material which can take the form of thin lenses or beds up to 40cm thick and up to 150cm long (Figure 3-29). Locally, the bioclastic rich beds or lenses grade upward from being fossil-rich (25% bioclasts) at the base to less fossil-rich (10% bioclasts) at the top. Trace fossils are common on bedding surfaces within this lithofacies, with *Zoophycos*, *Rhizocorallium*, *Planolites* and indeterminate vertical and horizontal burrows.

Interpretation: Depositional Environment

The dominant lithologies of wackestone and packstone indicate that this is still a low-energy environment, but the presence of more bioclasts than the underlying C1 lithofacies (deep water / low energy) lithofacies would suggest conditions were more favourable and that the environment was slightly higher energy and was perhaps subject to limited reworking (Gutteridge 1990b). Abrasion and disarticulation both suggest reworking and their present within this unit would therefore also infer higher-energy conditions. The bioclasts indicate fully marine conditions and normal salinity (e.g. Beus 1984). The discontinuous bioclastic layers were likely formed through higher energy conditions and events within the generally low-energy environment (e.g. Gutteridge 1990b). Graded beds are common and are analogous to those described by Wright (1986), where they are interpreted as single depositional events from waning flow, possibly storm surges. Graded beds contain transported shallow-water fauna and some terrigenous material which are inferred to have been reworked into deeper water areas as a result of periodic storm activity (Somerville & Strogen 1992). The periodic nature of such storm activity is emphasised by the presence of heavily bioturbated bedding surfaces which would indicate relatively low sedimentation rates and little or no current activity. As mentioned in Section 3.4.1.1 *Zoophycos* traces are commonly found in offshore sites below the storm wave-base, it has been postulated that *Zoophycos* may also occur in shallow water settings during the Palaeozoic (Brett *et al.* 1990). This in conjunction with the presence of both *Rhizocorallium* and *Planolites* trace fossils which both indicate deposition between the daily wave-base and the storm wave-base (Frey & Pemberton 1985) would indicate that storm activity was present during this time. Locally, the fossils within this lithofacies are less disarticulated than those found in the surrounding sediment

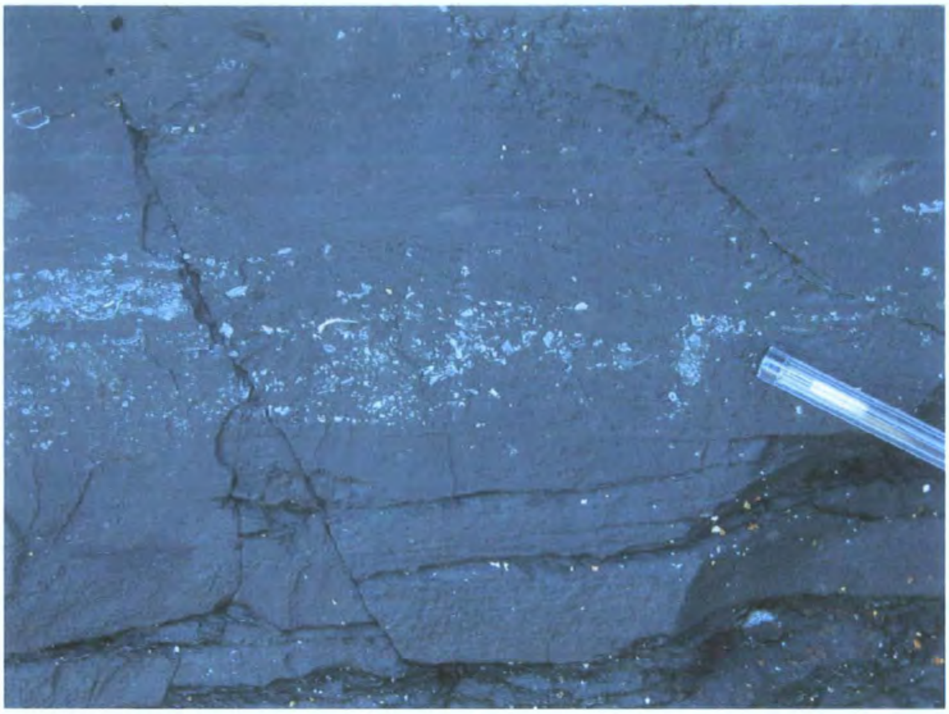


Figure 3-29 Field photograph of lens-shaped bioclastic accumulations within C2 lithofacies. Photograph taken at Howick. Visible length of pen is 8cm for scale.

Figure 3-30 Field photograph of unabraded bioclastic material and sub-rounded quartz grains within C3 lithofacies. Photograph taken at base of Great limestone (Pendleian) at Beadnell. Visible length of pen is 10cm for scale.

which would indicate rapid deposition which may also be the result of such storm activity.

Interbedded shales within this lithofacies may also be indicative of storm activity as they may be the result of periodic terrestrial input caused by increased surface-run off due to increased amounts or higher intensity of rainfall during storm periods (e.g. Somerville & Strogen 1992) or they may be the result of periodic incursions of clay due to distant tectonic uplift and erosion or climate change (Wilson 1975). It has also been suggested that thin shale interbeds found within Mid Carboniferous carbonates are the result of pressure dissolution (Bathurst 1991). The generally low-energy conditions with the occasional higher events, and the lack of wave-formed structures, would indicate that this lithofacies was deposited below normal wave-base but above storm wave-base. The upward increase in bioclastic content from wackestone to packstone and from the underlying lime mudstone of the C1 lithofacies indicates increasing energy and / or a shallowing-upward succession.

3.4.1.3 C3 Lithofacies – Transgressive / shallow water

Occurrence and Bed Characteristics

This lithofacies is not as common as the previous two (C1 and C2) carbonate platform lithofacies and is seen at only a few localities for example the Sandbanks limestone (Brigantian) (Grid reference NU 237292) (Ref. C3.1 in Appendix 2) at Beadnell coastal section and the Iron Scars limestone (Pendleian) at Howick coastal section (Grid reference NU 266158) (Ref. C3.2 in Appendix 2). It is not, however, restricted spatially or temporally.

It consists of a single bed of approximately 60 to 80cm which has an erosive contact below with D15 palaeosoil lithofacies or those of the distributary channel lithofacies. This lithofacies is commonly associated with sediments of the C1 (deep water / low energy) or the C2 (shallowing upward) carbonate platform lithofacies.

Lithological Description

This unit consists of a medium-grained mid-grey bioclastic packstone, although it is commonly dolomitised. The bioclastic content consists of disarticulated fragments of crinoids and brachiopods and general shell hash. The fossil fragments are very small (less than 2mm) and are abraded. There is abundant siliciclastic material within this unit which takes the form of sub-rounded quartz grains and locally, quartz clasts up to 3mm in diameter make up to 5% of the unit (Figure 3-30).

Interpretation: Depositional Environment

The coarse-grained nature of this lithofacies, in addition to the disarticulated, fragmented and abraded state of the bioclasts found within the unit indicates high energy conditions. In addition to the presence of fully marine biota, this indicates a shallow-marine environment. The occurrence of this unit directly overlying terrestrial lithofacies indicates that it was deposited in shallow, high-energy waters during the reflooding of the shelf following emergence (e.g. Gutteridge 1990). The inclusion of sub-rounded quartz grains and local quartz clasts suggests that the transgression reworked the underlying terrestrial sediments.

3.4.1.4 C4 Lithofacies – Shallow water / anoxic and/or hypersalinity

Occurrence and Bed Characteristics

This lithofacies is restricted to the north-east of the study area and has only been found by the author at the Spittal / Scremerston outcrop (Grid reference NU 019503) (Ref. C4.1 in Appendix 2). It has been described by other authors (Leeder 1975) however from elsewhere in the north of the study area although it is restricted to the Woodend limestone cycle in the Late Asbian. Lateral continuity is good in the north of the study area where the lithofacies can be correlated for many kms; there is little evidence for this lithofacies in the south of the area.

The unit consists of a single bed approximately 60cm thick with no visible sedimentary structures (Figure 3-31).

Lithological Description

The calcareous mudstone matrix of this lithofacies is pale green in colour and contains no visible bioclasts or lithoclasts. The unit is 85% composed of oncoids, ranging in diameter from 30mm to 60mm. They are spherical in shape with some more elliptical forms being noted. Internally, the oncoids are composed of concentrically laminated calcareous algae from the centre to approximately halfway

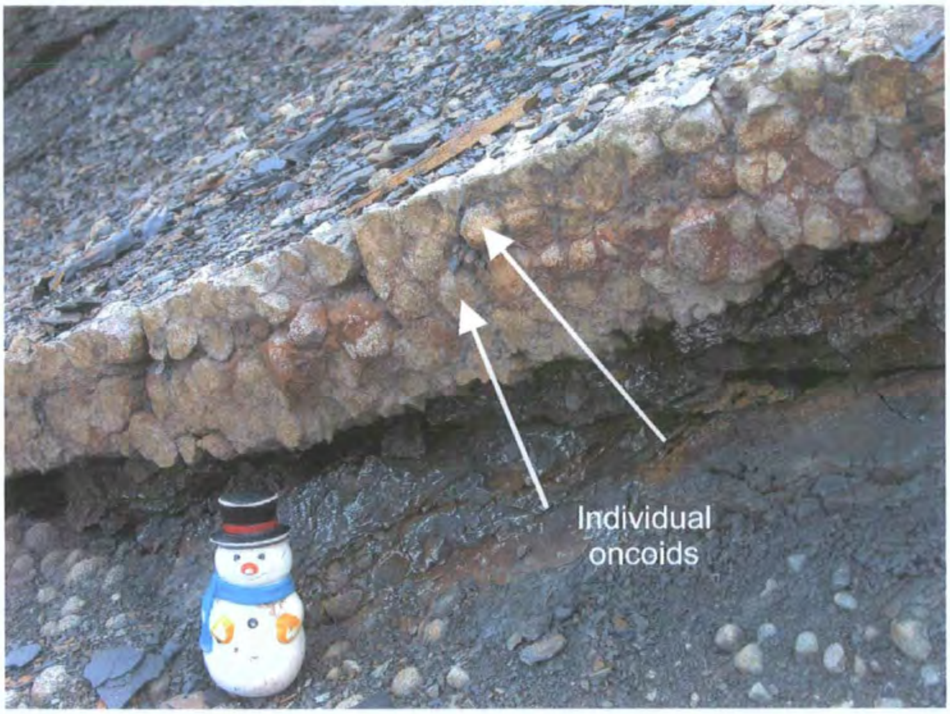


Figure 3-31 Field photograph of C4 lithofacies.Cross-sectional view of 'oncoid bed' with individual oncoids marked. Photograph taken at Spittal. 'Snowman' is 15cm in height for scale.

Figure 3-32 Photograph of internal structure of an oncoid found within C4 lithofacies. Note concentric laminations nearer to centre of oncoid whilst radiating tubules are visible towards the exterior. Scale bar is 1cm in length.

through the entire structure, when radiating tubules of *Garwoodia* (Leeder 1975) become the dominant structure. The tubules are approximately 1mm in width and visible on the surface of the oncoid as protruding features. In between the tubules, the structure of the oncoid is composed of very fine-grained micrite matrix. The nucleus of the oncoid is indeterminable. For a photo of the internal structure of the oncoids see Figure 3-32. The oncoids are evenly distributed throughout the unit.

Interpretation: Depositional Environment

The generally spherical nature of the oncoids within this lithofacies indicates that there was persistent agitation within the environment of growth (Leeder 1975). The two stages of growth found within each oncoid indicate the two very different stages within this depositional environment; the well laminated inner core indicates that the oncoid was rolled frequently while the outer *Garwoodia* portion indicates less frequent rolling although it has been suggested that the *Garwoodia* tubules were more resistant to breakage than other algal forms (Wright 1983). The reasons for this change in growth form could be the result of either a change in energy level or else the oncoid was growing to such a size that it was no longer rolled about as often (Wright 1983). The persistent fine-grained nature of the matrix of the lithofacies would indicate that the energy levels remained consistent. Algae are generally found in very shallow waters with abnormal salinity (e.g. Eliuk 1998) whilst the pale green coloration may indicate reducing conditions (e.g. Tucker 2001). The lack of any other bioclasts and high energy indicators would suggest that this was a very shallow, moderately high energy, restricted (abnormal salinity and / or reducing conditions) environment, probably in a sub-tidal environment.

3.4.1.5 C5 Lithofacies – Shallow water / low-oxygen and/or abnormal salinity

Occurrence and Bed Characteristics

The occurrence of this lithofacies is restricted to one limestone, the Oxford Limestone (Early Brigantian) but is not geographically restricted as it can be traced over many kms. This is evident as there is good exposure of this lithofacies in a disused quarry at Barrasford, in the North Tyne Valley (Figure 3-2), some 80 kms away. The best outcrop of this lithofacies is seen at Spittal / Scremerston (Grid reference NU 021498) (Ref. C5.1 in Appendix 2). Beds of the lithofacies range in thickness from 7cm to

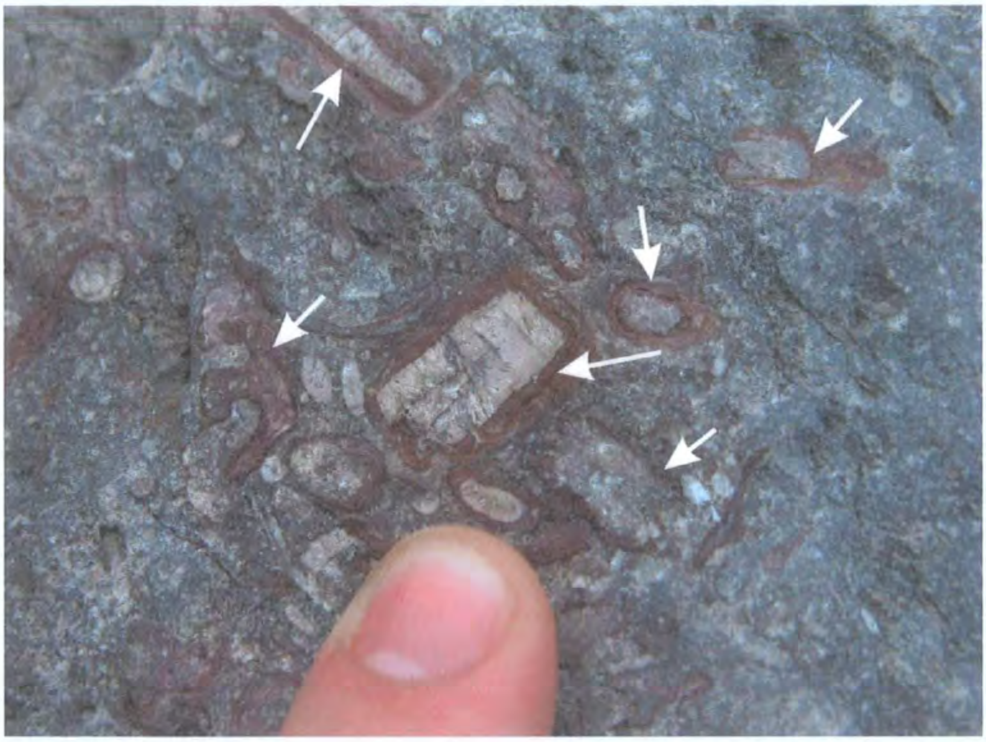


Figure 3-33 Field photograph of algal halo surrounding bioclasts (marked with arrows) within C5 lithofacies. Photograph taken at Oxford limestone (Brigantian) at Spittal. Field of view is approximately 10cm wide.

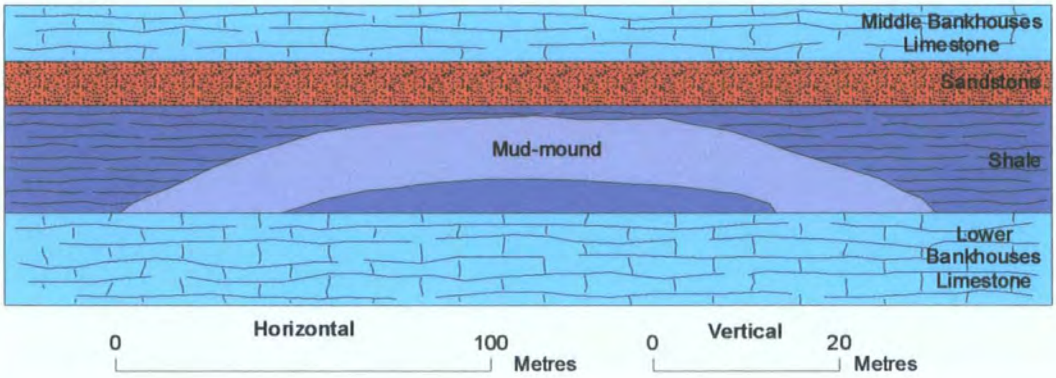


Figure 3-34 Reconstructed section of the mud-mound within the Lower Bankhouses limestone cycle (Brigantian) exposed at Tipalt Burn. After, Johnson (1959).

60cm and locally display laminations. The entire thickness of the lithofacies is approximately 4m. This lithofacies commonly found overlying the C2 (shallowing upward) lithofacies and is found in the upper part of the carbonate component of each cycle.

Lithological Description

The lithology of this lithofacies varies greatly from a wackestone to packstone to a grainstone all of which are mid-grey in colour. Broken fossil fragments are abundant (25%) within this unit and consist of crinoids, disarticulated brachiopods, horn corals and bryozoa, and they are all commonly abraded. Clusters of fossil debris similar to those described in the C2 (shallowing upward) lithofacies but much smaller in size, are seen in the lower beds of this lithofacies. Less disarticulated fossils are also present with crinoid stems of up to 6 ossicles, and articulated Productids being found. The diagnostic feature of this unit is the presence of 'algal haloes' around most of the bioclastic fragments (Figure 3-33). The 'algal halo' consists of a 1 to 2mm thick rim around each bioclast that is deep-red in colour.

Interpretation: Depositional Environment

The lithological variation within this lithofacies would suggest that the energy levels varied also. Wackestone which are indicative of low-energy environments are found in addition to grainstone which are indicative of moderate- to high-energy environments. The bioclasts are of fully marine origin and indicate normal marine salinity. Clusters of bioclasts can be inferred as indicating that there is some influence by storms as seen in the C2 (shallowing upward) lithofacies (Section 3.4.1.2) or could represent concentration of bioclasts along burrows. However, the occurrence of less disarticulated crinoid stems would infer rapid deposition which would further support the hypothesis of storm activity. The 'algal-haloes' around the bioclasts have been interpreted as oncolitic coatings which formed due to an agitated marine environment and are common in shallow turbulent waters (Gutteridge 1990). The presence of storm features such as concentrations of bioclasts as discrete lenses would indicate that this lithofacies was deposited above the storm wave-base. The presence of oncolitic coatings on bioclasts suggests agitated conditions so this suggests deposition above the fair-weather wave-base also. The occurrence of algae within this lithofacies advocates slightly restricted conditions, indicating a poorly oxygenated or abnormal salinity environment (e.g. Eliuk 1998).

3.4.1.6 Carbonate Platform Lithofacies Group Summary

While not fully comprehensive, the variety of carbonate lithofacies indicates many environmental changes. There is some evidence to suggest a shallowing-upward trend in the lithofacies. It is impossible to tell whether this is due to the depositional gradient or due to changing sea-level. For this reason, the term carbonate platform has been given to the lithofacies group.

3.4.2 Carbonate Platform Related Lithofacies Group

There are further carbonate lithofacies present within the study area that have been described from the literature available on the area but have not been witnessed by the author. It is impossible to describe these in detail without visiting the outcrops mentioned but they have been briefly mentioned in order to produce a complete depositional environment model for the area.

3.4.2.1 Carbonate mud-mounds or 'knoll-reefs'

Johnson (1959) describes a 'knoll-reef, more commonly known as carbonate mud-mounds, exposed in Tipalt Burn in the Roman Wall District, up to 10m thick, up to 137m long and 60m wide. There are three major units within the mud-mound which consist of crinoidal under-reef deposits which comprise grey crinoidal limestone, overlain by coral limestone which comprises light grey limestone up to 3m thick almost completely composed of compound rugose corals both in situ and non in situ, overlain again by brachiopod beds comprising 2m+ of pale-grey and cream limestone containing abundant brachiopod fragments (Figure 3-34). The mud-mound itself outcrops within the basal shale component of the Lower Bankhouses Limestone cycle. Although mud-mounds are not common within the study area they have been described by other authors from the northern Pennines (Black 1950) Grassington (Joysey 1955) and Wensleydale (Moore 1958) where they all occur at the same stratigraphic horizon as the one described here.

3.4.2.2 Biostromes

Within the study area there are two unusually thick limestones, with the normal thickness of limestones in the study area being between 1m and 10m. The first of these is the Melmerby Scar Limestone which is up to 40m thick and was deposited during the Early Asbian; the second of these limestones is the Great Limestone which is up to 30m thick and was deposited during the Early Pendleian. Within both of the limestones are laterally persistent fossiliferous tabular beds commonly referred to as biostromes. The Great Limestone contains three such biostromes, the *Chaetetes* Band which is at the base of the limestone, the Brunton Band below the centre of the limestone, and the Frosterley Band above the centre of the limestone which is characterised by the presence of numerous *Dibunophyllum* (Johnson 1958; Fairbairn 2001). Other limestones within the study area may contain biostromes but the two mentioned here are the best documented.

3.4.3 Carbonate Platform Lithofacies Association Summary

In Northumbria, unlike areas further to the south, carbonate platform deposition was interbedded with thick clastic units attributed to the delta and marine shoreline lithofacies, with repeated marine transgressions occurring over a basin wide exposed surface. The carbonate content within each cycle diminishes gradually throughout the Upper Viséan and Early Namurian especially on the Alston Block areas where cycles are dominantly carbonate at the start the Asbian and by the Late Pendleian, clastics dominate the succession. A full environmental reconstruction for the carbonate platform lithofacies association can be seen in Figure 3-35.

3.5 Vertical Associations

The depositional environments of the Viséan and Namurian of Northumbria were extremely diverse, yet it is impossible to obtain a full and accurate impression of the evolving palaeogeography without investigating the vertical associations of the lithofacies.

Each lithofacies has been described with their position within the depositional cycle given. There are two general trends that occur; the first contain predominantly deltaic lithofacies association sediments, whilst the second contains predominantly marine shoreline lithofacies association sediments.

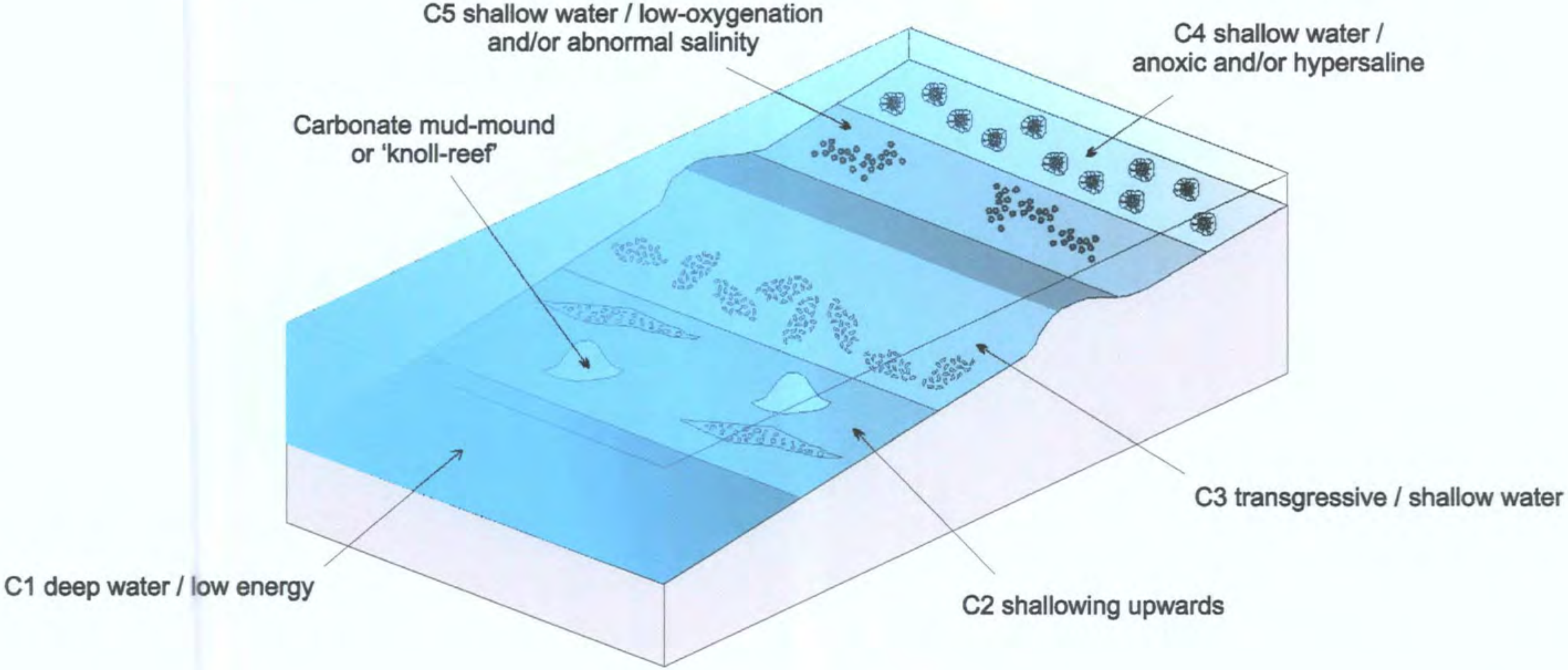


Figure 3-35 Palaeoenvironmental reconstruction of the Mid Carboniferous carbonate platform setting. The reconstruction shows the likely depositional environments of the major lithofacies identified in this study. See text for full descriptions of each lithofacies within this association.

The deltaic lithofacies cycle occurs as follows: the base of the cycle consists of carbonate platform lithofacies (as do all of the depositional cycles). This is followed by the prodelta lithofacies group, the delta front group, the lower delta plain group and finally, by the upper delta plain group. This vertical and therefore temporal change of environment is demonstrated in Figure 3-36

The marine shoreline lithofacies cycle occurs as follows: the base of the cycle consists of carbonate platform lithofacies. This is followed by sediments of the prograding shoreline lithofacies group (starting with the offshore shelf lithofacies and ending with the upper shoreface lithofacies). This temporal change in environment is demonstrated in Figure 3-36.

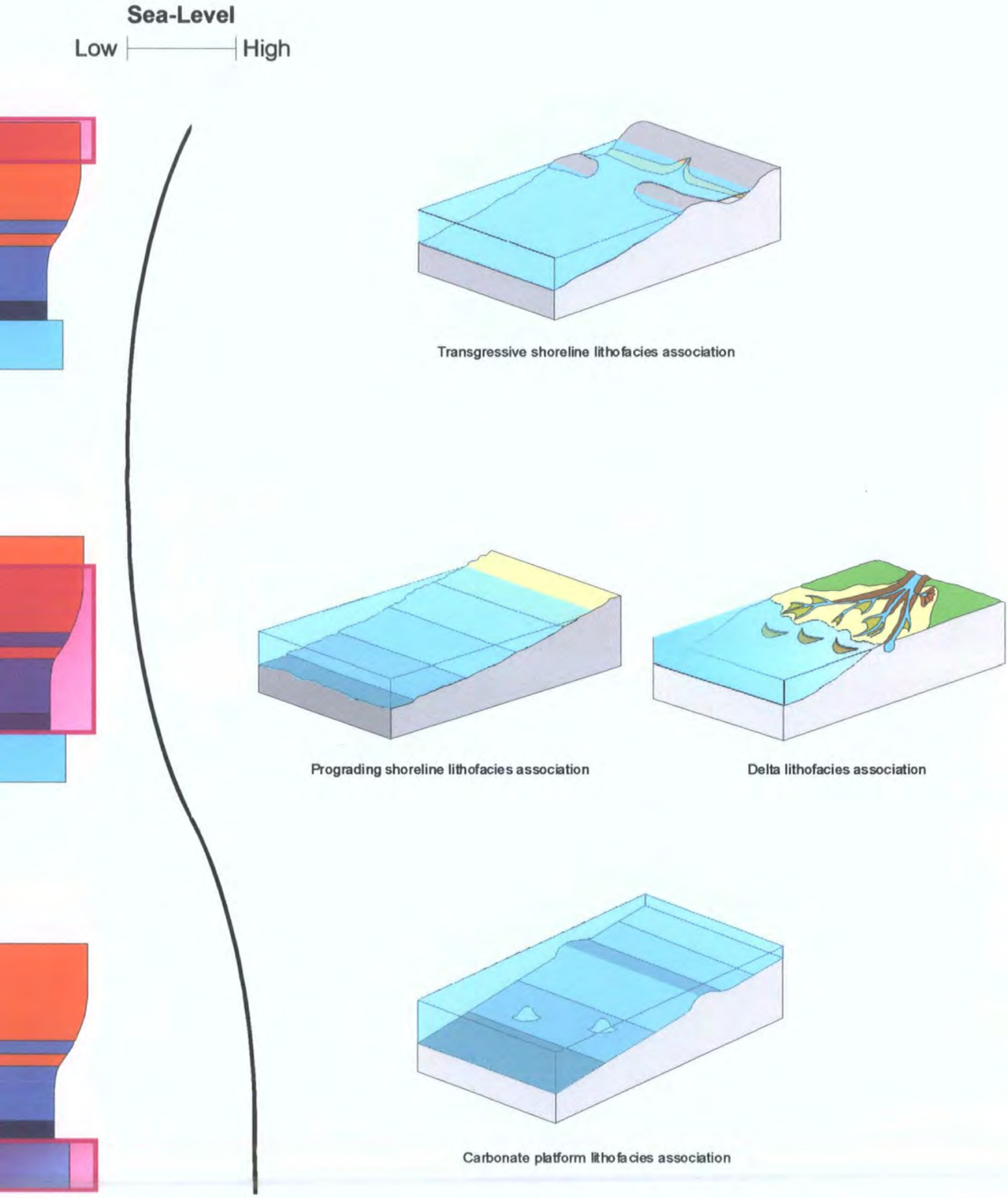
Sediments of the transgressive shoreline lithofacies group may occur on top of both of the previously mentioned vertical associations. This is demonstrated in Figure 3-36.

3.5.1 Changing Sea-Level

The temporal change in depositional environment is most likely related to repeated fluctuations in sea-level. This is evident as the carbonate platform lithofacies group can be correlated over the entire area indicating a regionwide marine transgression. The Carboniferous period was a time of many such fluctuations (e.g. Ross & Ross 1987), the causal mechanisms of which are discussed in Section 4.4.

3.5.2 Tectonic Variation

Changes in sea-level may account for the majority of temporal changes in depositional environment, but there were various other factors in operation that may have influenced the area. Northern Britain was an active extensional province during the Early Carboniferous period, with active intrabasinal faulting until the Late Carboniferous. This would have had a profound effect on river drainage and base-level, but such effects are more likely to have been restricted to localised events. This is discussed in greater detail in Section 8.4.1.



Transgressive shoreline lithofacies association

Prograding shoreline lithofacies association

Delta lithofacies association

Carbonate platform lithofacies association

Figure 3-36 Schematic cartoon diagram demonstrating lithofacies association, their position within each depositional cycle reflecting the increasing sea-level change within each cycle. The position of each lithofacies association within the classic depositional cycles has been shown in relation to their position within each sea-level cycle.

3.5.3 Summary

The vertical associations of the lithofacies reflect a regionwide change in sea-level, indicating repeated transgressions and regressions. Tectonic activity may have influenced the depositional environment but the associations found indicate that relative changes in sea-level were a major control on vertical changes in depositional environment.

3.6 Lithofacies associations and summary

In total, 26 major lithofacies are identified and grouped into three main associations. Lithofacies D1 to D11 are included in the deltaic lithofacies where sedimentation was in a shallow-marine to alluvial plain environment. Sedimentation generally outpaced subsidence leading to the formation of a progradational deltaic environment. Lithofacies M1 to M8 were deposited in marine shoreline environments where they either formed a progradational beach (M1 to M4) or transgressive beach barrier / sand bar (M5 to M8), depending on where they are found within each depositional cycle. The remaining lithofacies (C1 to C5) can be grouped into a carbonate platform depositional environment where they represent open marine predominantly low-energy deposition in varying water-depths.

Chapter Four

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Chapter 4 – Sequence Development and Cyclostratigraphy

4.1 Introduction

The first account of the Carboniferous succession of Northern England was recorded by Westgarth Forster in 1809, but it was not until 1887 that the rhythmic nature of these deposits was recognised (Miller Jr.1887). The succession of limestone, shale, sandstone and then coal was previously recognised by Phillips (1836) in the Wensleydale Valley of North Yorkshire and thus named the 'Yoredale Beds' after the former valley name of Uredale.

The name that is now used to describe such cycles is Yoredale Cycles and these have been defined by Dunham (1950) as marine limestone, marine shale, unfossiliferous shale, sandy shale / shaly sandstone / 'grey beds' (interbedded shales, siltstone and sandstone), sandstone, ganister or underclay, and then coal (Figure 4-1). Dunham's classification of a typical Yoredale Cycle has been used throughout this thesis as introduced in Section 1.3 and has been used as a basis for further cycle descriptions.

Such cyclic deposits are found throughout Northern England in both the Viséan and Namurian periods and the cycles themselves are repeated many times across the region. For correlation purposes, the base of each cycle, the marine limestone, is used as it is the most consistent component of each cycle and can often be traced for 10's if not 100's of kilometres across the region. The most laterally persistent limestones found are the Great Limestone (Lower Pendleian) and the Oxford or Jew Limestone (Mid Brigantian). Although many of the limestones can be correlated across the region, problems arise due to various names given to the same limestone by early geological workers. A correlation chart has been constructed to ease this problem (Figure 4-2).

The cyclic nature of deposition has been attributed to various causes, and in particular, eustatic sea-level changes. This chapter will look at the sequence stratigraphic implications of such cycles (Section 4.2) and assess the contribution that sea-level change had on the formation of Yoredale cycles. Cyclicity will be investigated by looking at the time-scales of such events (Section 4.3.1) and any additional cyclicity recognised by using statistical methods such as Fischer plots

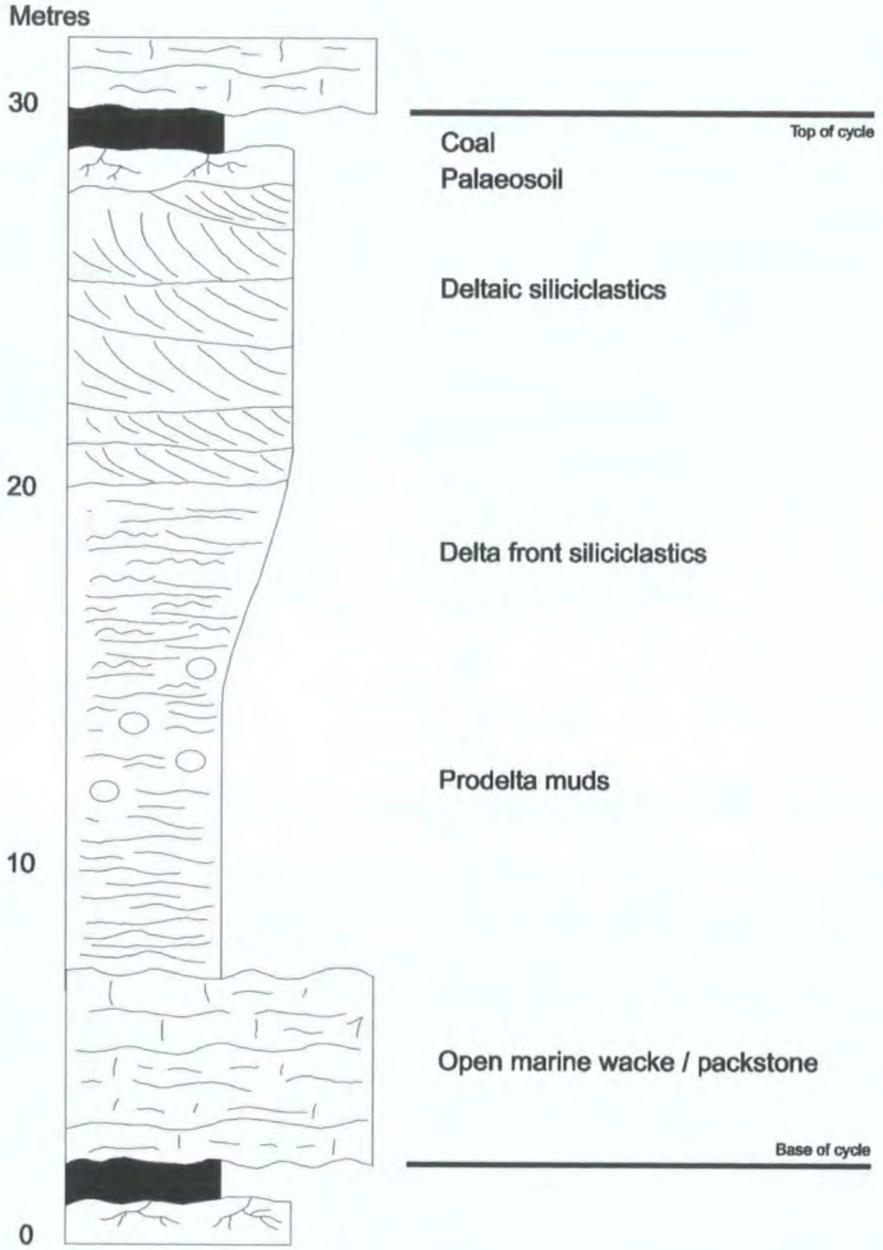


Figure 4-1 Sketch vertical succession of a basic Dunham Yoredale cycle. Actual cycle height has been marked on succession. Adapted from, Dunham (1950).

Figure 4-2 Limestone correlation chart compiled for the Mid Carboniferous strata of Northumbria. The chart is vertically subdivided into structural regions as described in main text. Many of the limestones in the chart cannot be directly correlated so have been left blank. There is no data available for the whole of the Asbian and early part of the Brigantian of the Northumberland Basin (west), and only information for the latter part of the Asbian is available for the Tweed Basin and Cheviot Block. These areas are therefore left blank on the chart. Information taken from, Miller (1887), Gunn (1895), Gunn (1927), Fowler (1926), Carruthers *et al.* (1930), Carruthers *et al.* (1932), Trotter & Hollingworth (1932), Fowler (1936), Day (1970), George *et al.* (1976), Burgess & Holliday (1979), Frost & Holliday (1980), Arthurton & Wade (1981), Dunham (1990), Johnson (1995), and Mills & Holliday (1998),

Key:

🟦 Arnsbergian

🟩 Pendleian

🟥 Brigantian

🟪 Asbian

⬜ No direct correlation

Tweed Basin / Cheviot Block	Northumberland Basin (east)	Alston Block	Northumberland Basin (west)
		Grindstone / Newton	
Upper Foxton		Upper Felltop / Thornborough	
Lower Foxton	Corbridge	Lower Felltop	Archerbeck Ochre Beds
Sugar Sands		Belsay Dene	
Iron Scars		Knucton Shell Beds	
Howick / Lickar	Oakwood	Crag	
Cushat	Little	Little	Blae Pot
Great	Great	Great	Catsbit
Sandbanks	Four Fathom	Iron Post	Under
		Four Fathom	Buccleuch
Acre	Three Yard	Three Yard	
Eelwell	Red House Burn	Five Yard	
	Eelwell		Harelawhill
Several small unnamed limestones	Shottowood	Scar	Gastropod
	Upper Bathhouse Wood		
	Lower Bathhouse Wood		
		Cockleshell	
	Colwell	Single Post	
	Dalla Bank		
	Haughton	Tynebottom	Tombstone
	Barrasford		
Oxford	Oxford	Jew	Linns
	Greengate Well	Lower Little	Bridge
		Grainbeck	
Watchlaw	Upper Bankhouses	Smiddy	Penton
	Middle Bankhouses		
		Upper Peghorn	
		Lower Peghorn	
	Lower Bankhouses	Birkdale	
Woodend	Lower Camphill	Robinson	
	Upper Demesne	Melmerby Scar	
	Lower Demesne		
Dun	Denton Mill		
	Upper Gunnerton Fell		
	Lower Gunnerton Fell		
	Fourlaw / Newton		
	Redesdale		

(Section 4.3.2). A comparison will be made with other areas with similar features (Section 4.3.1.3) and the causes of cyclic deposition will be evaluated (Section 4.4).

4.2 Sequence Stratigraphy

The nature of the Mid Carboniferous succession of Northumbria, with its well defined cyclicity and numerous marine bands, means that it is an ideal candidate for sequence stratigraphic study. The methods and concepts of sequence stratigraphy are particularly applicable to a succession deposited at times of glacial eustasy such as those found in the study area, when high magnitude and high frequency fluctuations in sea-level result in distinctive signatures in the stratigraphic record (Hampson *et al.* 1997).

Throughout this chapter the Exxon sequence stratigraphy model initially developed by Vail *et al.* (1977) and further revised by Coe & Church (2003) is used. This concept postulates that most coastal sediments are eustatically controlled (Read 1994). However, the study area was tectonically active up until the end of the Asbian period with differential subsidence prevailing between 'blocks and basins'. After this point regional subsidence took over and differential subsidence came to an end (Chapter 8). Therefore even though it is likely that eustasy was the main controlling factor on cyclicity, and active tectonism only occurred at the beginning of the study period, the final signature on stratigraphy was modified by both sediment supply and subsidence (Martinsen 1993).

Lithofacies relationships are evaluated in terms of key surfaces that are considered to reflect changes in relative sea level. Between these key surfaces, units of genetically related strata (or systems tracts) were deposited and different portions of a relative sea level curve can be recognised (e.g. Hampson *et al.* 1997). Sequence stratigraphy is particularly useful in this study as systems tracts differ, often quite dramatically, in their lithofacies associations and interpretations, such that certain environments may be dominant in some systems tracts but completely absent from others, therefore allowing the interpretation of fluctuations in relative sea level regardless of lithofacies association.

4.2.1 Systems Tracts and Key Surfaces

There are 4 systems tracts discussed within this section; the falling stage systems tract (FSST), the lowstand systems tract, the transgressive systems tract (TST) and the highstand systems tract (HST). The content of this section is based on the work of Coe & Church (2003). The position of each of these systems tracts on a relative sea-level curve in addition to the geometry and features of each are shown in Figure 4-3.

4.2.1.1 Falling Stage Systems Tract (FSST) and Lowstand Systems Tract (LST)

Falling relative sea-level has 2 major consequences: there is a basinward lithofacies shift, and an increase in the amount of siliciclastics into the sea. Rivers are rejuvenated and river mouths will lie at a much lower position than previously. In response to the fall in relative sea-level, rivers begin cutting incised-valleys into the shelf, the erosion associated with these valleys occurs across the whole shelf, defining a regional unconformity or Type-1 Sequence Boundary. This results in sediment being bypassed across the shelf and deposited directly on the slope and in the basin as lowstand fans and these define the FSST and the early part of the LST. These features are shown in Figure 4-3A.

During the subsequent rise in relative sea-level during the LST, accommodation space is created on the shelf. This results in the cessation of river incision, and the onset of infilling of incised valleys with sediment. The amount of sediment bypassing the shelf decreases as sediment is preferentially deposited within the incised valleys, thus marking the LST. These features are shown in Figure 4-3B.

4.2.1.2 Transgressive Systems Tract (TST)

As the rate of relative sea-level rise increases, sediment supply is outpaced by the rate at which accommodation space is created. A thin widespread transgressive surface forms over the shelf, known as the initial flooding surface (IFS). Transgression often results in shallow-marine environments becoming flooded and suitable for carbonate production. During transgression siliciclastic supply tends to be low as sediment is trapped in more proximal areas. The maximum extent of the transgression is marked by a widespread condensed section or maximum flooding surface (MFS). The TST is referred to as the strata lying between the IFS and the MFS. The features of the TST are summarised in Figure 4-3C.

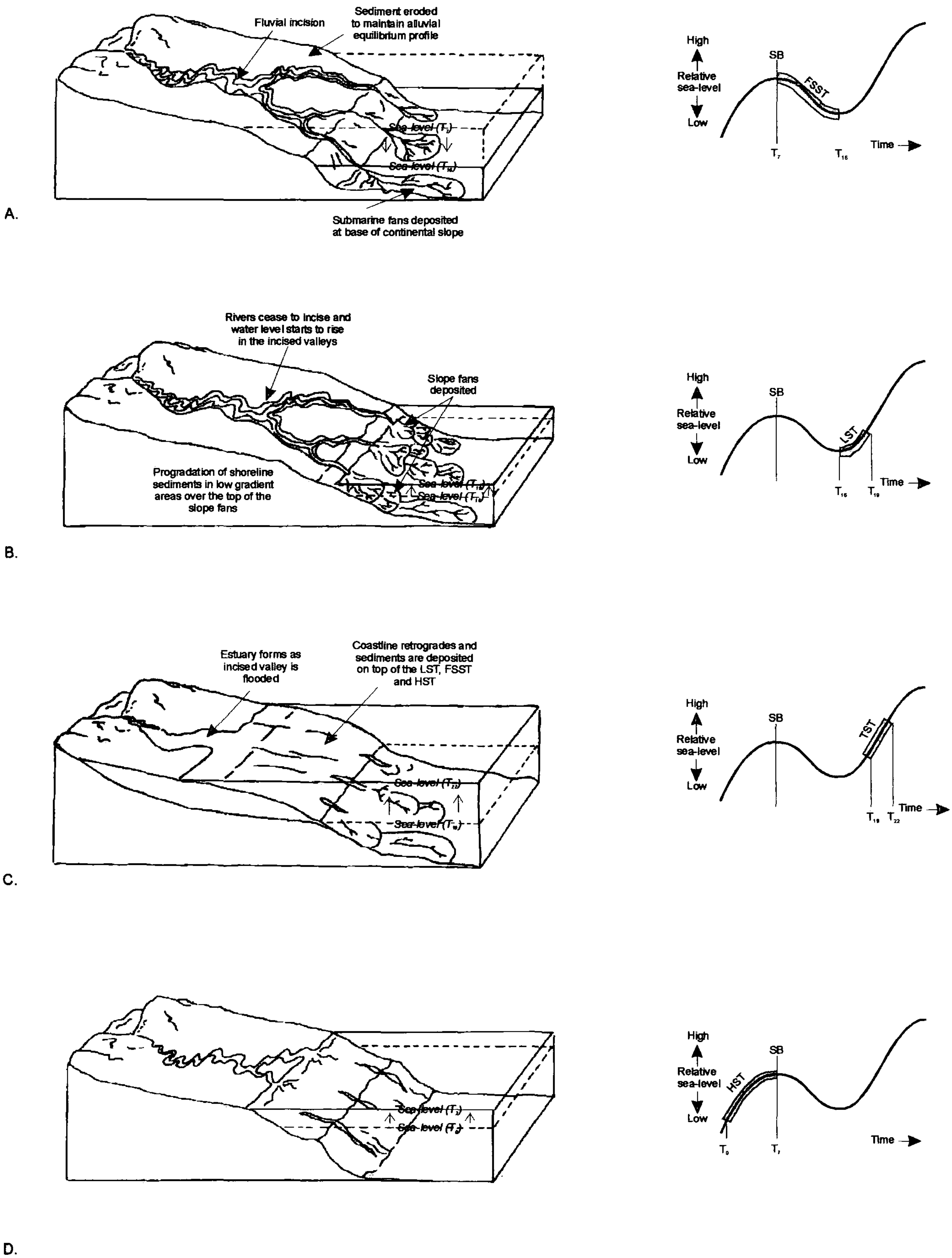


Figure 4-3 Geometry and features of individual sequence stratigraphic systems tracts and their relative sea-level curve. A. = FSST (Falling Stage Systems Tract), B. = LST (Lowstand Systems Tract), C = TST (Transgressive Systems Tract), D = HST (Highstand Systems Tract). Adapted from, Coe & Church (2003).

4.2.1.3 Highstand Systems Tract (HST)

Once the rate of relative sea-level rise slows down, sediment supply can keep pace with and then outpace the rate at which accommodation space is created. The shoreline stabilises (early HST) and then builds out or progrades (late HST). If there is a constant sediment supply, the rate of shoreline progradation will increase as the rate of relative sea-level rise decreases. Relative sea-level reaches a peak and then starts to fall, producing fluvial incision and the formation of another Type-1 Sequence Boundary. The HST is defined as the strata lying between the MFS and the second Type-1 Sequence Boundary. The features of the HST are summarised in Figure 4-3D.

4.2.2 Cycle Types and Sequence Stratigraphic Interpretation

Each of the various cycles found throughout the Mid Carboniferous succession of Northumbria will be examined in terms of their sequence stratigraphic implications.

In addition to the Basic Cycle, there are two other groups of cycle variants; Cycle Variant A is the name given to those cycles that contain an Incised Valley-Fill, and Cycle Variant B is the name given to those cycles that have an IFS that varies from the Basic Cycle.

Detailed cartoon logs in addition to lithostratigraphic characteristics and sequence stratigraphic interpretations can be found in Figures 4-4 to 4-9. Complete lithostratigraphic interpretations can be found in Chapter 3.

4.2.2.1 Basic Cycle

The Basic Cycle is the most commonly observed cycle type within the study area and will be examined in terms of key surfaces and systems tracts. All other cycles are seen as a variation on this cycle so will not be described in detail except for the component that varies. The basic cycle and its sequence stratigraphic components are shown in Figure 4-4. Examples of the basic cycle are the Sandbanks cycle at the Howick coastal section (Ref. BC.1 in Appendix 2) and the Oxford limestone cycle at the Spittal / Scremerston coastal section (Ref. BC.2 in Appendix 2).

Evidence for the FSST to LST is generally in the form of palaeosoils seen at the top of each cycle. As the FSST to LST forms during falling relative sea-level,

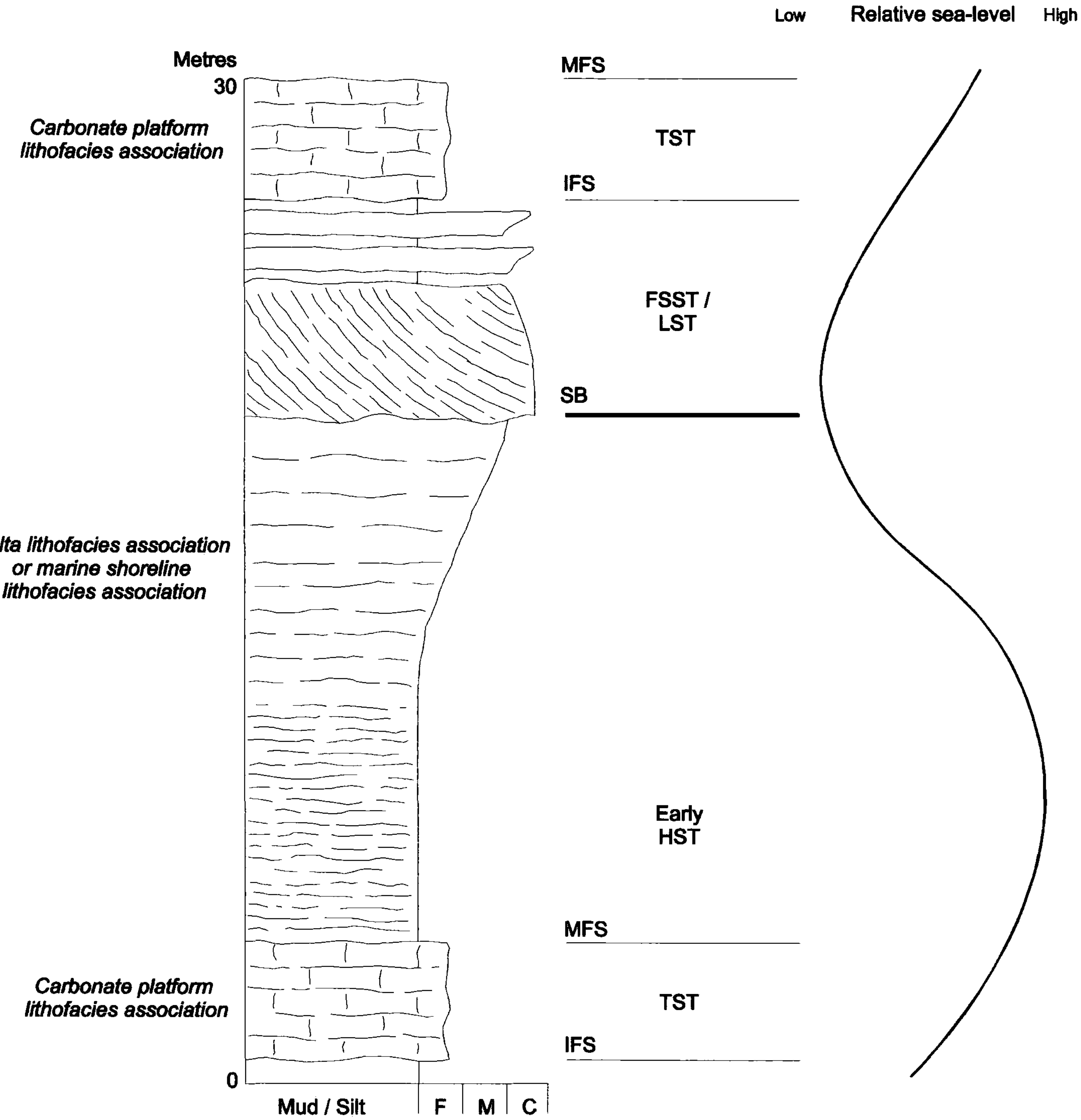


Figure 4-4 Diagram of a basic cycle with the relevant sequence stratigraphic components indicated to the right. The following abbreviations have been used: MFS = Maximum flooding surface, IFS = Initial flooding surface, TST = Transgressive systems tract, HST = Highstand systems tract, FSST = Falling Stage systems tract, LST = Lowstand systems tract. A sea-level curve has been provided on the right-hand side of the diagram. Grain size indicator is give along the bottom of sequence; mud/silt=mud/silt sized grains, F=fine-grained, M=medium-grained, C=coarse-grained.

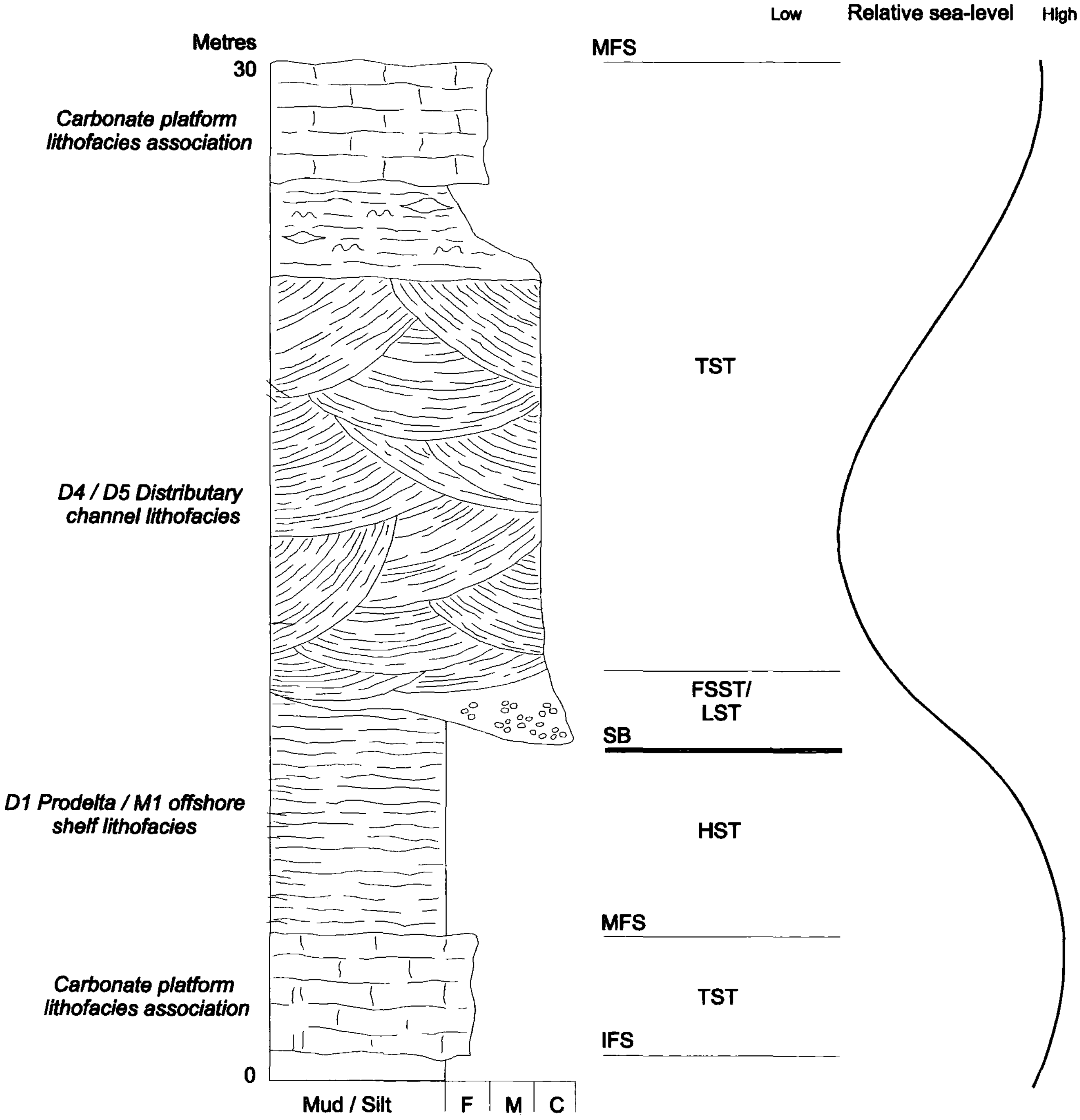


Figure 4-5 Diagram of a Cycle A1 with the relevant sequence stratigraphic components indicated to the right. The following abbreviations have been used: SB = Sequence boundary, MFS = Maximum flooding surface, TST = Transgressive systems tract, HST = Highstand systems tract, FSST = Falling Stage systems tract, LST = Lowstand systems tract. A sea-level curve has been provided on the right-hand side of the diagram. Grain size indicator is give along the bottom of sequence; mud/silt=mud/silt sized grains, F=fine-grained, M=medium-grained, C=coarse-grained.

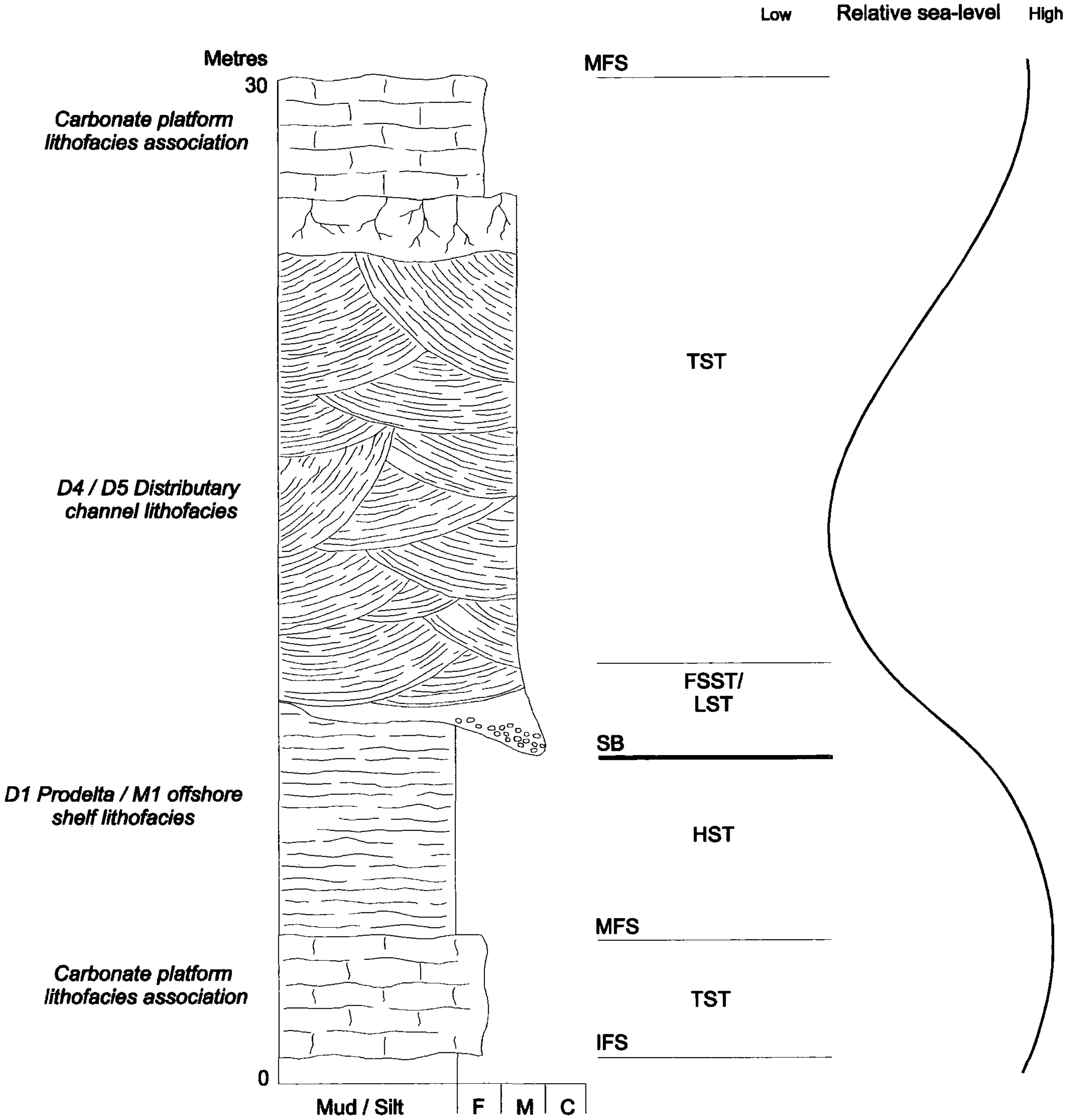


Figure 4-6 Diagram of Cycle A2 with the relevant sequence stratigraphic components indicated to the right. The following abbreviations have been used: SB = Sequence boundary, MFS = Maximum flooding surface, IFS = Initial flooding surface, TST = Transgressive systems tract, HST = Highstand systems tract, FSST = Falling Stage systems tract, LST = Lowstand systems tract. A sea-level curve has been provided on the right-hand side of the diagram. Grain size indicator is give along the bottom of sequence; mud/silt=mud/silt sized grains, F=fine-grained, M=medium-grained, C=coarse-grained.

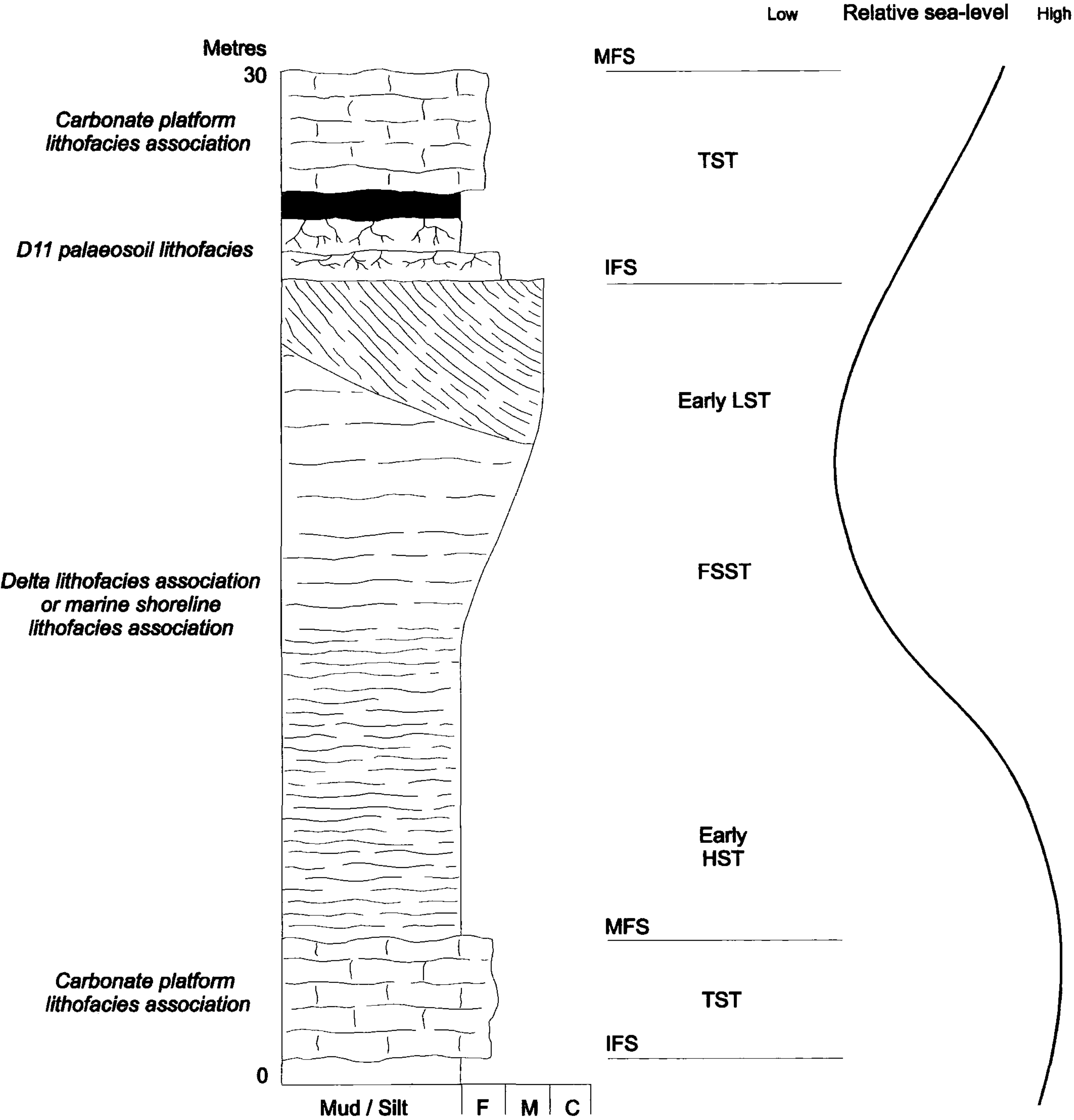


Figure 4-7 Diagram of a Cycle B1 with the relevant sequence stratigraphic components indicated to the right. The following abbreviations have been used: MFS = Maximum flooding surface, IFS = Initial flooding surface, TST = Transgressive systems tract, HST = Highstand systems tract, FSST = Falling Stage systems tract, LST = Lowstand systems tract. A sea-level curve has been provided on the right-hand side of the diagram. Grain size indicator is give along the bottom of sequence; mud/silt=mud/silt sized grains, F=fine-grained, M=medium-grained, C=coarse-grained.

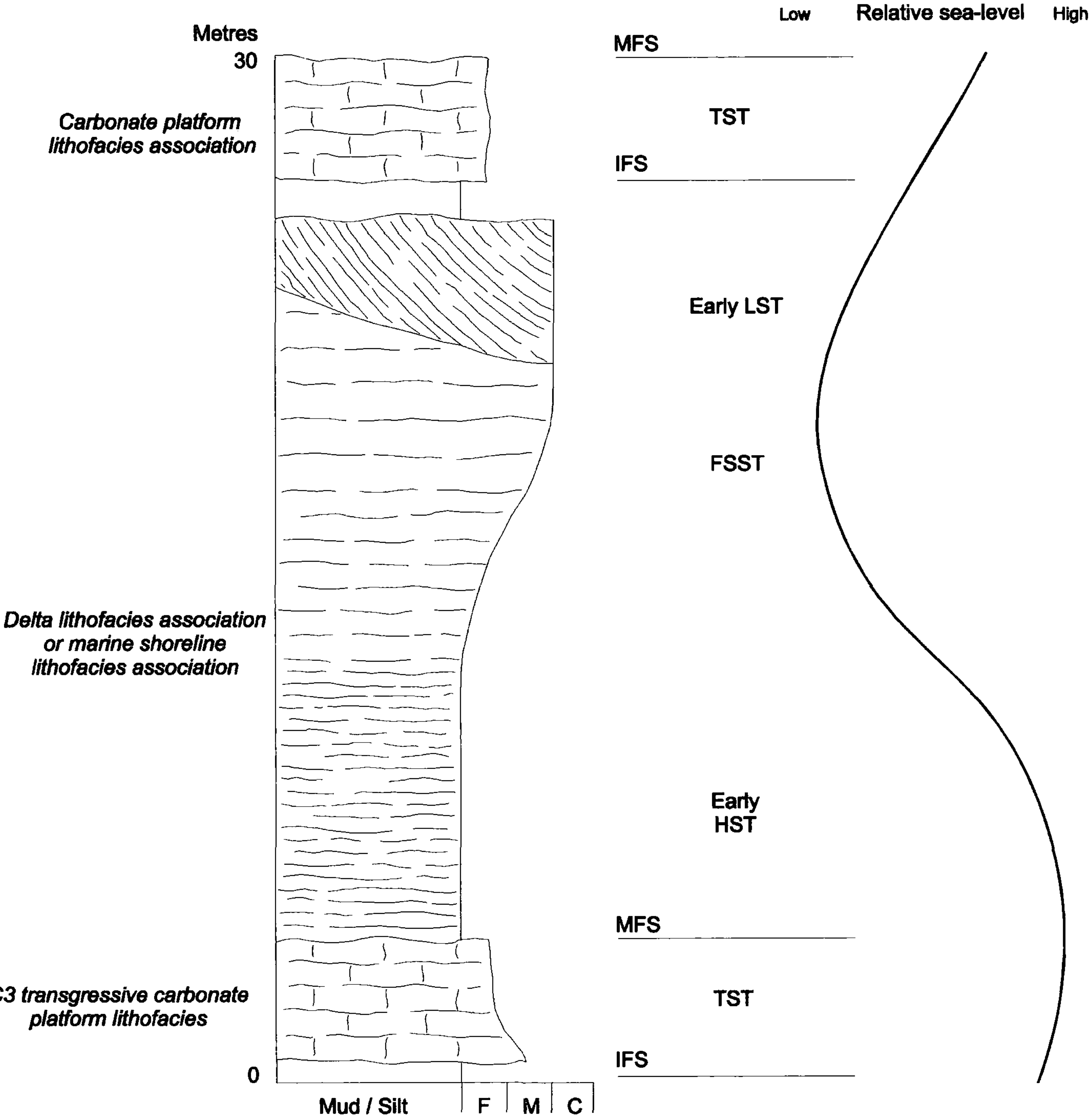


Figure 4-8 Diagram of a Cycle B2 with the relevant sequence stratigraphic components indicated to the right. The following abbreviations have been used: MFS = Maximum flooding surface, IFS = Initial flooding surface, TST = Transgressive systems tract, HST = Highstand systems tract, FSST = Falling Stage systems tract, LST = Lowstand systems tract. A sea-level curve has been provided on the right-hand side of the diagram. Grain size indicator is give along the bottom of sequence; mud/silt=mud/silt sized grains, F=fine-grained, M=medium-grained, C=coarse-grained.

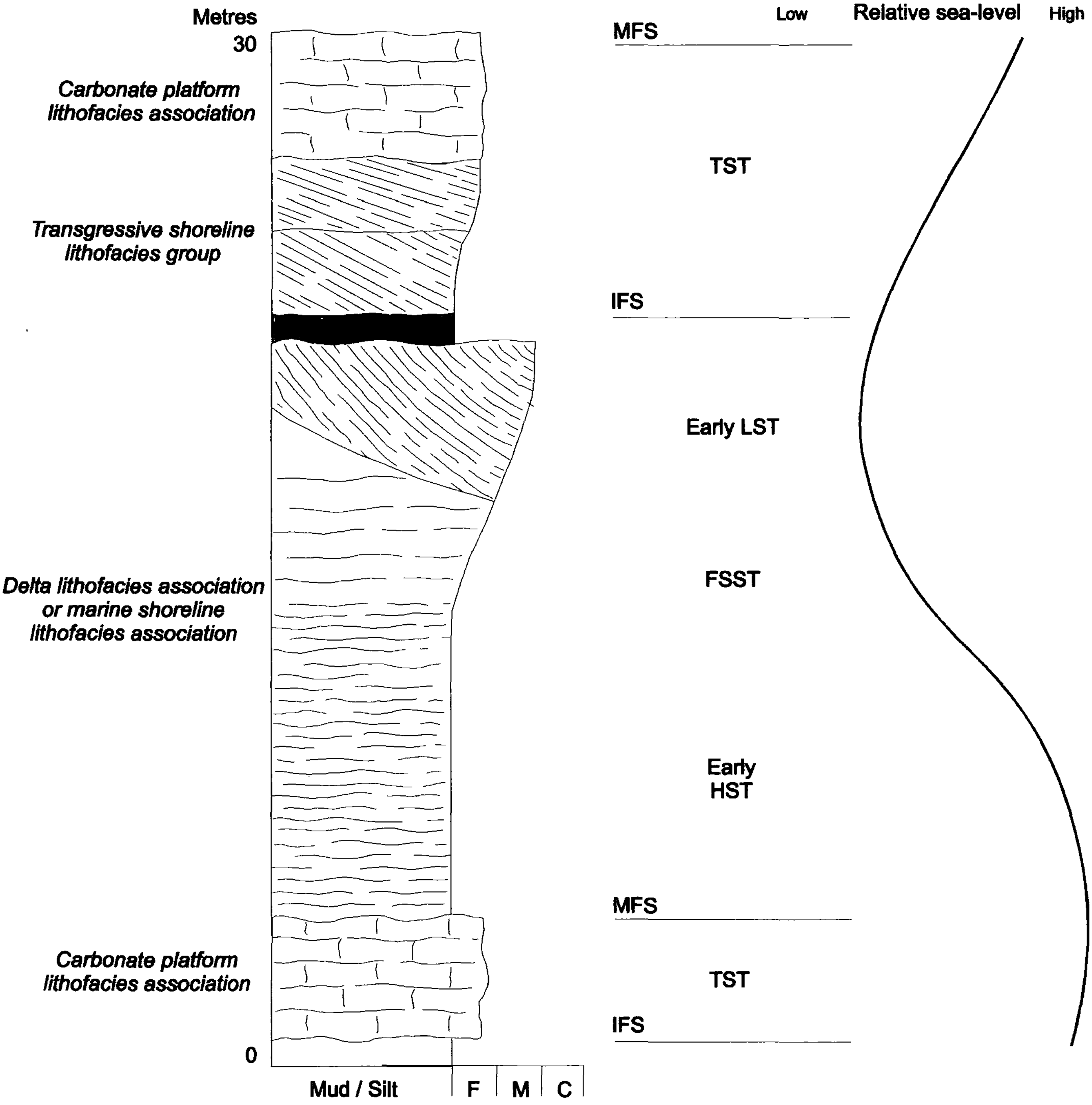


Figure 4-9 Diagram of a Cycle B3 with the relevant sequence stratigraphic components indicated to the right. The following abbreviations have been used: MFS = Maximum flooding surface, IFS = Initial flooding surface, TST = Transgressive systems tract, HST = Highstand systems tract, FSST = Falling Stage systems tract, LST = Lowstand systems tract. A sea-level curve has been provided on the right-hand side of the diagram. Grain size indicator is give along the bottom of sequence; mud/silt=mud/silt sized grains, F=fine-grained, M=medium-grained, C=coarse-grained.

accommodation space is at its minimum and no sediment can accumulate on the former shelf. An unconformity results over the exposed shelf and terrestrial processes such as pedogenesis take place. These pedogenic surfaces may be the lateral equivalent of Incised-Valley Fills (see Cycles A1 and A2) and form in interfluve areas. A Type-1 sequence boundary, which is commonly recorded during the early part of the LST, is not seen within the basic cycle.

The IFS that is characteristic of the beginning of the TST is taken as the base of the marine limestone of the basic cycle. The base of the limestone is interpreted as a transgressive lag deposit due to the high amount of coarse siliciclastic content and/or fragmented fossil debris (Tucker 2001). As the rate of relative sea-level rise increases, terrestrial systems are drowned and the fluvio-deltaic system is forced to retreat into the source area and siliciclastic sediment input into the basin ceased. The TST culminates with the MFS taken as the top of the surface of the marine limestone (see discussion below). The limestones of the Mid Carboniferous of Northumbria therefore characterise the TST and have regional chronostratigraphic correlative value.

The defining surface of the base of the HST is the MFS. Problems arise in the Mid Carboniferous sediments when recognising this surface as it is a mixed carbonate-siliciclastic succession and the entire section represents deposition in shallow marine conditions (e.g. Mancini & Tew 1997). Since the MFS formed when relative sea-level was at its highest, water depth was at its greatest and the shoreline was at its most landward limit it is typically marked by a condensed unit on the shelf when sedimentation rates were at their slowest (e.g. Hampson *et al.* 1997). There are several surfaces that could be taken as the MFS, these include the mid-point of the limestone marking the mid point of open marine deposition (e.g. Read 1994), an anoxic horizon some way up the limestone, a point two-thirds up the limestone marking the peak microfossil density or the top surface of the limestone could be used, heralding the end of carbonate production. It is beyond the scope of this study to evaluate fully the merits of each of the contenders for the MFS. There is no single feature that is found within each limestone, except for the top surface of the limestone which is readily identifiable at both outcrop and borehole level. The top of each limestone does represent a significant moment in time and is a consistent feature within each cycle so it has therefore been decided to use this horizon as the MFS.

The HST is most commonly represented by firstly, the aggradation of the deltaic / shoreline sediments (early HST) and then by the progradation of such sediments (late HST). A common feature of these basic cycles (and indeed within the cycle variants described below), the HST contains minor cycles of deltaic origin. These are generally caused by small scale events such as individual floods and crevasse splay units and should be considered to be a product of autocyclicity. As these minor cycles are of limited lateral extent and cannot be correlated across the study area or indeed even between outcrops it is unlikely that these were controlled by changes in relative sea-level.

4.2.2.2 Cycle Variant A1

Cycle Variant A1 and its sequence stratigraphic components are shown in Figure 4-5. The LST of Cycle Variant A is composed of an Incised Valley Fill (IVF), the base of which constitutes a Type-1 Sequence Boundary (Section 4.2.1.1). Such erosional unconformities are produced by river systems that are in net erosion during the period when relative sea-level is falling most rapidly (i.e. during the FSST) and is a pronounced feature of the lower reaches of rivers (Hampson *et al.*. 1997). To distinguish an incised valley-fill from a fluvial channel there are a few key characteristics; the basal surface of the valley fill should be regionally extensive, the lithofacies association that overlies the unconformity should differ radically from the underlying association, the erosional unconformity removes underlying strata sometimes at a scale that gives rise to an identifiable time gap and finally, they have a distinctive internal architecture, usually reflecting a subsequent increase in accommodation space caused by rising sea-level (Hampson *et al.* 1997). The basal surface of the valley fill should also be laterally equivalent to an interfluve surface. An interfluve surface is the name given to the areas of non-deposition in between the incised valleys. Any sediment deposition was bypassed through the incised valleys. Interfluve surfaces were commonly subject to pedogenesis and are therefore often characterised by palaeosoil development. The characteristics of an IVF compared with a fluvial channel is summarised in Table 4-1.

A good example of this type of cycle is seen at Bowlees Beck River Section (Ref. A1.1 in Appendix 2) where there is a thick fluvial channel cutting into marine shales approximately 2m above the Five-Yard Limestone (Brigantian) (Figure 4-10). The

Incised Valley-Fills	Fluvial / Distributary Channels
Basal surface regionally extensive. Tied to interfluve surface.	Basal surface seldom regionally extensive. Not tied to interfluve surface.
Overlying facies associations differ radically from those below.	Overlying facies associations similar to those below.
Erosional unconformity removes underlying strata. Preserved beneath paleosoils.	Erosional unconformity of much lesser extent. Not preserved beneath paleosoils.
Internal sediments record increasing accommodation space due to rising sea level.	No record of increasing accommodation space due to rising sea level.

Table 4-1 Table of the essential characteristics of incised valley-fill sediments in comparison to those of fluvial / distributary channels. After, Hampson *et al.* (1997).

Figure 4-10 Photograph of the base of an incised-valley fill at Bowlees Beck River section. Section is approximately 3m high and displays fluvial sandstones directly overlying the marine shales above the Scar limestone (Brigantian). The boundary between the 2 depositional environments is marked with a dashed red line.

channel is approximately 30m thick and is highly erosive in nature, removing the majority of what would be present as a 'normal' Yoredale cycle. The cycle reflects a change in accommodation space upwards as the lithofacies association changes from that of a low sinuosity river, to a high sinuosity river to estuarine conditions. This reflects a change in environment from freshwater to brackish / marine environment with the increasing rise in relative sea-level (e.g. Weimer 1994). Similar features are observed in the Upper Devonian Catskill Formation of the Appalachian Foreland Basin of Pennsylvania (Cotter & Driese 1998) where the channel fill of approximately 30m thickness is observed to change vertically from braided fluvial to estuarine deposits. Incised valley-fills prevailed in the Carboniferous (especially the Namurian) and many examples can be found from the low latitude Carboniferous localities such as the Silesian Basin of Poland (van der Belt *et al.* 2002), the Rough Rock Sandstone of Northern England (Hampson *et al.* 1997) numerous other incised valley-fills in the Craven-Askrigg area of Northern England (Martinsen 1993), and have previously been described from the study area by Hampson *et al.* (1999).

4.2.2.3 Cycle Variant A2

Cycle Variant A2 and its sequence stratigraphic components are displayed in Figure 4-6. Although the LST are interpreted as incised valley-fill deposits, the estuarine conditions formed during the subsequent rise in relative sea-level are absent. The top of the incised valley-fill is capped by a palaeosoil which immediately precedes the IFS of the marine limestone. This variation is seen in the incised-valley fill deposit found at Howick Coastal Section (Ref. A2.1 in Appendix 2) where the valley-fill is incised into marine shales below and removes the majority of the Howick Limestone Cycle (Pendleian) (Figure 4-11). The base of the valley-fill is coarse-grained, massive in nature and contains numerous plant fragments suggestive of rapid deposition. The nature of the deposition changes from low sinuosity to high sinuosity upwards and the overall grain size decreased upwards. However, a thin palaeosoil (30cm) is found containing abundant carbonaceous rootlets, immediately overlying the incised valley-fill.

This occurrence is common throughout the Upper Carboniferous incised valley-fills and would suggest that the valleys were filled prior to transgression, contrary to the notion of increased accommodation space during valley filling. This is explained by

Figure 4-11A Photograph of base of fluvial channel (marked with dashed red line) interpreted to be base of incised valley-fill. Underlying strata is marine shale and limestone (Howick limestone). Photograph taken at Howick coast section. Height of cliff is approximately 2m.

Figure 4-11B Photograph of sandstone at base of fluvial channel interpreted to be base of incised valley-fill. Photograph taken at Howick coast section. Height of figure is approximately 1.5m for scale.

Hampson *et al.* (1997) as being the effect of an increased sediment supply during this period meaning that sediment supply outpaced the creation of accommodation space.

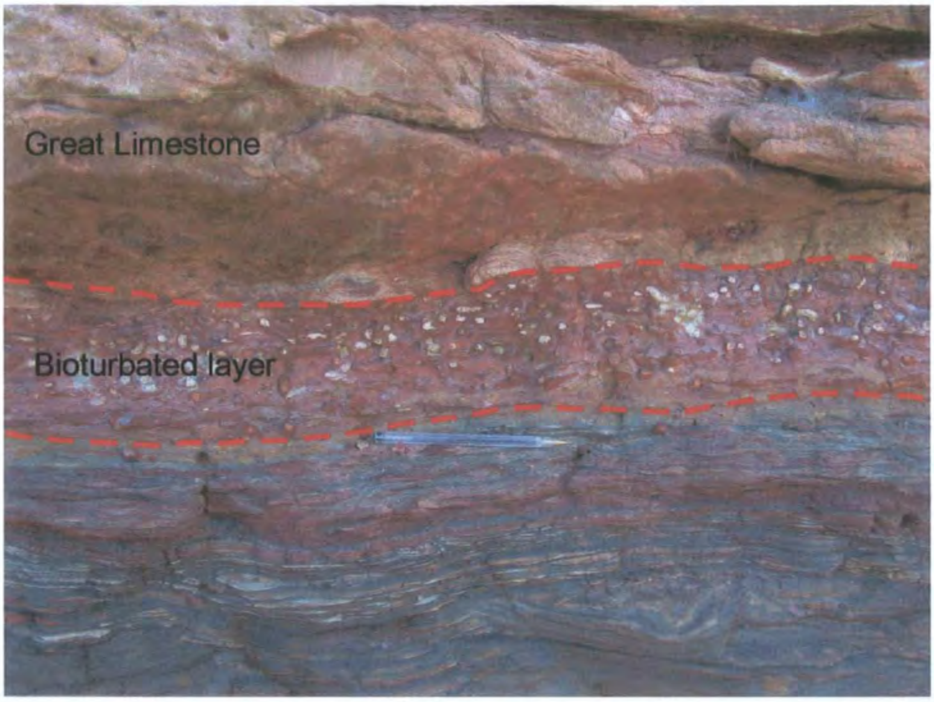
4.2.2.4 Cycle Variant B1

Cycle Variant B1 and its sequence stratigraphic components are displayed in Figure 4-7. In the Basic Cycle Type, the IFS is interpreted as being the base of the marine limestone. There are however other examples of IFS's. One of these is a series of stacked palaeosoils immediately preceding the marine limestone. Although it was previously stated that the presence of palaeosoils is usually indicative of the LST, a series of palaeosoils is often developed reflecting increasingly hydromorphic conditions (Section 5.3.2). During the LST mature palaeosoils are commonly developed, but due to reworking and lateral migration of channels the preservation potential for such palaeosoils is low, especially on channel margins. During the TST, weakly developed palaeosoils may be found as rate of increase in accommodation space is relatively high and vertical accretion is rapid. During the late TST, as the rate of formation of accommodation space decreases, the potential for vertical accretion declines and more mature soils develop or the water table may be raised so much that mires develop and coals are preserved instead (Figure 4-12). The base of the TST is taken as the base of a series of increasingly more hydromorphic palaeosoils directly beneath a marine limestone A good example of this is seen at Howick Coastal Section (Ref. B1.1 in Appendix 2) where there is a series of palaeosoils developed, with a well-drained palaeosoil at the base (LST), followed by a gleyed hydromorphic palaeosoil (early TST and IFS), followed by a thin laterally extensive coal (late TST), with the succession being immediately overlain by the Sandbanks Limestone (Figure 5-16).

4.2.2.5 Cycle Variant B2

The sequence stratigraphic components of Cycle Variant B2 are displayed in Figure 4-8. Underneath some of the marine limestones there is a transgressive surface characterised by a relatively thin (<30cm) quartz-rich lag with minor amounts of shell fragments, fish bone fragments (Maurice Tucker *pers comm.*), or lithic fragments. The top surface of which is commonly heavily bioturbated such as that found beneath the Great Limestone (Pendleian) at the Beadnell Coastal Section (Figure 4-13) (Ref. B2.1. in Appendix 2). This unit occurs directly above the palaeosoils of the LST.

Figure 4-12 Photographs of coal layers immediately beneath a marine limestone. The photographs shown are both showing the Dun limestone (Asbian) at Spittal coast section. In upper photograph the tape measure is approximately 10cm for scale, in the lower photograph, the figure on the left-hand side is approximately 1.55m for scale.



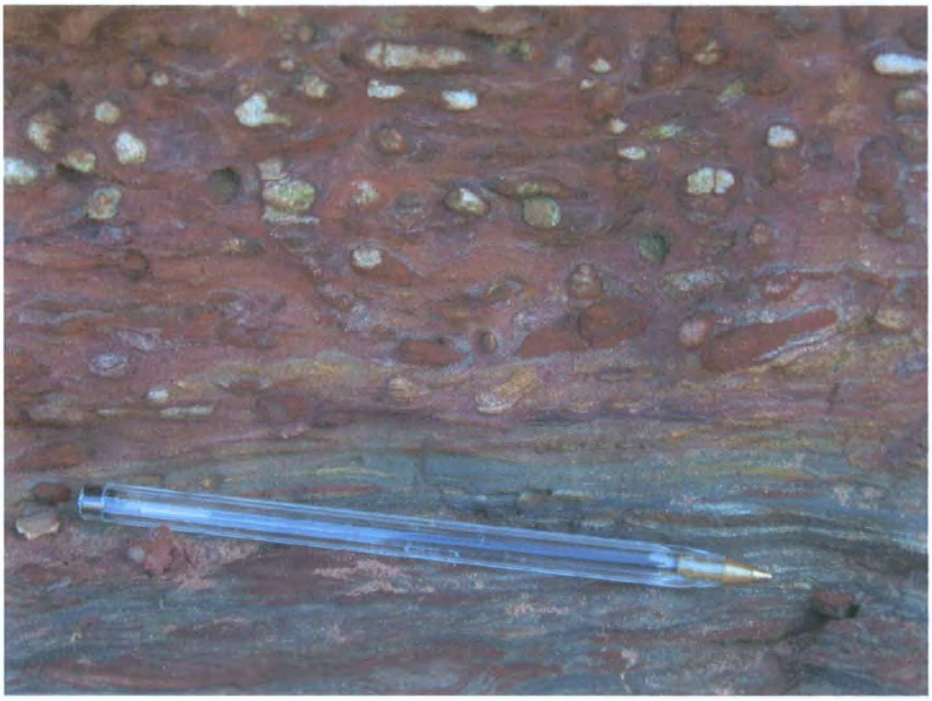


Figure 4-13 Photographs of the bioturbated layer found beneath the Great Limestone (Pendleian) seen at the Beadnell coast section. The upper photograph shows the Great Limestone, the bioturbated layer beneath, and the upper part of the underlying Sandbanks Limestone cycle (Late Brigantian). The lower photograph shows the bioturbated layer in more detail. Pen is approximately 15cm long for scale. .

The position of the unit directly above the palaeosoils of the LST and the diagnostic lag deposits of a marine dominated environment directly overlying a terrestrial environment, it is suggested that this unit represents a transgressive surface or IFS. This is then preceded by the marine limestone which occupies the late TST.

Similar features have been observed by George (2000) in the Basal Grit Group of the South Wales Variscan peripheral foreland basin.

4.2.2.6 Cycle Variant B3

Cycle Variant B3 and its sequence stratigraphic components are displayed in Figure 4-9. The final alternative to the early TST and IFS is given where transgressive siliciclastic shoreline deposits (Section 3.4.2), directly overlie LST palaeosoils. Such deposits are interpreted as well-developed transgressive units within the cycles and are best described by Percival (1992) in the Harthorpe Ganister in County Durham. These deposits are immediately succeeded by marine limestone and can therefore be described as early TST deposits.

4.3 Cyclostratigraphy

The cyclic nature of the Northumbrian stratigraphy presents a useful case to assess the effects of various cyclic processes, namely relative sea-level change and climate.

4.3.1 Cycle Duration

The duration of each Yoredale cycle has been calculated by taking key dates from the Carboniferous time-scale of Menning *et al.* (1999) to define a set time-period during the Mid-Carboniferous, and then dividing this by the maximum number of cycles within that time period. In this case, the dates used are the Asbian / Brigantian boundary and the Pendleian / Arnsbergian boundary, thus including the whole of both the Brigantian and Pendleian periods. The maximum number of Yoredale cycles has been used to reduce the number of missed cycles that are common in shallow-marine successions (Sadler *et al.* 1993). Using the above mentioned calculation the approximate duration of each Yoredale cycle is 200,000y. These calculations are summarised in Table 4-2. Based on the inferred duration of each cycle, each Yoredale cycle represents a fourth-order sea-level cycle, as they fall within the 0.1 to 1Ma duration bracket (Vail *et al.* 1977).

Carboniferous time-scale dates	**Number of cycles**	**Cycle duration**
Asbian / Brigantian boundary *331Ma* Pendleian / Arnsbergian boundary *324Ma* Duration of period **7Ma**	Maximum number of cycles during this period **35**	$\frac{7\text{Ma}}{35}$ =0.2Ma **=200,000 years**

Table 4-2 Calculations used to deduce the duration of each Yoredale cycle. Carboniferous dating figures are from Menning *et al.* (2000).

It should be noted at this stage that the calculation of cycle duration is very uncertain as there are significant variations throughout the study area regarding the number of cycles within each time period. Perhaps most obvious is the inaccuracy in the radiometric dating ages; the error bars given for the ages stated may be up to ±8.0Ma which could have a huge impact on the cycle durations provided. By taking an average figure for the whole time period looked at within this thesis there is also significant room for error. This fact is emphasised by looking at the cycle variation within each time period (Table 4-3); if cycle duration is calculated for each time period individually, the duration varies from 200,000years to 400,000years.

Carboniferous time-scale dates	**Number of cycles**	**Cycle duration**
Asbian period 334.5Ma to 331Ma = **3.5Ma**	8	0.43Ma / 430,000yrs
Brigantian period 331Ma to 326.5Ma = **4.5Ma**	21	0.21Ma / 210,000yrs
Pendleian period 326.5Ma to 324Ma = **2.5Ma**	6	0.41Ma / 410,000yrs

Table 4-3 Calculations used to deduce the duration of each Yoredale cycle within individual time periods. Carboniferous dating figures are from Menning *et al.* (2000).

4.3.1.1 High-frequency Sequences

In this study, the 'cycles' are inferred to have formed during a period of time when sea-level falls from a highstand position, through a lowstand and returns to a highstand. The necessary diagnostic criteria for a depositional sequence is therefore evident in each cycle. In many areas of the geological record, with moderate to high depositional rates in a greenhouse climatic phase, sequences defined in this manner fall into third-order cyclicity (1 to 2My) (Vail *et al.* 1977). However, sequences are now recognised with all the necessary components occurring with fourth-order frequencies leading to their classification as high-frequency sequences (Mitchum & Van Wagoner 1991). These are especially common during icehouse times and this particular classification is applicable to the Yoredale cycles of Northumbria.

4.3.1.2 Milankovitch Cycles

The principal control on the growth and decay of ice sheets can be attributed to the fluctuations in incoming solar radiation commonly referred to as Milankovitch cycles. There are three orbital properties that determine how the sun's radiation is distributed over planetary surfaces (Figure 4-14); the position of the equinoxes in their precessional cycle (22,000 year cycle), the tilt of the axis of rotation (41,000 year obliquity cycle) and the eccentricity of the Earth's orbit around the sun (100,000 year and 400,000 year cycles). Variations in eccentricity and precession are large enough to cause ice sheets to expand and contract, causing fluctuating global sea-level. Due to the similarity in cycle duration, it is the 100,000 year eccentricity cycles that has been proposed as the major control on Yoredale cyclicity through fluctuations in glacio-eustasy. The duration used for each Milankovitch cycle within this study is that known from Recent deposits i.e. Quaternary to present day, and it is likely that this duration has changed throughout geological time (Imbrie & Imbrie 1979).

4.3.1.3 Comparison to other areas

There are many occurrences of cyclic deposition in Northern Britain and farther afield throughout the Mid-Late Carboniferous reflecting the global control on cycle development. The dominant Milankovitch mechanism is heavily disputed with both the short eccentricity (100Kyr) signal being proposed by some authors (e.g. Maynard & Leeder 1992; Weedon & Read 1995; Wright & Vanstone 2001), from the Late Carboniferous of Northern England and Southern Scotland, and the long eccentricity

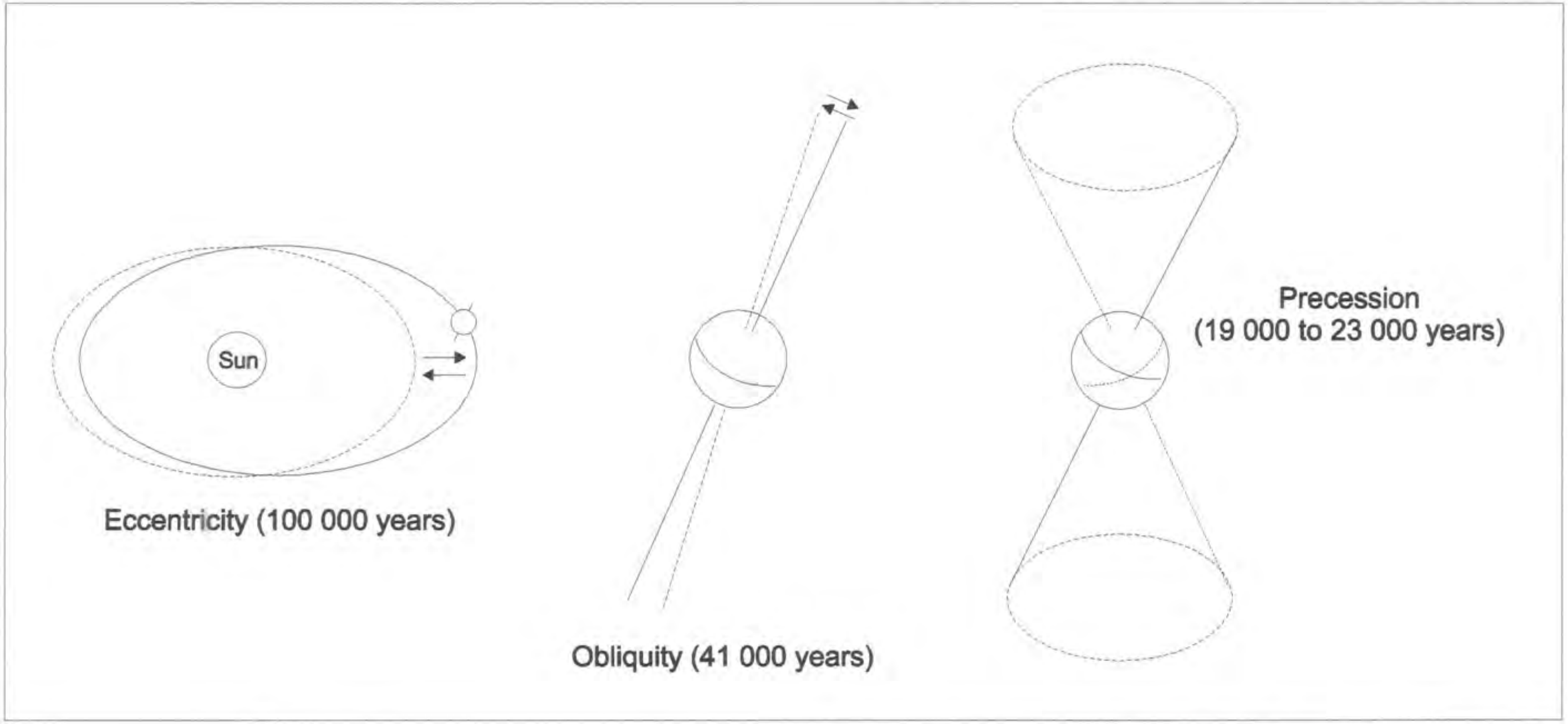


Figure 4-14 Illustration of the variations in the Earth-Sun system commonly referred to as Milankovitch rhythms or cycles. See text for details. After, Retallack (1995).

(400Kyr) signal being proposed by others (e.g. Smith & Read 1999, 2000). There are however other authors such as Riley *et al.* (1994) who propose a periodicity of 65Kyr which does not conform with any of the Milankovitch rhythms suggesting a cycle origin completely different from that of glacio-eustasy. The comparison of cycle duration between areas is summarised in Table 4-4.

Author/s	**Cycle duration**	**Milankovitch Parameters**	**Age**	**Location**
Veevers & Powell (1987)	400Ky	Short eccentricity	Mid to Late Penn.	Mid Continent, North America
Riley *et al.* (1994)	65Ky	Unknown	Mid Carb. boundary	North Yorkshire, U.K.
Tandon & Gibling (1994)	200Ky	Short eccentricity	Westphalian	Nova Scotia, Canada
Weedon & Read (1995)	100Ky	Short eccentricity	Pendleian	Central Scotland
Smith & Read (2000)	400Ky	Long eccentricity	Mid Carb. Boundary	Central Scotland
Wright & Vanstone (2001)	100Ky	Short eccentricity	Asbian / Brigantian	British Isles
Barnett *et al.* (2002)	100Ky	Short eccentricity	Asbian / Brigantian	British Isles
Olzewski & Patzkowsky (2003)	<100Ky	Short eccentricity	Penn. / Permian	Mid Continent, North America

Table 4-4 Table summarising the durations of other Carboniferous cycles and their interpreted Milankovitch parameters.

4.3.2 Fischer Plots

The analysis of high-frequency changes in accommodation space is commonly done by using Fischer plots. This method was first used by Fischer in 1964 when explaining the variations in thickness of the peritidal Triassic Lofer cyclothems of the Calcareous Alps. Fischer plots have since been used in numerous carbonate depositional environments (e.g. Bosence et al. 2000; Mingxiang *et al.* 2001; Martin-Chivelet 2003). Their use to date on siliciclastic-dominated depositional environments is more limited and has been restricted to those cycles that shallow upward to sea-level (e.g. Simpson & Eriksson 1991).

Fischer plots are used to track the cumulative departure from mean cycle thickness through a vertical succession of upward-shallowing units (Sadler *et al.* 1993), thus allowing an interpretation of long-term sea-level and subsidence histories.

There are however, many authors who have speculated as to the effectiveness of this method. Drummond & Wilkinson (1993, 1996) suggested that the patterns produced may be indistinguishable from results of random depositional processes. Burgess & Wright (2001) have stated that variations in sediment transport can produce parasequences in apparently ordered hierarchies despite the absence of ordered allocyclic processes. Hillgartner & Strasser (2003) stated that Fischer plots do not account for sediment accumulation that does not reach the water surface during a sea-level cycle and that erosion and sea-level fall below the depositional surface are therefore rejected.

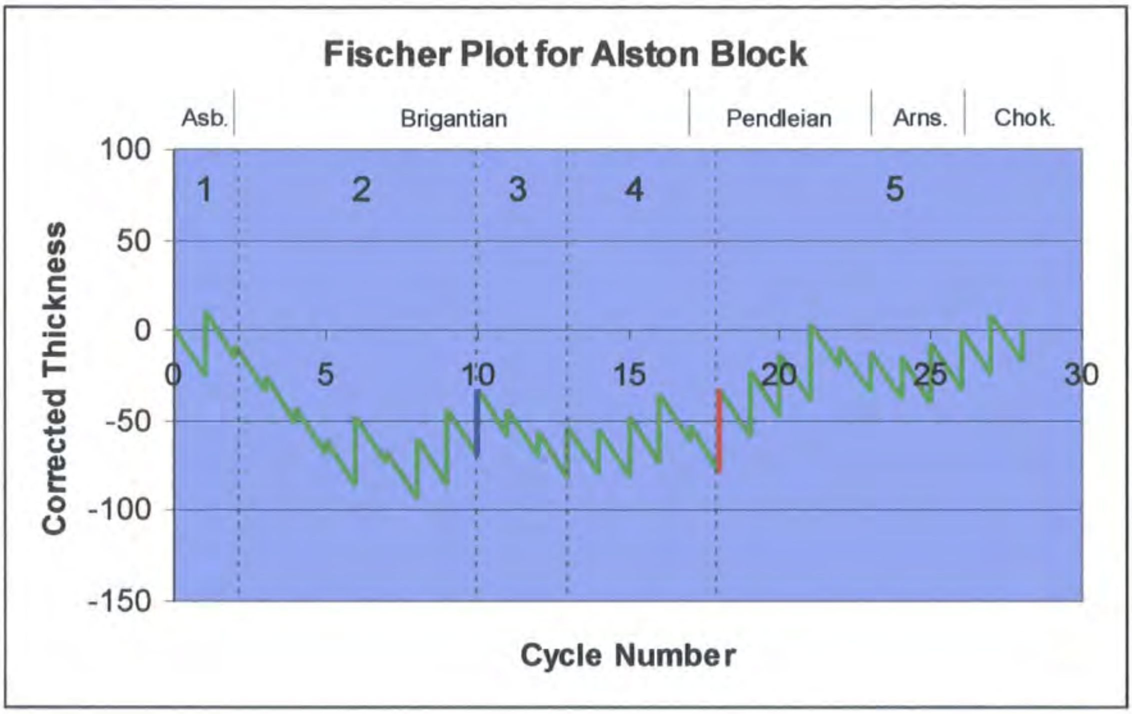
Fischer plots have been used in this study despite the speculation regarding their effectiveness. Sediment accumulation within all cycles of the Mid Carboniferous succession of Northumbria did reach sea-level, and prior knowledge of the regular fluctuations in relative sea-level during this period, have all led to this decision. In this case, what the changes in accommodation space represent is the interplay between relative sea-level change (tectonic and eustatic) together with sedimentation rates.

The number of cycles varies between the Alston Block and the Northumberland Basin. It is however possible to correlate key limestones such as the Oxford / Jew limestone (Brigantian) and the Great limestone (Pendleian). The Fischer plots should be observed with this in mind and although the number of cycles may vary, the time-scale and the overall trends can be compared successfully.

4.3.2.1 Results and Interpretation

Two Fischer plots have been produced for the study area; one for the Northumberland Basin area to the north (Figure 4-15A) and another for the Alston Block to the south (Figure 4-15B). The reason for this is to try and eliminate any tectonic variations that may exist between the two areas as a control on changes in accommodation space.

A.



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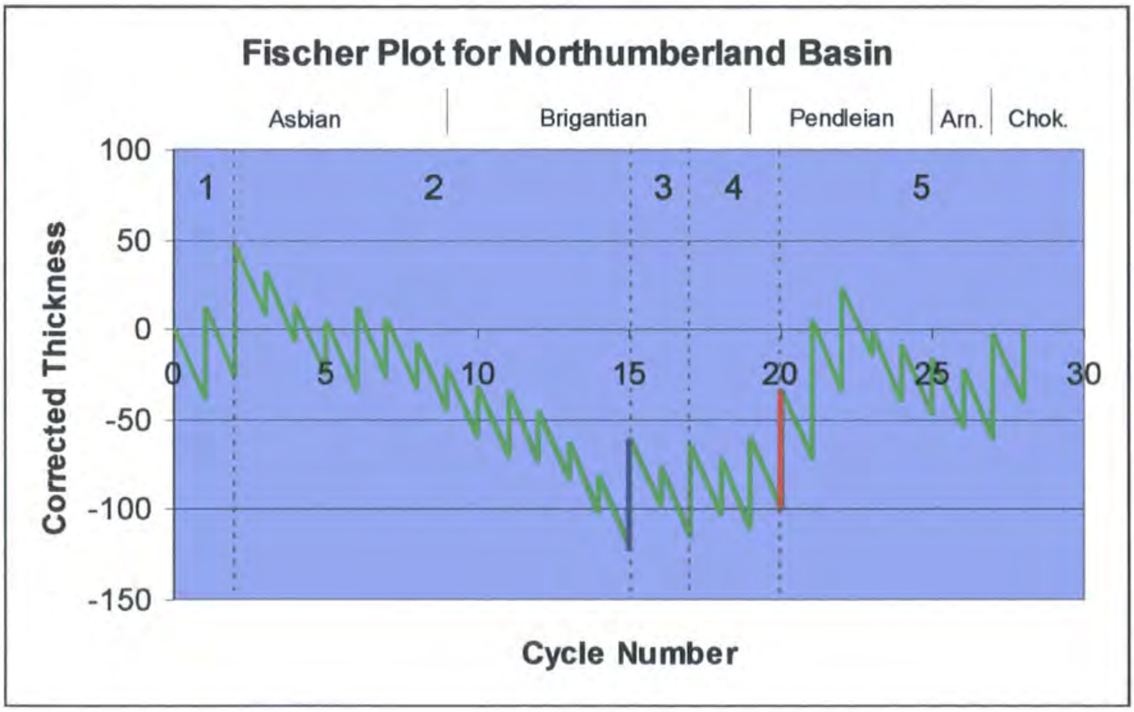

Figure 4-15 Fischer plots for both the Northumberland Basin (A) and Alston Block (B). The five phases that have been identified within each Fischer plot are numerically indicated in the upper part of each plot. The corrected thickness of each plot is in m's. The cycle number is not a means of correlation, this merely refers to the amount of cycles within each area, and it should be noted that the number of cycles within each time period varies across the area. Two limestones have been plotted for correlation: a thick blue line indicates the Oxford / Jew limestone, a thick red line indicates the Great limestone.

Looking at both of the plots produced, when correlated between the equivalent depositional cycles, it is clearly visible that both areas show similar trends. An initial increase in cycle thickness to a peak in the Mid Asbian is observed, followed by a significant decrease in cycle thickness until the Mid Brigantian. This is followed by an increase in cycle thickness which tapers off at the top of the succession in the Arnsbergian / Chokerian.

The very different structural areas show very similar trends, suggesting that the overall control on accommodation space was that of relative sea-level and not tectonic activity. The results can be interpreted as indicating that the early cycles from the Early to Mid Asbian were laid down in a period of highstand of relative sea-level when accommodation space was at its greatest and then a lowstand of relative sea-level to the Mid Brigantian, when accommodation space would have been greatly reduced. This was followed by a transgression from the Mid Brigantian to the Mid Pendleian when accommodation space would have once more been increasing, before another period of highstand (greatest accommodation space) and falling to a lowstand of relative sea-level (decreasing accommodation space). The likely duration of the full relative sea-level cycle revealed by looking at the Fischer plots is approximately 4Ma. This change in sea-level has been interpreted as a third order sea-level cycle, a cycle that is of 0.2Ma to 5Ma duration (Church & Coe 2003).

There are 5 phases that can be identified that constitute third-order cyclicity within both the Alston Block and the Northumberland Basin which are marked on Figure 4-15. These have been summarised in Table 4-5.

The variations that occur between the two areas appear to be minimal. The overall trend is more subdued in the Alston Block as it has not undergone such rapid subsidence as the adjacent basins (Section 8.6).

Phase 1	Gentle rise in relative sea-level
Phase 2	Fairly uniform relative sea-level fall
Phase 3	Initial thick cycle followed by a series of thin cycles representing a relative sea-level fall
Phase 4	Initial thick cycle (Oxford / Jew limestone) followed by a series of thinner cycles
Phase 5	Initial very thick cycle centred on the Great limestone with fairly uniform relative sea-level rise
Phase 6	Initial thick cycle followed by thinner cycles, reflecting relative sea-level fall

Table 4-5 Table illustrating the 5 major phases identified within the Fisher plots seen in Figure 4-15.

One other feature that should be mentioned is the temporal difference between phases 2 and 3. In the Northumberland Basin these occur for the Mid Asbian to the Mid Brigantian whereas in the Alston Block they do not occur until the Late Asbian to Mid Brigantian. As mentioned in Section 3.4, the Asbian succession of the Alston Block area is dominated by carbonates, for example, the Melmerby Scar limestone cycle of the Alston Block, is equivalent to 7 limestone cycles of the Northumberland Basin (Figure 4-16). Although these cycles are undoubtedly present within the Melmerby Scar limestone they are difficult to identify without detailed analysis that is beyond the scope of this work. It is therefore difficult to correlate the data sufficiently between these 2 areas during the Asbian period.

Some of the transgressive events that deposited these limestones are thought to be diachronous (Johnson 1960), especially during the Asbian period. If this was the case then any change in accommodation space resulting from a rise in relative sea-level would appear to occur later in the Northumberland Basin (to the north) than in the Alston Block (to the south) which is the case seen here.

In sequence stratigraphic terms, both of the successions from the Asbian to Arnsbergian / Chokerian represent a third order sea-level cycle of approximately 4Ma duration. This figure is obtained by multiplying the number of Yoredale cycles within

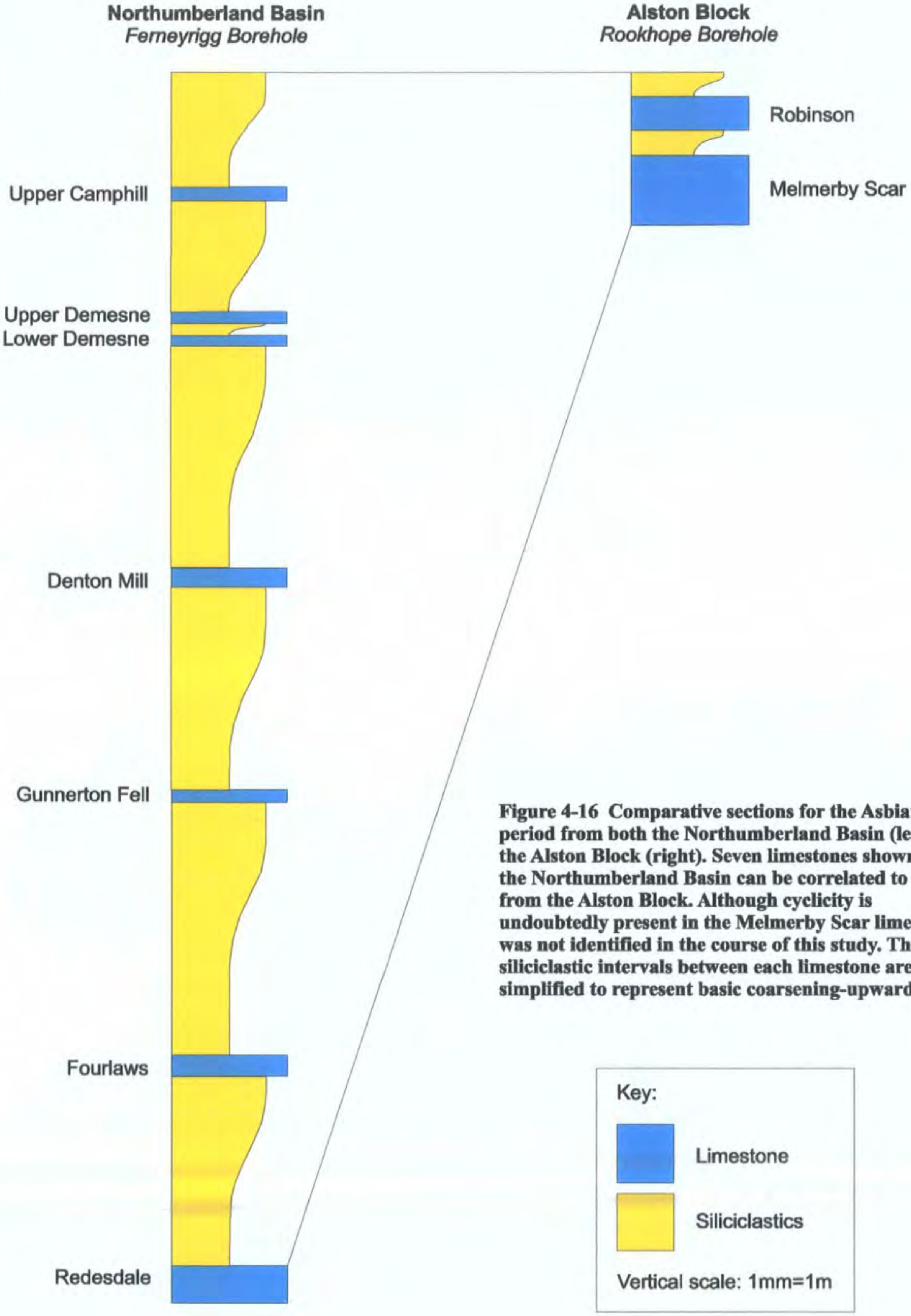

Figure 4-16 Comparative sections for the Asbian period from both the Northumberland Basin (left) and the Alston Block (right). Seven limestones shown from the Northumberland Basin can be correlated to two from the Alston Block. Although cyclicity is undoubtedly present in the Melmerby Scar limestone is was not identified in the course of this study. The siliciclastic intervals between each limestone are simplified to represent basic coarsening-upward units.

the proposed third-order cycle (20) by the duration of each individual Yoredale cycle (200,000 years).

During this cycle there are major systems tracts (Section 4.2.1) visible within the third order sea-level cycle. The Mid Asbian peak in relative sea-level represents a third order highstand before a long period of relative sea-level fall resulting in a third order sequence boundary in the Early to Mid Brigantian. A third order initial flooding surface is represented by the thicker cycle associated with the Oxford / Jew limestone. A maximum flooding surface represented by the thick cycle of the Great limestone occurred during the Early Pendleian.

4.4 Causes of Cyclicity

It is not the aim of this research to provide a comprehensive study of the causes of cyclicity within the Mid-Carboniferous Yoredale succession. As the time-scales of various cycles have now been established a summary of the proposed causal mechanisms are outlined below.

4.4.1 Fifth-Order Cycles

Although fifth-order cycles have not been mentioned previously within this Chapter, they are discussed as part of Section 5.3.2. The evidence for such cycles is found as intracycle palaeosoil sequences that reflect changes in base-level. There is no way to date such changes within each cycle but as the duration of each Yoredale cycle is approximately 200,000 years, then obviously such changes in base-level must be of a lesser duration. Fifth-order cycles have a duration of between 0.01 and 0.1Ma and it is assumed that the features found within each Yoredale cycle have a similar duration.

The causal mechanism of such small cycles is unknown. They may be the result of changes in relative sea-level, or they may be the result of eustatic sea-level changes perhaps related to the obliquity or precessional Milankovitch cycles. As there is no way to correlate such cycles, such causal mechanisms are purely speculative.

4.4.2 Fourth-Order Cycles

Tectonic activity has been proposed as a causal mechanism for Yoredale cyclicity. There are two components of this; the first is that of extrabasinal influence, fluctuating siliciclastic input due to repeated hinterland uplift (Hudson 1924; Weller 1930, 1956), the second is that of episodic subsidence along the basin / block marginal faults (Bott & Johnson 1967). This second aspect would mean that areas of greatest subsidence contain more recorded cycles as they would have more accommodation space than those areas of little subsidence. This has been noted in the Mid-Carboniferous of Southern Scotland (Read & Dean 1976). Although there is no doubt that tectonic activity had a significant influence on sedimentation during the study period, and that it is feasible that plate tectonics have a strong influence on long-term first order cyclicity, such short-term uniform tectonic activity is unlikely. Although Cisne (1986) proposed that syn-sedimentary strike-slip faulting could produce small relative rises in sea-level rises and therefore produce cyclicity, faulting would have to be periodic and uniform to result in repetition of cycles instead of the apparent unpredictability of fault activity. The scale of sedimentation and the poor resolution of dating could mean that tectonism could appear to be 'regular' as stresses build up and then faulting periodically breaks through. A more detailed account on the affects of tectonic activity on the sedimentation of the Mid Carboniferous in Northumbria is given in Section 8.3.

Another proposed mechanism is that of a purely sedimentary mechanism based on the lobe-avulsion theory suggested by Moore (1958, 1959). This idea is based on the fact that fluvially-dominated deltas create their own delta-marine cyclicity through entirely sedimentary mechanisms (e.g. Fisk *et al.* 1954). The depositional environments that are present, especially those of fluvial and deltaic origin, have strong sedimentary autocyclic components in their stratigraphy so this mechanism seems very plausible. However, the global climate and sea-level were such that sediments were being deposited close to sea-level and cyclicity would be very likely to have been caused by variations in relative if not global sea-level change.

Glacio-eustasy was first proposed as a causal mechanism for the Yoredale cycles by Wanless & Shepherd in 1936. They suggested that delta progradation during falling and low sea-level stands, followed by marine transgression and carbonate sedimentation during periods of rising sea-level as the delta front retreated across the shelf would produce cycles during glacio-eustasy. Such a large magnitude of glacially-induced sea-level fluctuations would have major effects upon basin margin sedimentation (Leeder 1988) such as the incised-valley fills seen within the study area. This theory has more recently been by and large accepted due to the widespread occurrence of cyclicity, not only in Northern Britain, but farther afield in areas such as the Midcontinent U.S.A. (e.g. Heckel 1994; Beuthin & Blake 2002). More recently, it has been possible to use biostratigraphy to correlate various horizons between Northern Britain and North America for successions during this period (Titus & Riley 1997), suggesting that sea-level change was indeed global. It is not possible for global or eustatic sea-level changes to occur as a result of purely sedimentary mechanisms. Although global sea-level change can occur as a result of tectonic activity, it is not possible for this to occur with such regularity and for each cycle to be such a short duration. It is therefore the consensus of the majority of authors that glacio-eustasy was the main controlling mechanism on the cyclicity of the Yoredale cycles, which were more than likely locally altered by both sedimentary and tectonic activity. This theory depends on the presence of Gondwanan icesheets during the Late Palaeozoic, whose presence has been detected from glacial deposits in Australia, South Africa, India and South America (Section 2.9); as the icesheets waxed and waned, they produced changes in eustatic sea-level and resulted in cyclic sedimentation. Isbell *et al.* (2003) have stated however that the icesheets that were present in Gondwana during the Late Palaeozoic were not as extensive as first thought and could therefore not be the major cause of eustatic sea-level change during this time.

4.4.3 Third-Order Cycles

During the later part of the Palaeozoic era, major sea-level fluctuations have been recorded which are global, not regional, in extent having a duration of 0.2 to 5My, that is, a third-order cyclicity (Church & Coe 2003). Third-order cycles are generally attributed to major regression and transgression generally associated with glacio-eustasy (Ross & Ross 1987). Tectonics can also be important in third-order cyclicity due to the attenuation of active faults and intervals of tectonic quiescence (e.g. Fraser & Gawthorpe 1990; Fraser *et al.* 1990).

4.4.3.1 Palaeozoic Glaciation and Third-Order Cycles

Late Palaeozoic glaciation in the southern hemisphere is evident at outcrop from all over the Late Palaeozoic supercontinent of Gondwana (Section 2.9). Indirect evidence for such an event is however, seen elsewhere from Late Palaeozoic sediments, especially from those that lay at low latitudes during this time such as the Mid Carboniferous sediments of Northumbria.

Only one complete third-order cycle is seen within the study period, suggesting a sea-level transgression in the Mid Asbian followed by major regression until the Mid Brigantian. Although tectonic activity has been suggested as a causal mechanism for third-order sea-level changes, Titus & Riley (1997) have correlated the major Mid Asbian transgression between the Antler Foreland Basin of Western Utah with the Craven basin of Northern England using ammonoid strata. The existence of such a major flooding event in different tectonic settings more than 5000km apart would suggest a geographically widespread eustatic mechanism (Barnett *et al.* 2002).

Using the stable isotope values of brachiopods, Wright & Vanstone (2001) recognised two major phases of glacial activity during the Late Palaeozoic: 1. Late Tournaisian and 2. Mid to Late Viséan. Although there were two phases of glacial activity, it was not until the latter of these two phases that glacio-eustasy began, and it is inferred that this began abruptly in the Early Asbian (Wright & Vanstone 2001). Such a rapid change to a world with regular glacio-eustatic fluctuations would imply that some form of threshold was crossed that triggered a change in the behaviour of the Gondwanan ice sheets. Wright & Vanstone (2001) suggested that from the Asbian onwards, the ice sheets grew sufficiently large to trigger decametre scale sea-level oscillations and to become sensitised to solar insolation. The occurrence of third-order sea-level changes within the study area may therefore be attributed to the onset of a major phase of glacial activity associated with the onset of the Late Palaeozoic glaciation. This is confirmed by the ability to correlate such changes in sea-level across vast areas and from global stable isotope evidence as previously mentioned.

4.5 Summary

Various cycle durations have been inferred from the study area reflecting the huge influence that glacial activity can have upon sedimentation in equatorial areas. These have been summarised in Table 4-6.

An assortment of types of fourth order cycle have been identified, termed as high-frequency sequences which are inferred to be the result of cycles of 100,000 year magnitude of variations in the eccentricity of the earths orbit around the sun. Different depositional environments produce slight variants in cycle type, but each component of a sea-level cycle can be found within each of these sequences.

Order of Cycle	Cycle Duration	Description
Fifth *(Section 5.3.2)*	0.01 to 0.1Ma	Palaeosoil surfaces indicating transgressions found within Yoredale cycles
Fourth	0.2Ma	Individual Yoredale cycles
Third	4Ma	Changes in accommodation space identified by using Fischer plots

Table 4-6 Summary of the duration of each type of cyclicity found within the Mid Carboniferous strata of Northumbria.

In addition to the fourth-order cycles that have been identified, there are third-order cycles, both of which occur simultaneously as composite eustatic fluctuations. These have been interpreted as the result of sea-level fluctuations on a much grander scale due to various glacial episodes in Gondwanaland during this time. The glacial episode represented during the Mid Carboniferous is that of glacial episode III, a period when the glacial extent was of a high enough magnitude to be affected by changes in solar radiation resulting in worldwide cyclicity.

Chapter Five

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Chapter 5 – Palaeosoil development: classification and interpretation

5.1 Introduction

The Mid Carboniferous strata of Northumbria contain numerous palaeosoils. Palaeosoils are useful for the recognition of sequence boundaries as previously discussed in Section 4.2.1, and have previously been referred to as various names such as ganister, seatearth and fireclay. They function as stratigraphic marker horizons, but they are also invaluable as palaeoclimatic indicators.

In geological terms, palaeosoils are somewhat unique in that they represent breaks in deposition with little or no erosion, as opposed to most sedimentary rocks, which record exclusively depositional events. The most commonly quoted definition of a palaeosoil is that of Valentine & Dalrymple (1976): 'a palaeosoil is a soil formed on a landscape of the past'. It becomes apparent that the study of palaeosoils can yield a great deal of information with regards to the Mid Carboniferous landscape of Northumbria; they can provide information on a multitude of environmental factors including climate, parent material, topographic relief, organisms and time (Percival 1986).

The aim of this chapter is to assess the nature and distribution of the palaeosoils (Sections 5.2 & 5.3) within the Viséan and Namurian of Northumbria and to present an insight into the landscape that existed during this time.

5.2 Palaeosoil Facies Description and Interpretation

Palaeosoils were recorded from all outcrops studied (Table 1-1) using the palaeosoil recording sheet in Appendix A5.7. Palaeosoil identification criteria from Retallack (1997) were used and are summarised in Appendix 5.

There are five distinct palaeosoil facies within the study area. These are described in detail below. A summary of the palaeosoil descriptions and interpretations can be seen in Table 5-1, with a graphic representation of each palaeosoil facies given in Figure 5-1. Classification of the palaeosoils is by reference to the various published schemes (e.g. Retallack 2001, Duchaufour 1998), the reason for this being that no one unique classification is suitable for classifying all the palaeosoil types found.

PF	Palaeosoil Facies	Number of horizons	Lithology	Colour	Thickness	Upper boundary	Lower boundary	Evidence of plant life	Evidence of animal life	Pedogenic structures	Lateral continuity	Bedding present	Environmental Interpretetation
1	Histosol	1	Coal and associated organic-rich shale	Black	10cm to	Sharp & planar	Sharp & planar or locally	Indet. Plant fragments	None seen	None seen	Commonly over 100's of km's	None seen	Precipitation exceeds evaporation; commonly equatorial and mid latitudes
2	Podzol	2	*Upper:* Quartz cemented fg to	Buff to pale grey	10cm to	Sharp & planar	Sharp & undulose	Carbonaceous rootlets, *Stigmaria,*	Vertical burrowing	'Lobateprojections' into horizon below	10's to 100's of m's	None seen	Well-drained conditions in humid climates
			Lower: Fg to mg sandtstone / siltstone	Grey to dark grey	10cm to 120cm	Sharp & undulose	Gradational & planar	Little seen	None seen	None seen			
2a	Vertic Podzol	2	As for Pf2	As for Pf2	As for Pf2	As for Pf2	As for Pf2	As for Pf2	As for Pf2	*Upper:* Siderite nodules. Minor slickensides and shrinkage cracks	As for Pf2	As for Pf2	Well-drained conditions in humid climates; pronounced wet and dry seasons
										Lower: Root mottling and ferric			
3	Gleysol	1	Claystone, mudstone, siltstone or very fine-grained	Buff, mid-grey to dark grey (often darkens upward)	45cm to 150cm	Sharp & planar. Locally irregular	Gradational & planar	Carbonaceous plant fragments and rootlets, *Stigmaria*	Rare sub-vertical burrowing	None seen	10's to 100's of m's	Relict bedding decreasing upward	Found in all climatic regions
3a	Pseudo-gleysol	1	As for PF3	As for Pf3	As for Pf3	As for Pf3	As for Pf3	As for Pf3	As for Pf3	Fe-rich (sideritic) horizon in middle of unit. Siderite nodules also seen.	As for Pf3	As for Pf3	Found in all climatic regions; evidence of slight dry season
3b	Vertic gleysol	1	As for Pf3	As for Pf3	As for Pf3	As for Pf3	As for Pf3	As for Pf3	As for Pf3	Shrinkage cracks. Root mottling in lower	As for Pf3	As for Pf3	Found in all climatic regions; strong dry season and fluctuating water-table
4	Vertisol	1	Siltstone or fg sandstone	Pink to very pale grey	35cm to 160cm	Sharp & undulose	Sharp & planar	Rare carbonaceous rootlets,	None seen	Abundant shrinkage cracks and slickensides	10's to 100's of m's	Relict bedding decreasing upward	Climate zone with strongly seasonal climate
5	Aridisol	1	Mudstone to very fine-grained sandstone	Pale red or pink	20cm to 60cm	Sharp & undulose	Sharp & undulose	None seen	None seen	Small, irregular carbonate nodules. Locally in elongate ribbon-like geometries. Local pale green mottling around carbonate. Shrinkage cracks and slickensides	10's of m's	None seen	Arid or semi-arid environments with pronounced seasonal influence
R F	Groundwater calcrete	1	Very fine-grained sandstone or argillaceous limestone	Pale grey to green	170cm	Sharp & undulose	Not seen	None seen	None seen	Abundant carbonate nodules seen throughout unit. Amount of carbonate increasing upward from small nodules to massive carbonate	10's of m's	Seen throughout	Arid to semi-arid environment

Table 5-1 Table summarising the various palaeosoil facies and subfacies found within the Mid Carboniferous strata of Northumbria. Also included is a brief description of the environmental made based on the information gleaned from each of the palaeosoil facies and subfacies.

5.2.1 Palaeosoil Facies 1 (PF1) - Histosols

Description

This facies consists of black coal and associated organic-rich shales, with various carbonaceous plant fragments found locally, and is usually found overlying any of the other palaeosoil facies. It is itself overlain by a marine limestone (Figure 5-2), which indicates the commencement of a new Yoredale cycle. Typically ranging from 10cm to 40cm thickness, the coals vary a great deal laterally and vertically. The quality of the coal is also highly variable between outcrops but the majority is dull and clay-rich. Only a few are bright and of good quality. The upper boundary of this facies is sharp and planar whereas the lower boundary is more commonly sharp, undulose or planar, and locally gradational with the underlying sediments.

Interpretation

PF1 can be compared to the organic hydromorphic palaeosoils of Duchaufour (1998) and are considered by analogy to be predominantly deposits of shallow submerged swamps. The abundance of plant material and a lack of pluvial water circulation meant that highly reducing conditions were established and this allowed widespread preservation of plant debris (Duchaufour 1998). Coal deposits of the British Carboniferous are generally regarded as being deposits of rheotrophic mires (Falcon-Lang 2000), which are low-lying mires that form in poorly drained areas that are regulated by regional groundwater flow (Roberts & McCabe 1992). They are analogous to the classic low-lying mires of the Mississippi Delta (Kosters *et al.* 1987). The coals are typically found underlying marine limestones suggesting that the coals were formed by ponding of drainage and perching of the water-table in response to a rise in base-level at the approach of the marine transgression (Joeckel 1995). The high water-tables necessary for peat accumulation tend to occur in climates where precipitation exceeds evaporation and where rainfall is evenly spread throughout the year (McCabe & Parrish 1992), and such conditions are found today in equatorial and high mid-latitudes (Parrish & Barron 1986). The clastic influence to the coals can be attributed to the formation of coals on lower delta plains, which would lead to the addition of sediment from within the deltaic system. The discontinuous nature of the coals and the stratigraphic pattern of the palaeosoils where coal is absent indicate that several metres of relief existed on the pre-coal surface (Joeckel 1995). This is

Figure 5-1 Summary logs of all palaeosoil facies found within the Mid Carboniferous strata of Northumberland. Colours, pedogenic features and grain size indicator can be seen to the left. For complete descriptions of palaeosoil facies refer to Table 5-1. Vertical scale in cm's.

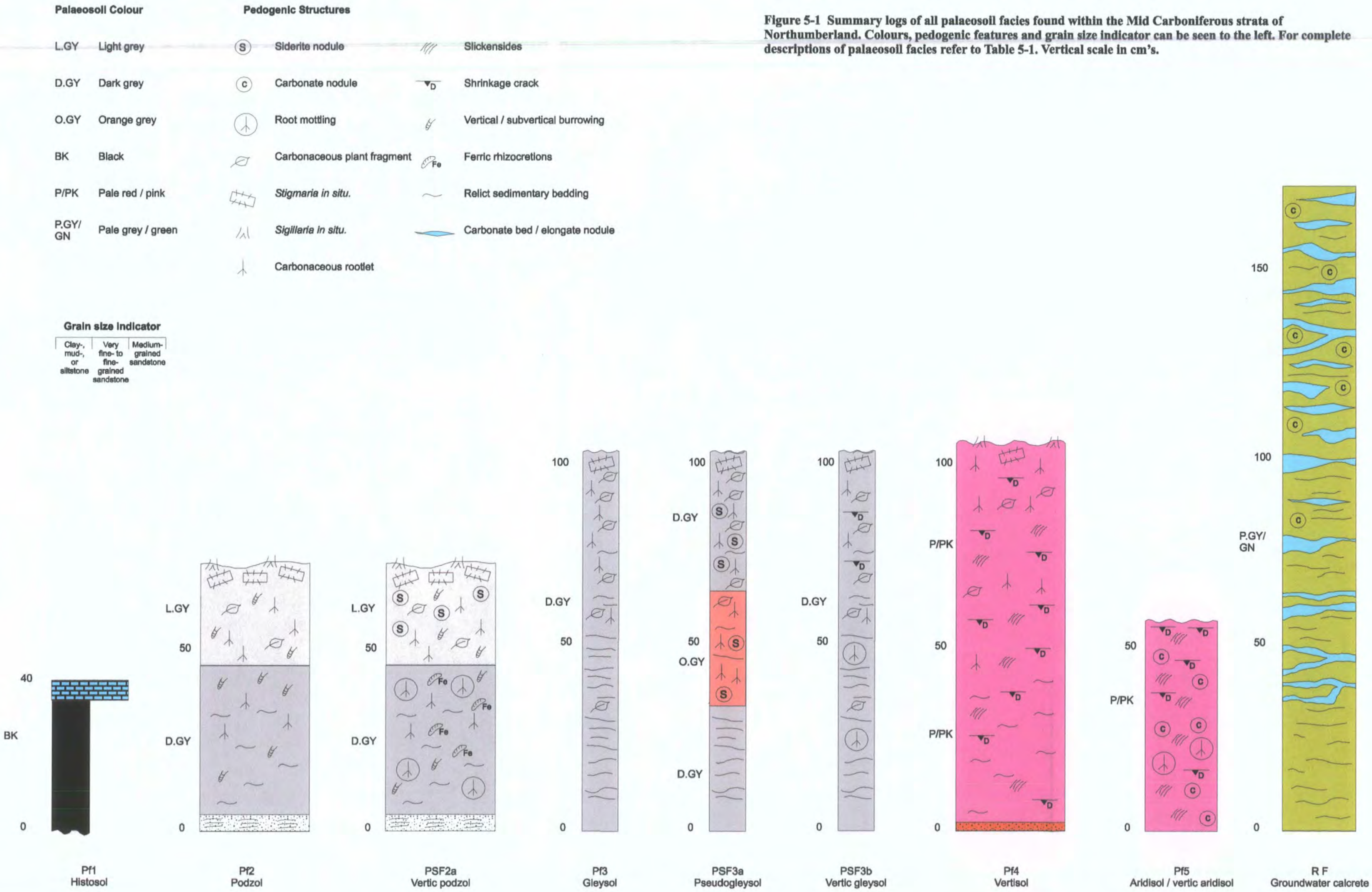


Figure 5-2 Photograph of PF1 (histosol) overlain by Dun limestone (Asbian). Photograph taken at Spittal / Scremerston coastal section. Height of tape measure is 8cm for scale.

emphasised by the wavy, low relief contact with the underlying sediments, which would indicate original soil microrelief as seen in the Upper Pennsylvanian palaeosoils of the Appalachian Basin, U.S.A. (Joeckel 1995). Coals of this nature have been classified as histosols (Retallack 2001) and they require the surface peat to have been more than 40cm in thickness. This is probable, as most coals have undergone seven-fold compaction since peat accumulation (Falcon-Lang 2000).

5.2.2 Palaeosoil Facies 2 (PF2) – Podzols

Description

PF2 consists of two parts, an upper horizon of buff to pale grey fine- to medium-grained siliceous sandstone with a thickness of 10cm to 120cm, and a lower horizon of grey to dark grey fine- to medium-grained sandstone to siltstone. In the upper horizon, abundant root traces can be found, especially *Stigmaria in situ* (Figure 5-3), varying in size from 10cm to 25cm in diameter and 1m to 5m long. Carbonaceous rootlets preserved within the top half of this unit are fine, tapering downwards and ranging from 5cm to 10cm in length. Locally carbonaceous plant fragments are seen but are only in the top few cm's of the unit. In one unit there are circular areas of up to 20cm increase in relief, and up to 40cm in diameter that appear to have formed around previously upright *Sigillaria* trunks (Figure 5-4). These structures have been compared to 'cradle knolls' formed in modern soils around trees (Gibling & Rust 1992).

Vertical burrowing can be found, comprising 10cm deep burrows that are approximately 1cm wide, filled with fine-grained sandstone. Burrows can be distinguished from rootlets as they lack carbonaceous material. In some outcrops, there are lobate projections up to 10cm long into the lower horizon (Figure 5-5). The upper boundary of this facies is abrupt and smooth whereas the boundary with the horizon above is abrupt and wavy. The boundary between the lower horizon and the underlying strata is generally planar and gradational. Locally, the only part of this profile observed is the upper quartz-rich horizon that resembles the 'ganisters' that have been described elsewhere in the Carboniferous strata of Northern England (e.g. Percival 1986).

Figure 5-3 ***Stigmaria* imprint found on upper surface of PF2 (podzol). Photograph taken at Howick coast section. Lens cap 7cm in diameter for scale.**

Figure 5-4 ***Sigillaria* relief found on upper surface of PF2 (podzol). Photograph taken at Howick coast section. Lens cap 7cm in diameter for scale.**

Figure 5-5 'Lobate projections' seen in PF2 (podzol), marked on photograph with red arrow. Photograph taken at Beadnell coast section. Lens cap is 7cm in diameter for scale.

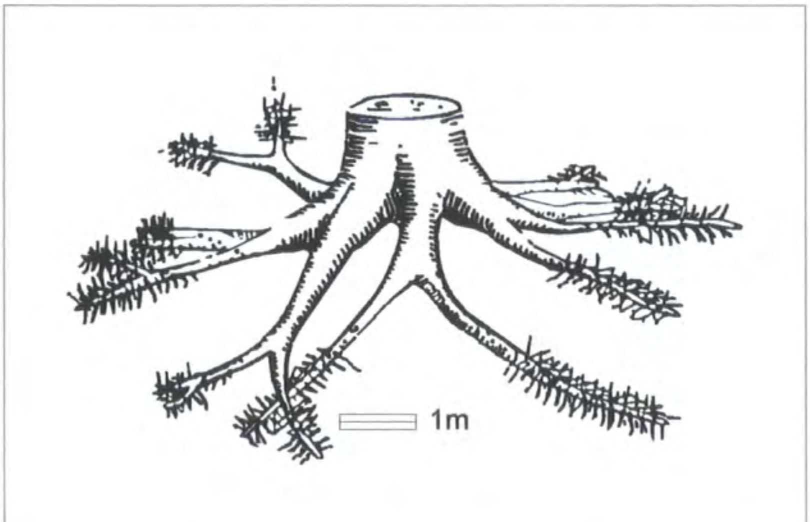


Figure 5-6 Reconstruction of the stump of *Stigmaria ficoides*, the root system of Carboniferous tree lycopsids. Adapted from, Retallack (1997).

Interpretation

PF2 contains numerous traces of organic activity including *Stigmaria* roots. These roots are short blunt, erect roots that are typically found in fossil soils and swamp and mangal vegetation (Retallack 2001). They have thin wall openings and spongy thin-walled tissues with hollow cavities, which allow the circulation of oxygen (needed for respiration) in waterlogged, reducing environments (Retallack 2001). *Stigmaria* have tabular root systems, meaning that roots spread out from near the surface of the soil without deep penetration (Figure 5-6). Tabular root systems are typical of plants growing in soils with a high water-table or other unfavourable characteristics for deep root growth (Retallack 2001). Carbonaceous rootlets are also found preserved within PF2. As the root features are preserved with organic matter remaining, this can be attributed to periodic hydromorphism leading to a decrease in the rate of decomposition (Wright 1992). The presence of vertical burrows within the palaeosoil would indicate that hydromorphism did not prevail throughout the entire period of pedogenesis, as oxygenation would have been required for any ichnofauna to survive in such an environment. Bioturbation could have taken place during the ensuing marine transgression and therefore after soil formation. The abrupt and smooth / wavy upper boundary can be interpreted as remnants of original soil microrelief.

The white to pale-grey colour of the upper quartz-rich horizon is generally associated with an eluvial (leached) horizon (albic horizon) due to the removal of clay and free iron oxides (Wright 1992) and is locally the only part of the profile preserved. This type of soil process is characteristic of well-drained soil profiles although there is still evidence of some hydromorphism due to the presence of *Stigmaria* and preserved carbonaceous rootlets. The lobate projections described are similar to those found in ganisters of Pennsylvanian age (e.g. Waddens Cove Formation of Nova Scotia in Canada). They are analogous to features found in modern soils that are thought to have originated by the flow of soil material and water down tree-root channels and thus evidence of leaching (Gibling & Rust 1992). Leaching occurs as a result of both chemical and physical downward transport of material as a result of pluvial water percolation and this often results in an illuvial clay-rich horizon directly beneath the clay-depleted eluvial horizon (Besly & Fielding 1989). This process is referred to as podzolisation and these soils are similar to the tropical hydromorphic podzols described by Duchaufour (1998). PF2 resembles palaeosoils found by Percival (1986) in the Upper Carboniferous of Northern England and also by Fielding *et al.* (1988) in the Lower Carboniferous of Fife, Scotland. They are generally characteristic of the sandy coastal plains with a phreatic water-table of the very humid equatorial regions. These types of soil are characteristically found in acidic and oxidising conditions in moderately to well-drained soils of humid climates (Retallack 2001). The acidic conditions required are produced by the accumulation of humus that is favoured in cool-wet environments. However, in well-drained siliceous substrates podzols may also develop under a warmer climate (Sellwood & Price 1993).

5.2.2.1 Palaeosoil Subfacies 2a (PSF2a) – Vertic podzols

Description

This subfacies is very similar to PF2 (Section 5.2.2) but with a concentration of pedogenic sideritic nodules in the upper 30cm of the profile (Figure 5-7A). Locally, PSF2a contains a thin layer enriched with siderite approximately 1cm to 2cm thick (Figure 5-7B). The lower horizon locally contains root mottling and abundant ferric (sideritic) rhizocretions. These are approximately 3mm to 5mm in diameter and up to 10cm long. This subfacies also locally contains minor slickensides and small vertical fractures ranging in thickness from 1cm to 5cm and approximately 10cm in length, filled with pale grey fine-grained sandstone. It should be noted that it is impossible to tell whether the slickensides found within the palaeosoil profile are pedogenic in origin.

Interpretation

PSF2a has all the same features as PF2 but the upward increase in concentration of pedogenic siderite nodules reflects the upward transport and precipitation of iron during periods of slight water-table drops (Besly & Fielding 1989). The thin layer enriched in iron found at one outcrop can be interpreted as the same. The abundance of ferric rhizocretions seen in PSF2a in the lower part of the unit can be interpreted by periodic hydromorphism inducing reduction and mobilisation of iron around voids (Vanstone 1991). Iron mobilised as soluble Fe^{2+} in a waterlogged rhizosphere may be oxidised during dry periods to Fe^{3+} or goethite that cements the soil around the roots (Retallack 2001). The concentration of siderite along vertical root passages reflects the net upwards movement of iron during partial drainage with preferential

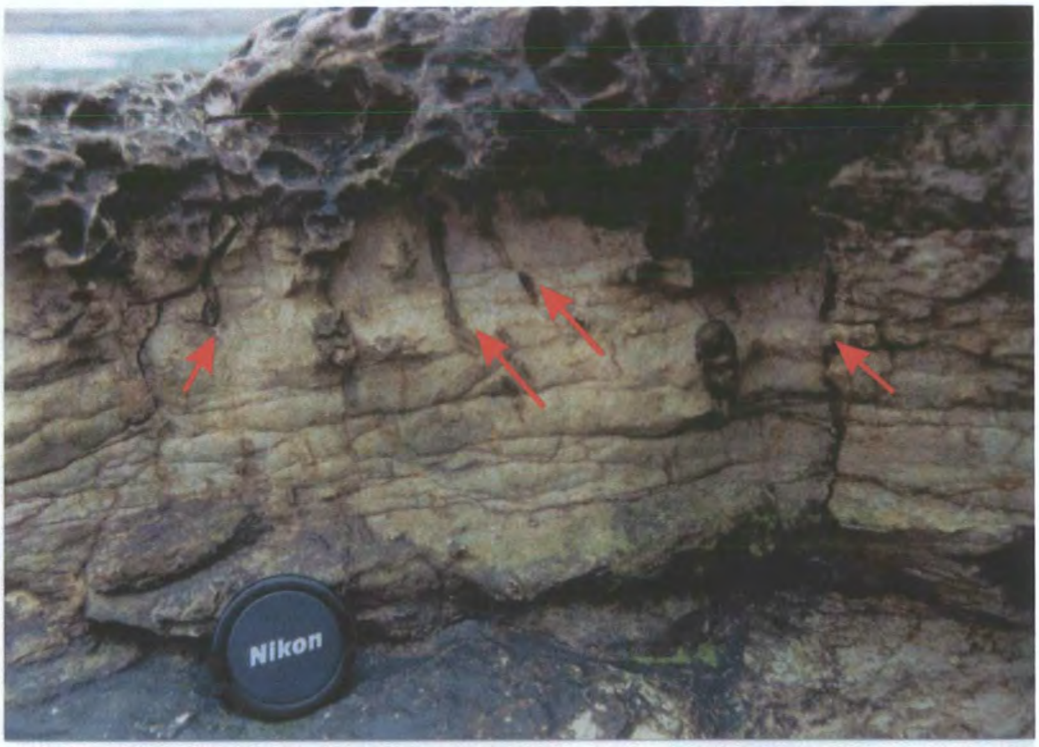


Figure 5-7A Plan view of ferric rhizocretions in PSF2a (vertic podzol). Ferric rhizocretions marked with red arrows. Photograph taken at Beadnell coast section. Lens cap is 7cm in diameter for scale.

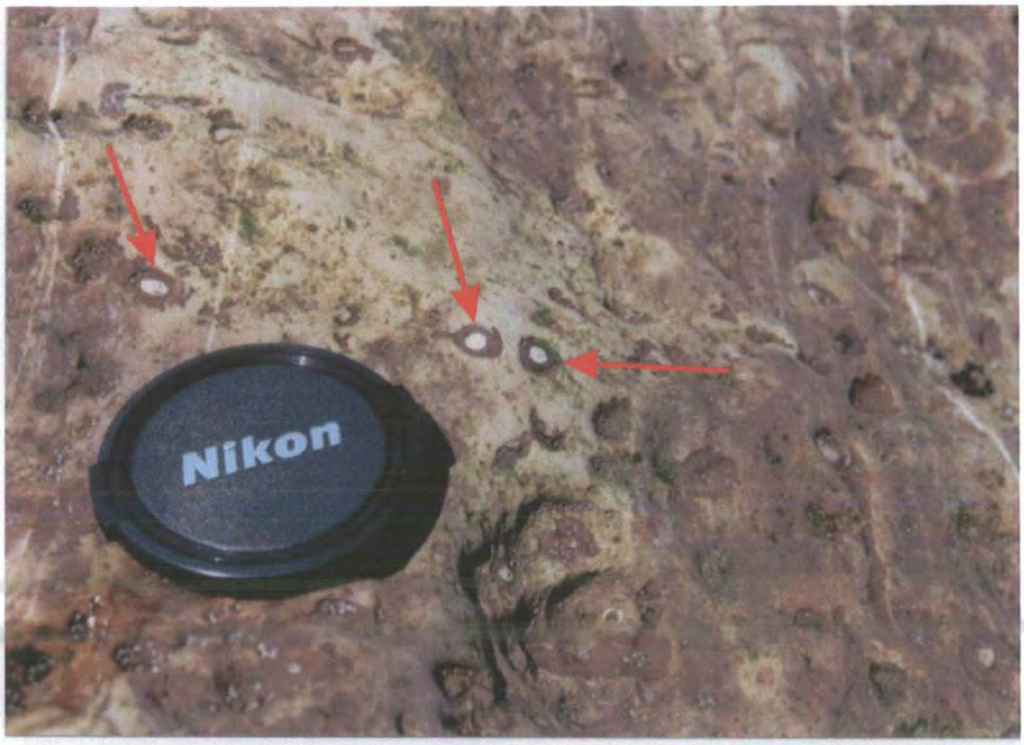


Figure 5-7B Cross section of ferric rhizocretionson upper surface of PSF2a (vertic podzol). Note internal fill of rhizocretion is visible. Ferric rhizocretions marked with red arrows. Photograph taken at Beadnell coast section. Lens cap is 7cm in diameter for scale.

precipitation in areas of oxidation of organic matter where carbon dioxide (necessary for siderite precipitation) was provided (Besly & Fielding 1989).

The presence of fracture fills can be attributed to the expansion and contraction of clays in response to wetting and drying cycles respectively. Stress fields develop both because of the clays and through the increase in bulk volume as surface material collapses into open desiccation cracks (fracture fills) and is trapped as they close (Vanstone 1991). The development of desiccation cracks indicates that at least partial drainage was present (Besly & Fielding 1989). The minor slickensides are similar to those found in the Upper Pennsylvanian palaeosoils of the Mid-Continent Basin, U.S.A. (Joeckel 1994), where they have formed as stresses develop due to the occurrence of wetting and drying cycles attributed to seasonal variations. The presence of more oxidised iron could be attributed to a greater oscillation in water-table leading to the formation of ferric rhizocretions. This is emphasised by the presence of many seasonal or vertic features (slickensides and fracture fills), which would suggest that the climate has a profound effect on pedogenesis, as alternating wet and dry seasons occur. PSF2a can be classified as a vertic podzol.

5.2.3 Palaeosoil Facies 3 (PF3) – Gleysols

Description

PF3 is composed of buff, mid-grey to dark grey, claystone, mudstone, siltstone or very fine-grained sandstone. The colour may darken towards the top of the unit however, if there is an overlying coal present. Thickness ranges from 45cm to 150cm and is once again laterally consistent. Traces of biological activity appear to be well preserved within this facies, as carbonaceous plant fragments are found in abundance in conjunction with carbonaceous rootlets. The abundance of rootlets decreases downwards through the unit. On the surface of this facies there are abundant *Stigmaria* root imprints, ranging in size from 10cm to 25cm in diameter and 1m to 2m in length. The presence of relict bedding seems to increase downwards through the unit. Sub-vertical burrowing is uncommon. The upper boundary of the unit is usually abrupt or sharp, and smooth, planar or irregular in nature.

Interpretation

The colour of PF3 can lead to many interpretations as the grey coloration of many of the outcrops suggests that they were formed in reduced settings such as hydromorphic (waterlogged) conditions. The reduced iron present in the profile will impart a darker grey colour as will organic matter that will accumulate due to anoxia (Wright 1992). Once again the presence of *Stigmaria* suggests growth in an area with a high water-table or other unfavourable characteristics (Section 5.2.2). The presence of carbonaceous rootlets would require hydromorphic conditions to prevent the decomposition of organic matter (Wright 1992). Some relict lamination is found within PF3 and as destratification is caused by pedoturbation in palaeosoils (Wright 1992), this would indicate that the palaeosoils are relatively poorly developed. Destratification increases upwards indicating that pedoturbation increases upwards also. Sub-vertical burrowing may be attributed to the presence of soil-dwelling ichnofauna but due to the lack of oxygen available this is highly unlikely. In this case it may be due to the onset of a marine transgression occurring above this horizon leading to the overprinting of marine trace fossils within the terrestrial soil environment. This explanation has been given for the occurrence of marine ichnofauna in rootlet-bearing horizons in the Upper Carboniferous of the Southern North Sea (Lawrence & Sutter 2002). PF3 can be classified as a gleysol (Retallack 2001) that formed when there is a permanent phreatic water-table with variable acidity. This type of palaeosoil can be found in all climatic regions (Duchaufour 1998).

5.2.3.1 Palaeosoil Subfacies 3a (PSF3a) – Pseudogleysols

Description

This subfacies is similar to PF3 but with a Fe-rich horizon. PSF3a consists of a 40cm thick layer with an orange coloured zone within the middle of the unit. There are also abundant siderite nodules ranging in size from 1cm to 3cm in diameter and 5cm to 20cm in length (Figure 5-8). The early pedogenic nature of these nodules is demonstrated by the growth of rootlets around these nodules and not within them.

Interpretation

PSF3a contains an iron-rich horizon within the middle of the soil profile which can be interpreted as an illuvial concentration of hematite (Vanstone 1991). This may

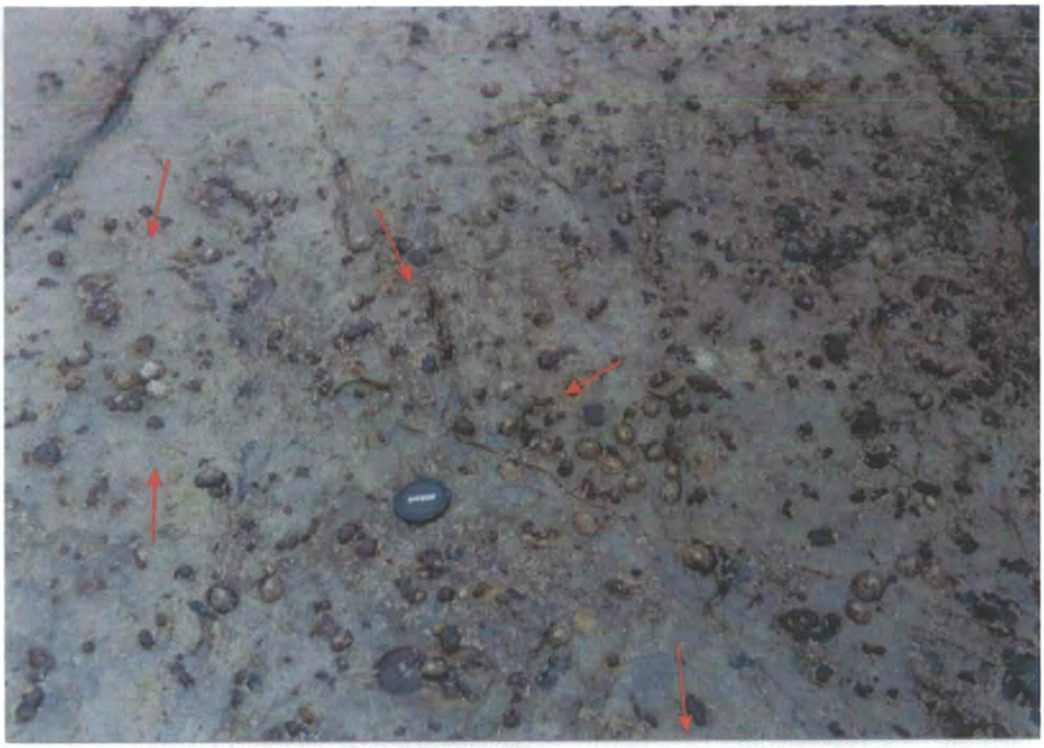


Figure 5-8 Siderite nodules seen on upper surface of PSF3a (pseudogleysol). Some nodules marked with red arrows. Note that surface has been partially colonised by limpet shells. Photograph taken at Beadnell coast section. Diameter of lens cap is 7cm for scale.

Figure 5-9 Polygonal cracks seen on upper surface of PSF3b (pseudogleysol). Photograph taken at Beadnell coast section. Diameter of lens cap is 7cm for scale.

represent a periodic lowering of the water-table allowing for oxidisation of the soil profile, but it may also reflect a diagenetic feature of the profile. However, there are abundant siderite nodules found within the profile that are known to be pedogenic in origin due to the nature of the growth of the carbonaceous rootlets around the nodules. These can be interpreted as forming due to the precipitation of iron during periods of slight falls in water-table (Besly & Fielding 1989). PSF3a can be classified as a pseudogleysol (Duchaufour 1998) with a temporary water-table that is moderately reducing. The iron in this case does not remain in the ferrous state but is reoxidised in the dry season. Once again, these palaeosoils can be found in all climatic regions, but the presence of a slight dry season can be deduced.

5.2.3.2 Palaeosoil Subfacies 3b (PSF3b) – Vertic gleysols

Description

This subfacies is similar to PF3 but contains fractures in the uppermost 40cm of the unit of up to 5cm at their widest point, filled with dark grey siltstone or claystone. Shrinkage cracks occur on the upper surface of the unit displaying a polygonal pattern with a spacing of approximately 30cm (Figure 5-9). Root mottling is found in the lower part of the unit (Figure 5-10), seen as pale green patches (up to 2cm wide) around any carbonaceous rootlets that are present within the unit.

Interpretation

The fracture fills and the presence of shrinkage cracks seen in PSF3b are all analogous to features found within modern-day vertisols formed due to the expansion and contraction of swelling clays during wetting and drying cycles resulting from a seasonal climate. As the palaeosoils from PF3 are generally very clay-rich this feature could be exaggerated. PSF3b would originate in a seasonal climate with at least partial drainage. The root mottling found can be interpreted as forming due to periodic waterlogging, leading to the reduction of iron within the rhizosphere. This is typically found in lowland soils with impermeable subsurface horizons (Retallack 2001). In view of the presence of structures resulting from seasonal climate, PSF3b can be classified as a vertic gleysol, which has had at least partial drainage for some of the year leading to the formation of many vertic features. The climatic regime during pedogenesis would have had to contain a plausibly strong dry season and the water-table would fluctuate regularly producing prolonged periods of hydromorphism.

Figure 5-10 Root mottling seen within PSF3b (vertic gleysol), marked with red arrows. Photograph taken at Beadnell coast section. Diameter of lens cap is 7cm for scale.

5.2.4 Palaeosoil Facies 4 (PF4) – Vertisols

Description

PF4 consists of pink to very pale grey siltstone or fine-grained sandstone. Thickness ranges from 35cm to 160cm. Carbonaceous rootlets are less common in this palaeosoil facies and only very rare *Stigmaria* roots are present on the surface of the unit. Locally, upright *Sigillaria* trunks have been noted. Slickensides (Figure 5-11) and shrinkage cracks (Figure 5-12) are common throughout the entire palaeosoil unit. Stratification increases downwards through the palaeosoil unit. The upper boundary of this facies is abrupt and wavy or smooth and the lower part is clear and wavy.

Interpretation

PF4 contains little evidence of plant life; there are scarce carbonaceous rootlets preserved, only a few *Stigmaria* roots are seen, and only in one outcrop is the presence of a *Sigillaria* trunk noted. This would imply there is much less hydromorphism and that the soil is much better drained. The main feature of this unit is the presence of slickensides and shrinkage cracks which can once again be compared to modern day vertisols (Section 5.2.3.2). Vertisols occur in regions with strongly contrasted seasonal climates, one of which is markedly dry (Duchaufour 1998) although they are present in areas that are as climatically diverse as equatorial Indonesia to the frigid piedmonts of Montana (Dudal & Batisse 1978). However, they are almost exclusively found in warm-temperate to tropical climates with four to eight dry months each year and usually in arid or semi-arid regions (Sellwood & Price 1993). Work carried out on the Late Mississippian vertisols in Monterey, Tennessee has enabled a quantitative assessment of palaeoprecipitation and has estimated the mean annual precipitation as being 648mm (Caudill *et al.* 1996). Vertisols usually require special site conditions with regards to topography and parent material. They generally occur in depressions that have been choked up by mud such as those occurring on low-lying plains with clay coming from weathering or from neighbouring slopes. This is usually in sites with poor internal or external drainage that intensifies the contrasts of the general climate (Duchaufour 1998). The downward increase in stratification can be interpreted as a downward decrease in the mechanical mixing of the profile by vertic movements resulting from seasonal variations in the volume of clay (Duchaufour 1998). PF4 contains all the features of vertisols (Wright 1982; Duchaufour 1998; Retallack 2001). They are known to form at the present day

Figure 5-11 Possible pedogenic slickensides seen within PF4 (vertisol). Photograph taken at Beadnell coast section. Diameter of lens cap is 7cm for scale.

Figure 5-12 Vertical section of shrinkage cracks (marked with red arrow) seen within PF4 (vertisol). Cracks have been filled with fine to medium grained sandstone. Photograph taken at Howick coast section. Diameter of lens cap is 7cm for scale.

in those climate zones with strongly seasonal climates (Duchaufour 1998). There are few features of hydromorphism suggesting that there was good drainage during pedogenesis and that the water-table was low.

5.2.5 Palaeosoil Facies 5 (PF5) – Aridisols / Vertic aridisols

Description

PF5 is a pale red or pink mudstone to very fine-grained sandstone unit, ranging in thickness from 20cm to 60cm. Varying stages of pedogenic carbonate development are found; in most cases small irregular nodules range from 5cm to 15cm in diameter, with locally elongate ribbon-like geometries, approximately 5m in length and up to 10cm in thickness (Figure 5-13). The colour of the carbonate ranges from white to deep red. Locally, there is mottling around the carbonate nodules, pale-green in colour and extending approximately 1cm away from the nodule. Shrinkage cracks of a polygonal nature with a spacing of approximately 20cm to 25cm are locally seen on the surface. Also present are abundant fractures filled with fine-grained sandstone and slickensides throughout the unit.

Interpretation

PF5 contains many features that are characteristic of calcretes, found both in modern and ancient semi-arid / arid environments such as those found in Holocene soils (e.g. Gile 1995) and Quaternary soils (e.g. Esteban & Klappa 1983). Calcretes are the near surface, terrestrial accumulations of $CaCO_3$ and usually reflect a net moisture deficit so that any carbonate precipitated is not later leached out (Wright & Tucker 1992). Generally calcretes form in areas with a warm to hot climate (mean annual temperature of 16 to 20°C) and a low but seasonal rainfall (100 to 500mm) (Strong *et al.* 1992). Although there are records of calcretes forming in Late Quaternary esker gravel in North Yorkshire (Goudie 1983) and during humid climatic regimes on the Mississippi River floodplains (Aslan & Autin 1998), these occurrences are the exception. Vertic features such as slickensides and fracture fills are also found within this palaeosoil facies which would mean that it formed in an arid or semi-arid climate with a much more pronounced seasonal influence (Section 5.2.3.2). PF5 can be classified as an aridisol or a vertic aridisol (Wright 1992; Duchaufour 1998) due to the presence of a carbonate-rich horizon within the soil profile.

Figure 5-13 Red pedogenic carbonate (marked with red arrow) seen with PF5 (aridisol). Photograph taken at Spittal / Scremerston coast section. Diameter of lens cap is 7cm for scale.

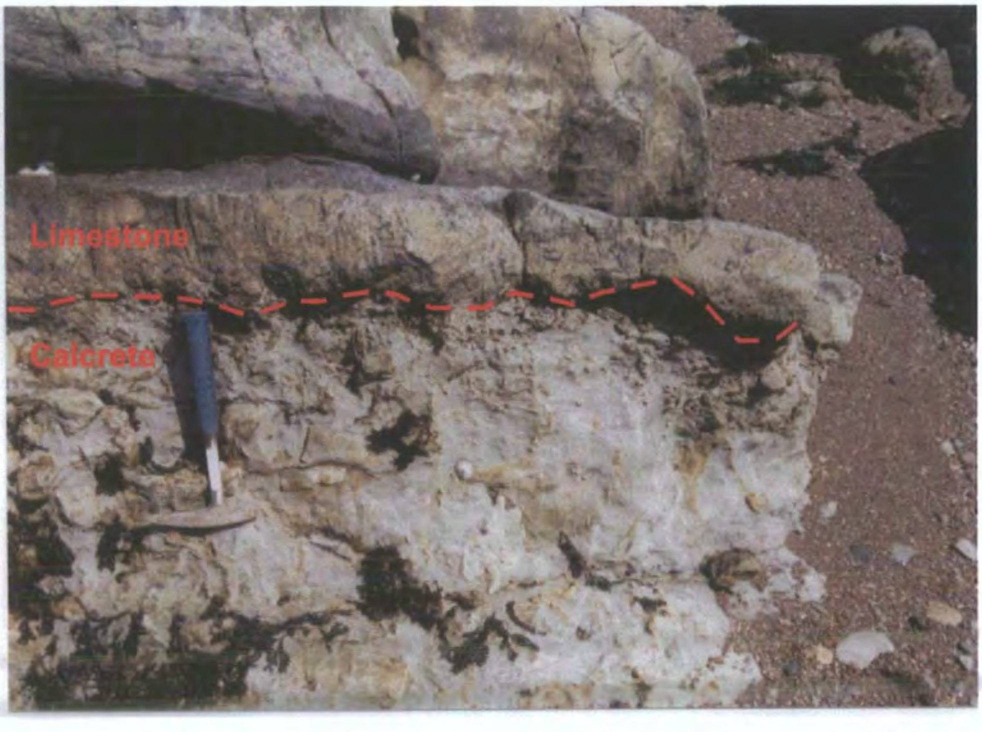


Figure 5-14 Groundwater calcrete (RF) seen beneath unnamed limestone of Asbian / Brigantian age.. Photograrh taken at Spittal / Scremerston coast section.Hammer shaft is 27cm long for scale.

5.2.6 Related Facies (RF) – Groundwater calcrete

Description

Locally, a 170cm thick unit composed of pale grey to green very fine-grained sandstone or argillaceous limestone, containing varying amounts of carbonate is found. Small (1cm to 2cm) carbonate nodules with very irregular boundaries can be seen towards the bottom of the unit with the amount of carbonate increasing upwards to elongate nodules of approximately 5cm to 10cm in diameter, culminating with the development of massive carbonate beds of 10cm to 20cm thickness (Figure 5-14). Relict bedding is seen throughout much of this unit.

Interpretation

The features displayed within the related facies unit are similar to those found in pedogenic calcretes but are discretely different. The lack of biological activity and the drab hue of the parent material in which the carbonate was precipitated is evidence that the horizon is a groundwater calcrete (Mack & James 1992). Carbonate in this case is precipitated mainly in the capillary fringe zone, directly above moving subsurface water, but it can also precipitate below the water-table (Wright & Tucker 1992). Calcrete formed in this manner is common in present-day arid to semi-arid alluvial basins (Wright & Tucker 1992).

5.3 Lateral and Vertical Relationships

Although each of the palaeosoil facies and their environmental implications have been described and interpreted, it is necessary to assess the vertical and lateral relationships between the palaeosoil facies in order to gain a full understanding of the various controls on pedogenesis.

Vertical stacking patterns of the palaeosoil facies have been identified on various scales in order to assess the temporal changes and controls on pedogenesis. The lateral relationships between palaeosoil facies have also been investigated to assess the regional extent and variation on pedogenic control.

5.3.1 Lateral correlation of palaeosoils

Correlation between each structural region in the Mid Carboniferous of Northumbria is based on the presence of regionally extensive limestone units (Section 4.1). As the majority of palaeosoils are found beneath a limestone it is therefore also possible to correlate the palaeosoils. Generally, the palaeosoils that are developed underneath limestone are regionally widespread and can be correlated for tens of kilometres. It should be noted, however that the individual palaeosoil facies can vary greatly between each correlatable horizon. This does not detract from the value of using palaeosoils as an analytical tool as the vertical relationships between palaeosoil facies can be traced laterally throughout the region and yield valuable information which is discussed below.

The presence of two very different structural regimes, the structurally negative basins and the structurally positive blocks, contributes to variations in lateral relationships. Palaeosoils are generally thinner in the structurally positive regions i.e. the Alston Block, with thinner profiles from the blocks being correlated with thicker profiles in the basins. At some horizons, there are no palaeosoils recorded from the blocks whereas they are evident at the same horizon within the basins. This is especially true during Asbian and Brigantian times. Within the basins, palaeosoils are more laterally consistent with slightly thicker profiles being developed towards the centre of the basin. Locally however, during the Mid Asbian in the Tweed Basin, palaeosoils vary greatly within a distance of a few metres from being a composite profile to a compound profile (see Section 5.3.4).

Interpretation

Lateral relationships between palaeosoils are well-documented throughout the stratigraphic record and even at the present day, the lateral variations of individual soils are vast. The most obvious lateral variation in the palaeosoils of Northumbria is that between the basins and blocks. Palaeosoil profiles are thicker in the basins than on the blocks, explained by a greater amount of accommodation space within the basins and therefore a greater accumulation of sediment within which pedogenesis could take place. This is especially true during the Asbian period and to a lesser extent the early part of the Brigantian period. This is due to differential subsidence between the blocks and basins which was at its greatest during these times (Section 8.6). This feature is taken to the extreme where there is locally no palaeosoil on the blocks, but there is a record of a palaeosoil at the same horizon within the basin. The absence of palaeosoil development may however be represented by an exposure surface, which would form as a palaeosoil would, at a time of non-deposition. Pedogenesis can only take place where there is sediment for a soil to develop within, and in the case of the block areas there may have been no sediment deposited so pedogenesis could not take place. Exposure surfaces in the form of palaeokarsts have been recorded from elsewhere in the Mid Carboniferous of England and Wales where exposure on the scale of a few hundred years to a few tens of thousands of years is likely to have taken place (e.g. Vanstone 1998). It was not possible during this study to identify exposure surfaces of the Mid Carboniferous of Northumbria, but their presence may be extensive, especially in the south of the area where carbonate rocks dominate the succession and is an area for further work.

On a much smaller-scale, the lateral variation in palaeosoil facies is seen on a scale of hundreds if not tens of metres. The depositional environment where pedogenesis took place was that of an extensive delta plain containing an intricate pattern of distributary channels, levee banks and crevasse splays which coexisted with backswamps in interdistributary settings (Arndorff 1993). Although relief would have been extremely low, there were still topographic highs in areas such as levee banks, whereas other areas such as backswamps would be waterlogged for much of the year. All these factors mean that the palaeosoils coexisted in catenas related to the slight surface topography (Besley & Fielding 1989). Such local variations cannot be attributed to fluctuations in climate as the various palaeosoil types often formed simultaneously. The localised variation found in the Mid Asbian of the Tweed Basin is similar to the patterns in the Upper Pennsylvanian palaeosoils of the Upper Lawrence Formation of the U.S.A., where areas of little or no pedogenesis contrast with thick complex profiles. In this case variations have been attributed to a supplementary sediment source due to local tectonism (Joeckel 1994), this is spatially similar to the Tweed Basin, where a small syn-sedimentary extensional fault separated the two outcrops described (Section 8.6).

5.3.2 Temporal palaeosoil relationships

Within the entire Mid Carboniferous succession there is distinct grouping of palaeosoil facies. During the Early to Mid Asbian times there are palaeosoils indicative of a humid, seasonal climate namely the vertic gleysols, vertisols and podzols, especially on the Alston Block, in the Tweed Basin and in parts of the Northumberland Basin. During the Late Asbian and Early Brigantian there is a shift to palaeosoils indicative of an arid or semi-arid seasonal climate such as aridisols and vertic aridisols, found on the Alston Block and in the Tweed Basin. In the Mid Brigantian to the end of the Pendleian there are palaeosoils indicative once again of a humid, seasonal climate, although seasonal climate indicators are not as widespread. Palaeosoils that are not climate specific, such as gleysols and histosols, are found throughout the studied succession.

Interpretation

The most obvious information obtained from the vertical relationships of the palaeosoils is that there is a distinct change from a humid, seasonal climate to an arid or semi-arid climate during the Late Asbian to Early Brigantian, and a return to a humid, seasonal climate at the end of the Brigantian and throughout the Pendleian (Figure 5-15). This is emphasised by a decrease in the amount of histosols (coals) during this period, as peat generally accumulates in areas where precipitation exceeds evaporation and therefore generally does not form under an arid or semi-arid climate phase. Some climatic features are not recorded regionwide however, especially seasonal and arid features. Seasonal features are recorded as vertic structures and these require the presence of swelling clays (Duchaufour 1998). If such clays are not present in the parent material then such features may not be fully developed. The palaeosoils in the region appear to be highly dependent on base-level fluctuations and therefore will be the main factor in their facies distribution. As there were repeated fluctuations in sea-level during this time and thus changes in base-level, palaeosoils that developed in basinal areas, especially those with a close proximity to the marine source (Northumberland Basin) are more likely to record increasing hydromorphism due to a base-level rise than the prevailing climate.

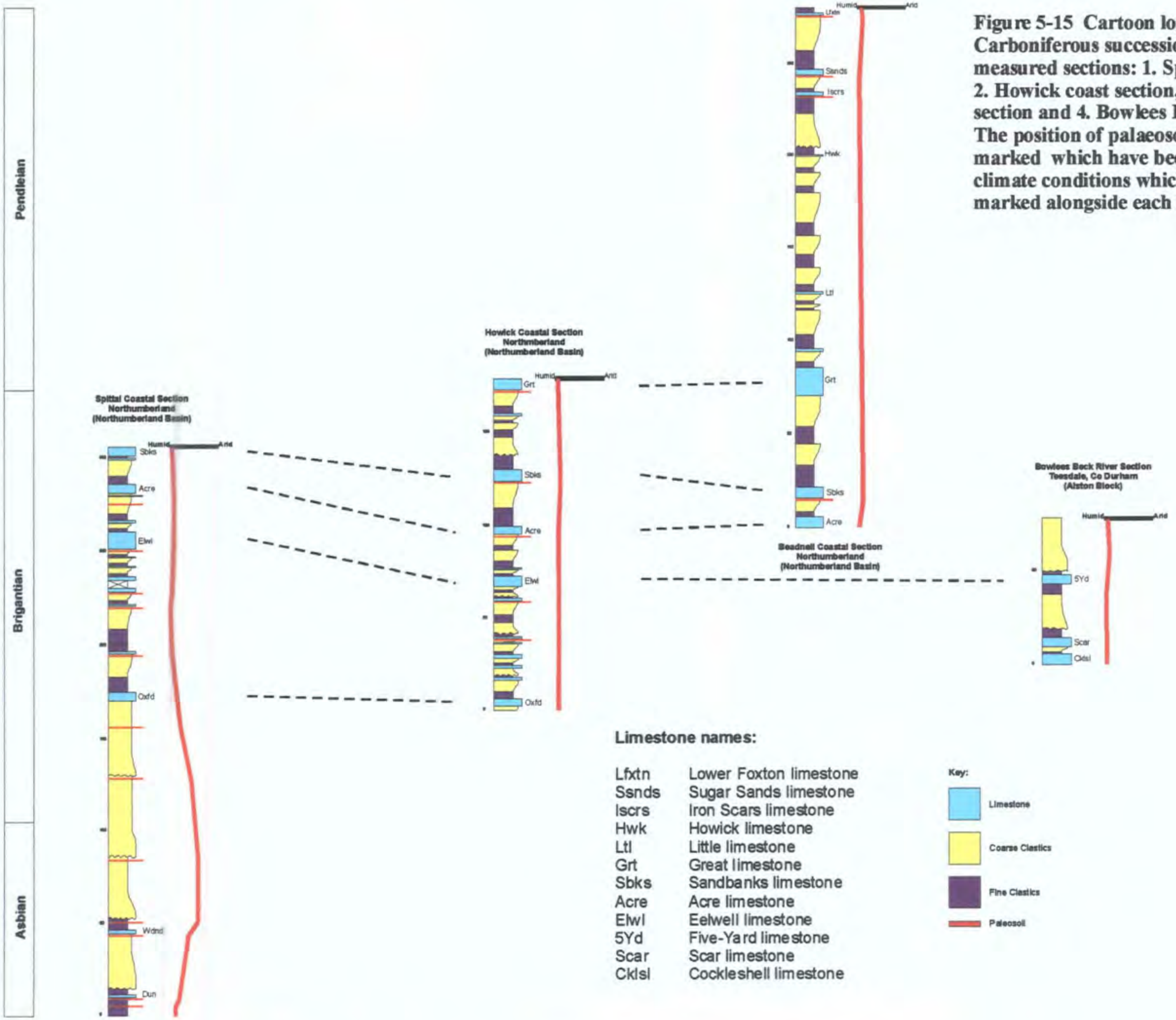


Figure 5-15 Cartoon logs of the Mid Carboniferous successions from 4 measured sections: 1. Spittal coast section, 2. Howick coast section, 3. Beadnell coast section and 4. Bowlees Beck river section. The position of palaeosoils have been marked which have been used to deduce climate conditions which have been marked alongside each log.

Limestone names:

Lfxtn	Lower Foxton limestone
Ssnds	Sugar Sands limestone
Iscrs	Iron Scars limestone
Hwk	Howick limestone
Ltl	Little limestone
Grt	Great limestone
Sbks	Sandbanks limestone
Acre	Acre limestone
Elwl	Eelwell limestone
5Yd	Five-Yard limestone
Scar	Scar limestone
Cklsl	Cockleshell limestone

5.3.3 Genetically-related vertical palaeosoil packages

Some of the palaeosoil units are isolated in their occurrence but the majority are found in genetically related vertical packages, similar to palaeosoils found elsewhere in the Carboniferous (e.g. Besly & Fielding 1989; Wright 1992). The vertically stacked patterns display palaeosoils with an increasing hydromorphic influence upwards, associated with rising base-level attributed to a relative rise in sea-level (Figure 5-16). This conclusion is further supported by the occurrence of such patterns directly beneath a marine limestone, indicating the onset of a marine transgression. Many of these packages are repeated within individual cycles (Figure 5-17), which would indicate periodic fluctuations in base-level on a smaller-scale than the 200,000 year overall cycle duration (Section 4.3.1).

During the Asbian period, genetically related vertically stacked palaeosoils are found in the basinal areas such as the Northumberland Basin and the Tweed Basin, especially towards the end of the Asbian. These features are best developed in the centre of the basins. The Alston Block displays no such repetitions during this period; it has not been possible to include the Cheviot Block in this section as there is no data available; differential subsidence during this period meant that far less accommodation space was created on the Alston Block than in the adjacent Northumberland Basin. Little or no siliciclastic deposition occurred during this period and limestone deposition dominates the succession (e.g. Figure 4-6). The blocks may not display palaeosoils as no sediment was present to enable palaeosoils to develop and it would therefore be more likely for limestone exposure surfaces to have developed during times of non deposition and sea-level fall rather than palaeosoils (Section 5.3.1). During the Early Brigantian, there are no repetitions displayed anywhere in the region, but in the Mid Brigantian, the Alston Block and the Northumberland and Tweed Basins display abundant repetitions of genetically related vertical stacking patterns. Towards the end of the Brigantian, there is an increasing abundance of such stacking patterns in the Northumberland Basin but only a few are recorded elsewhere in the region. It should be noted however, that there is no record of strata younger than Brigantian age in the Tweed Basin. The Northumberland Basin displays numerous vertically stacked palaeosoils throughout the Pendleian period.

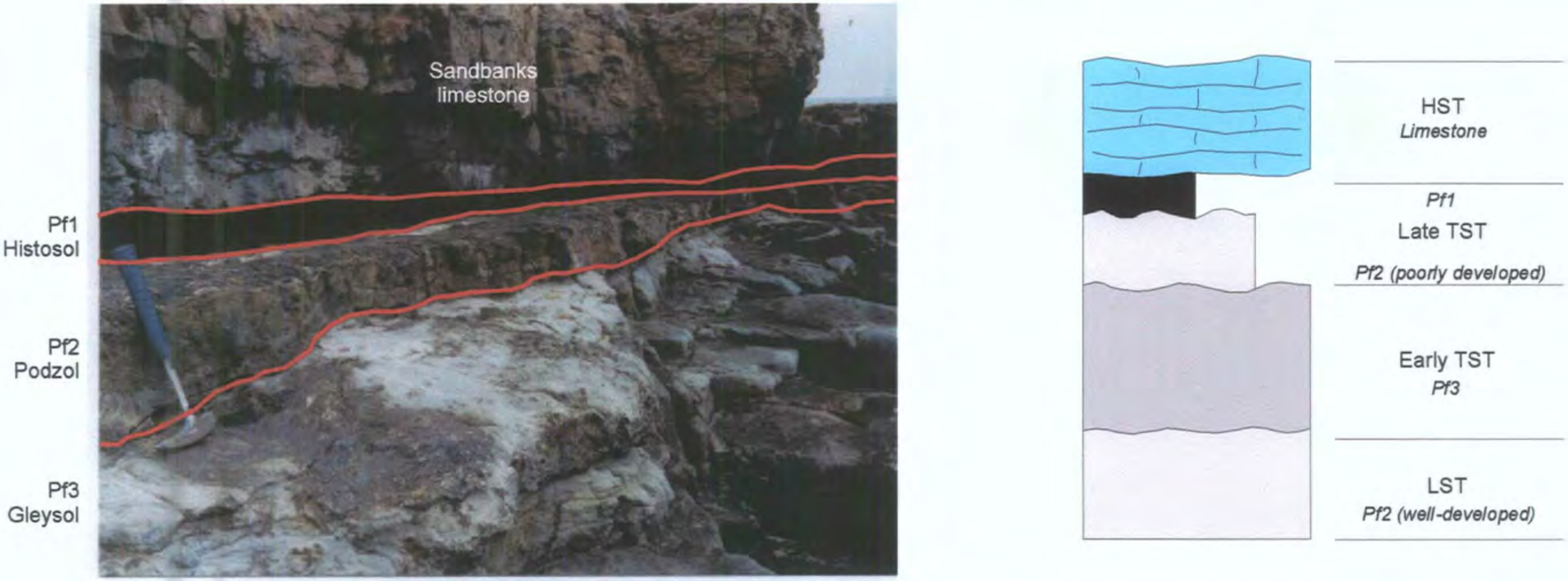


Figure 5-16 Photograph on the left displays the palaeosoil facies found beneath the Sandbanks limestone (Late Brigantian) at Howick coast section. The cartoon log on the right shows the vertical palaeosoil facies relationships that have been noted by Wright & Marriott (1993) from Carboniferous palaeosoils from fluvial depositional systems which have been interpreted as representing increasing hydromorphism. Although the lower well-developed palaeosoil facies 2 is not noted from the photograph on the left, all other features are directly comparable to those found by Wright & Marriott (1993).

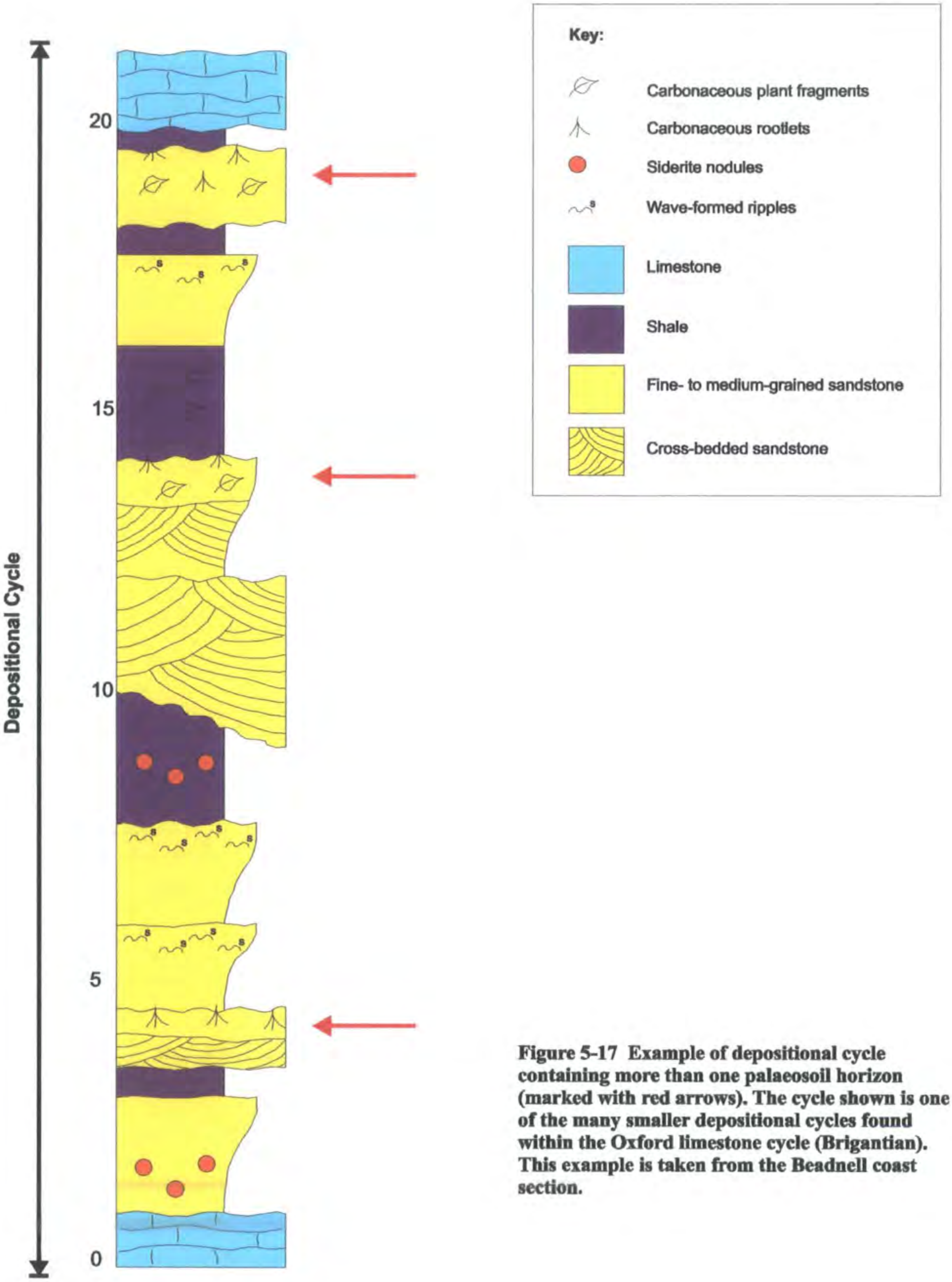


Figure 5-17 Example of depositional cycle containing more than one palaeosoil horizon (marked with red arrows). The cycle shown is one of the many smaller depositional cycles found within the Oxford limestone cycle (Brigantian). This example is taken from the Beadnell coast section.

Interpretation

The genetically-related vertical palaeosoil packages can be attributed to a regional increase in base-level as this feature is seen throughout the entire area. Similar relationships have been noted by Wright & Marriott (1993) in attempting to relate changes in base-level and accommodation space to alluvial architecture and soil development. By assessing palaeosoil types, the stage of base-level rise can be identified. During lowstand systems tract, mature palaeosoils such as podzols, vertisols and aridisols can be found in isolated areas, whereas during a transgressive systems tract, palaeosoils are more likely to be increasingly hydromorphic. Palaeosoil facies such as histosols and gleysols are likely to be formed under these conditions. If the rate of base-level increase is slow, then the palaeosoil will be mature; if the rate of base-level increase is fast, then the palaeosoil will be immature. During the highstand systems tract, mature palaeosoils will be developed as there is no sediment storage, but the preservation potential is extremely low due to sediment reworking during this stage. Similar patterns are found in the Virgillian (Upper Pennsylvanian) palaeosoils of the U.S.A. (Joeckel 1995) and in other parts of Northern England (Percival 1986), where a progressive marine hydromorphic sequence is identified. In the early stages of soil evolution there are well-drained palaeosoils but as the water-table rises later in the soil evolution sequence in response to a transgression, peat deposition occurs, resulting in histosol formation (Joeckel 1995). As these features are particularly widespread and laterally continuous in Northumbria, they can be interpreted as resulting from at least a relative sea-level change, and possible a eustatic sea-level change.

Vertical relationships are found on two very different scales. Firstly, they are found occurring beneath marine limestone at the top of each depositional cycle, indicating that they are the product of increasing hydromorphism associated with a marine transgression. This transgression is a result of cyclicity on a scale of approximately 200,000 years. Vertical relationships are also found on a much shorter time-scale, as intracyclical fluctuations in base-level as seen in Figure 5-17. In view of the difficulty of accurate correlation of clastic sediments within each cycle, it is difficult to assess whether such fluctuations in base-level are widespread. However, such small-scale vertical relationships are found throughout the Brigantian of both the Tweed Basin and the Northumberland Basin but are not recorded in the Alston Block, indicating that such a rise in base-level did not affect the raised blocks.

A lack of data for the Pendleian period prohibits any further comparisons. Fluctuations in base-level could be associated with smaller-scale eustatic sea-level fluctuations such as the 41,000 year obliquity cycles of the Milankovitch scale or perhaps even smaller scale than this on a 20,000 year precession cyclicity that did not transgress as far north as the study area but would still have affected base-level.

5.3.4 Compound and composite palaeosoil profiles

In addition to the genetically related packages there are distinct vertical relationships between palaeosoils, regardless of facies. By investigating the relationship of the palaeosoils with intervening sediment, information can be obtained on sedimentation rates and the rate of pedogenesis. There are two distinct relationships found. Compound palaeosoil profiles (Figure 5-18A) are weakly developed vertically stacked profiles separated by minimally weathered sediments. Compound palaeosoil profiles are the result of rapid and unsteady sedimentation where erosion is insignificant. Composite palaeosoils (Figure 5-18B) are vertically successive profiles that may partly overlap. Composite palaeosoil porfiles form during times when the rate of pedogenesis exceeds the rate of deposition (Kraus 1999). Although composite palaeosoil profiles form during times when pedogenesis occurred at a greater rate that deposition, in an ideal situation there would still be enough deposition occurring on top of a previous palaeosoil to allow a new palaeosoil layer to develop. If this does not occur however, there would inevitable be overprinting of palaeosoils and a pre-existing soil may become altered by later pedogenesis reflecting an inaccurate record of pedogenic conditions. Caution should therefore be taken when using this form of palaeosoil analysis.

The temporal and spatial distribution of compound and composite profiles are summarised in Figure 5-19. Compound and composite profiles are developed simultaneously throughout the Tweed Basin during the Asbian period. The Northumberland Basin varies, however, in that compound profiles developed at the start of the Asbian period and then as the Asbian / Brigantian boundary is approached there is an increase in the number of composite profiles. The Alston Block strata

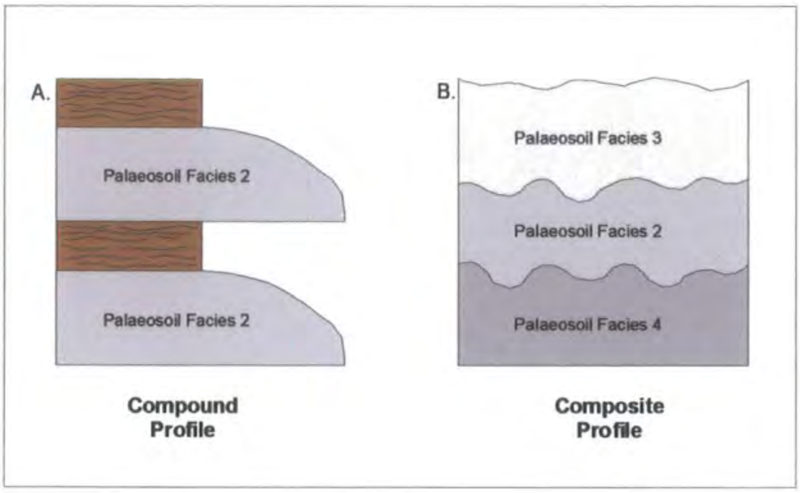
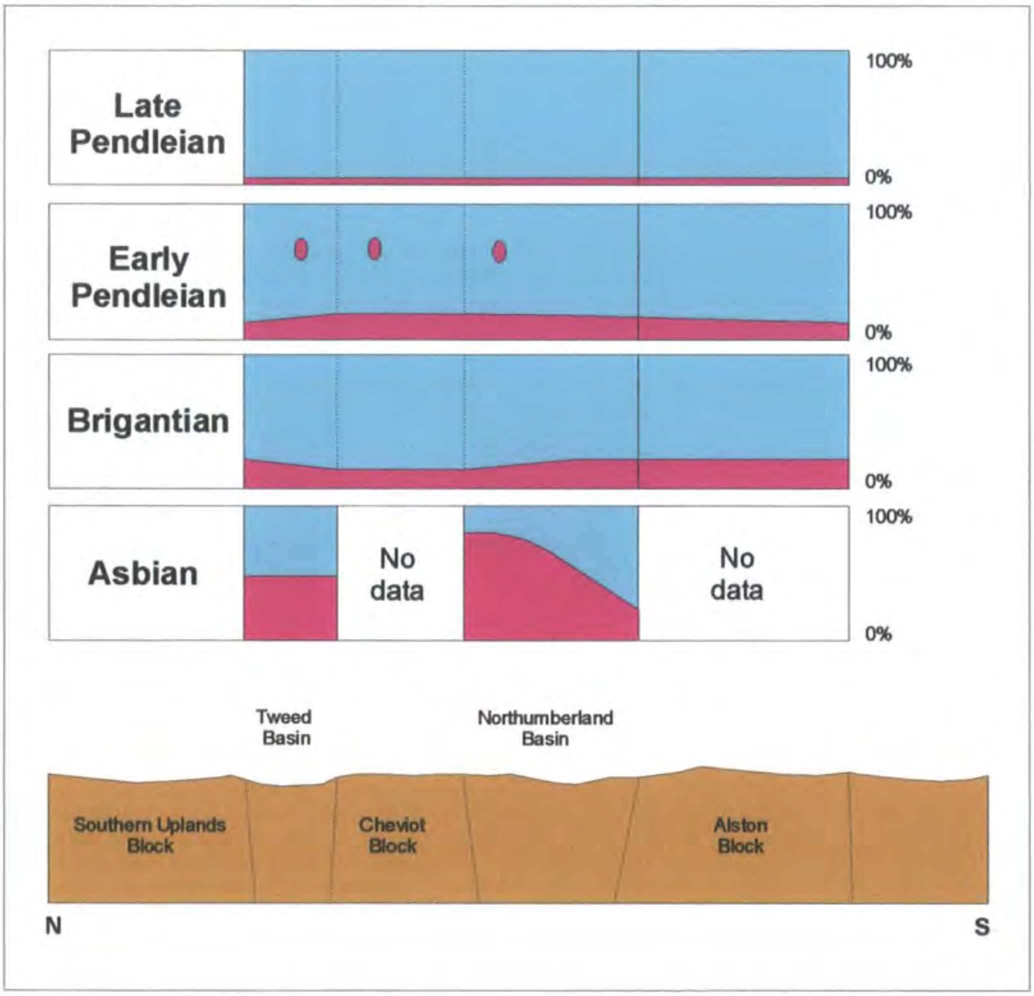


Figure 5-18A & Figure 5-18B Cartoon logs illustrating a compound palaeosoil profile (A) and a composite palaeosoil profile (B). Compound palaeosoil profiles contain intervening depositional sediment between each palaeosoil facies whilst composite profiles contain no intervening depositional sediment. Adapted from, Kraus (1999).



Key:

🟦 Composite palaeosoil profiles

🟥 Compound palaeosoil profiles

● Local compound palaeosoil profile

Figure 5-19 Cartoon cross-section of the study area displaying the main structural units and the distribution of palaeosoil profile types (composite and compound) across the area. Distribution of palaeosoil profiles is shown for the Asbian, Brigantian, Early Pendleian and Late Pendleian periods. Palaeosoil distribution is given in %.

It should be noted that the Cheviot Block and the Tweed Basin lose their independence and become part of the Northumberland Basin from the Brigantian period onwards. Their boundaries are therefore marked as a dotted line only.

display neither compound nor composite profiles. The Brigantian period displays a regionwide development of composite profiles, particularly in the centre of the Northumberland Basin. The abundance of composite profiles increases through the Pendleian with particularly well-developed ones in the southern and northern margins of the Northumberland Basin. Locally within the Northumberland Basin there are small numbers of compound profiles in the Early Pendleian.

Interpretation

The presence of compound palaeosoil profiles indicates that erosion was significant and sedimentation was rapid and unsteady, whereas composite profiles indicate that the rate of pedogenesis exceeded the rate of deposition (Kraus 1999). During the Asbian period, there was much variation throughout the area. While there was significant erosion and rapid and unsteady sedimentation during the Mid Asbian in both the Tweed Basin and the Northumberland Basin, towards the end of the Asbian, the rate of pedogenesis exceeded the rate of deposition on the Northumberland Basin. During the Brigantian period, the whole region shows that the rate of pedogenesis exceeded the rate of deposition (on both basins and on blocks). During the Pendleian period, there is a similar pattern seen between both basins and blocks, but towards the end of the Pendleian period, the Northumberland Basin records a period of increased erosion and rapid and unsteady sedimentation. There are many controls on sedimentation rates, the two most likely being tectonics and climate change. As previously mentioned, the Mid Carboniferous was affected by tectonics and a global climate change, so both of these factors need to be considered.

The variations seen between basins and blocks, such as those in the Late Asbian and the Late Pendleian, are tectonically-controlled events evident from the variations between structural units, due to differential subsidence (Section 8.2). During the Brigantian, there is a regionwide decrease in sedimentation rates that could be attributed to either a tectonic control in the sediment source area, decrease in differential subsidence or a regionwide climate change. In order to reduce sedimentation rates, climate would need to change from being humid (high sedimentation rates) to an arid or semi-arid climate (low sedimentation rates). An arid phase has been recognised at the start of the Brigantian from palaeosoil evidence and other climatic studies within the region (Section 6.12) and also from other areas such as the Midland Valley of Scotland (Andrews & Nabi 1998) and north-west Ireland (West *et al.* 1968), so this could be the main control on sedimentation rates.

5.4 Discussion

The most obvious control on the distribution and type of palaeosoil facies is that of changing base-level due to changes in sea-level. The repeated package of upward increasing hydromorphism is found regionwide regardless of temporal variations and accompanies a major marine transgression found in the form of an overlying marine limestone. As they are found to be particularly widespread and laterally continuous, this is compatible with glacio-eustatic sea-level fluctuations (Joeckel 1994; Section 4.4.2). The repetition of small-scale genetically related vertical packages of palaeosoils also suggests that a hierarchical system of cyclicity operated. These packages are most likely to have formed within a few 10's of 1000's of years. Similar features are seen in Holocene Mississippi River floodplain soils that are primarily controlled by episodic sedimentation and water table fluctuations (Aslan & Autin 1993). The major eustatic influence is inherent in this model, rather than climatic and / or tectonic controls alone.

As the Mid Carboniferous was a time of active tectonism this is undoubtedly going to have had an effect on the development of palaeosoils, as it would have affected local sedimentation and the sediment source. Differing subsidence rates is the occurrence of thicker palaeosoil profiles within the basins, whereas thinner profiles occur on the blocks or they are locally absent. Differing subsidence rates during the Asbian and Brigantian meant that smaller amounts of sediment accumulated on the blocks than in the basin, such that there was not as much material for pedogenesis on the blocks.

Sedimentation rates also affect the type of palaeosoil development. During times of rapid sedimentation, compound profiles are developed whereas during times of slow sedimentation composite profiles developed. Differential subsidence during the Asbian and parts of the Brigantian meant that sedimentation rates were higher within the Northumberland Basin and the Tweed Basin in comparison to the Alston Block. From the Brigantian towards the end of the Pendleian the sedimentation rates slow down and appear to have been the same throughout the area. This suggests that differential subsidence had ceased and thermal relaxation had begun. It should be taken into consideration that there are other factors controlling sedimentation rates such as climate. However, the spatial distribution of palaeosoil profile variations and the previous knowledge of tectonism within the area provide further evidence that the dominant control on sedimentation rates related to pedogenesis is primarily subsidence.

A major conclusion of this study is that a semi-arid phase was recorded within the study area close to the Asbian / Brigantian boundary. Evidence for semi-arid conditions has been found elsewhere in similar palaeolatitudes (Schenk 1967; West *et al.* 1968; Andrews & Nabi 1998). This is one of the many phases of aridity punctuated by phases of humidity during the Lower Carboniferous attributed to the formation of monsoonal circulation (Wright 1990). Climate change usually accompanies sea-level change (Tandon & Gibling 1994) and this major change to an arid / semi-arid climate has been associated with a major worldwide regression (Ross & Ross 1987). The change from a semi-arid climate to a wetter monsoonal regime has been attributed to an increasing importance of the wet season versus the dry season (Vanstone 1991). The occurrence of smaller scale cyclicity of possible obliquity and precession duration may help to explain this seasonal climate; the obliquity determines the degree of seasonality, although it may be less effective at low latitudes, and the precession controls the timing of the seasons and total radiative heating in each season (Weedon 1993). As these rhythms are thought to be controlling the repetitions of genetically related vertical packages of palaeosoils and they are found throughout the succession, then this could explain the seasonal climate that is observed, regardless of whether it is semi-arid or humid.

This study has utilised palaeosoils within the Mid Carboniferous succession of Northumbria as a tool for providing information on a variety of environmental factors such as climate change, sedimentation rates, and base-level changes. The age of the rocks studied means that pedogenic features may have since been obliterated by diagenesis or indeed not preserved in the first place. It should therefore be mentioned that there may be a lack of information and the complete environmental 'picture' may not be represented.

5.5 Conclusions

The main controls on the development of the Mid Carboniferous palaeosoils of Northumbria are eustasy, tectonism and climate. The most important control on pedogenesis is sea-level and in particular, eustasy. The record of rising base-level and therefore hydromorphism is widespread and indicates the onset of a marine transgression. Evidence for smaller scale changes in base-level may be attributed to varying Milankovitch rhythms on the scale of obliquity and precession but the poor distribution of palaeosoils within the clastic component of cycles makes them very difficult to correlate.

Basin and block development during the Mid Carboniferous seems to have played an active role in palaeosoil development. Differential subsidence rates meant that different amounts of accommodation space were created between the blocks and the basins. Greater amounts of deposition therefore occurred within the basins and on the blocks. During the Asbian and parts of the Brigantian, differential subsidence was at its peak and sedimentation rates were much higher within the basin. This led to the formation of thicker palaeosoil profiles because of greater amounts of sediment on which pedogenesis could occur. On the blocks palaeosoil profiles are thinner due to lack of sediments or in some cases absent altogether and may be represented as exposure surfaces. During the Late Brigantian and the Pendleian however, differential subsidence ceased and both the basins and the blocks subsided at the same rate due to thermal relaxation and the sedimentation rates were similar throughout.

The palaeosoils indicate a major change in climatic regime; from a humid, seasonal climate in the Early Asbian known from histosols, podzols and gleysols, all displaying varying amounts of vertic features, to semi-arid, seasonal climate in the Late Asbian to Early Brigantian, known from abundant pedogenic calcretes (aridisols) and groundwater calcretes, the former displaying vertic features. During the Mid Brigantian to Late Pendleian, the climate returned to a humid, seasonal climate once again. Such a feature is found regularly within the Lower Carboniferous due to the presence of monsoonal circulation although there is little record for this during the late Lower Carboniferous and perhaps monsoonal circulation continued later than previously thought.

Chapter Six

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Chapter 6 - Lithological Evidence for Climate Change

6.1 Introduction

The classic image conjured up when the British Carboniferous is mentioned is that of a tropical, humid, swamp-like environment. Although this may be correct for the majority of Carboniferous time, work in recent years has provided evidence for a significant amount of climate change throughout the period. Authors such as Wright (1990), Andrews & Nabi (1998), Falcon-Lang (2000) and Wright and Vanstone (2001) have all suggested that the climate was not uniform but instead punctuated by periods of aridity. This is not only true for the British Carboniferous but for other areas of similar palaeolatitudes as identified by Falcon-Lang (*pers comm.*), Schenk (1967), Van der Zwan *et al.* (1985) and Adams & Cossey (1981).

The reasons for such changes in climate have been mentioned in Section 2.7 with glaciation, continental configuration and changes in atmospheric CO_2 all being prime contenders for the causal mechanism for such climatic events. The major glaciation in Gondwana during the Late Palaeozoic, as suggested by authors such as Crowley *et al.* (1987) and Gonzalez (1990) to name but a few was greatly influenced by solar insolation to produce climate-driven sea-level changes (Milankovitch cycles) (Klein 1993; Rankey 1997; Olszewski & Patzkowsky 2003). The effects of these sea-level changes are inferred to be reflected in the cyclic deposition of Euramerica as a whole (Crowell 1978; Veevers & Powell 1987; Smith & Read 2000). However, the aims of this chapter are to investigate various lines of evidence for overall climate change throughout the Mid Carboniferous of Northumbria, and to assess the possibility of regional and global climate change on a variety of time-scales.

Due to the lack of outcrop in the Tweed Basin and Cheviot Block, data obtained from these areas has been incorporated into the Northumberland Basin dataset. Therefore, the area described as the Northumberland Basin refers to the area encompassing the Northumberland Basin, the Cheviot Block and the Tweed Basin.

6.2 Methods Used

The cyclic nature of the Mid Carboniferous sediments of Northumbria ensures that the diversity of rock-types within each cycle is repeated throughout the succession.

This allows for the assessment of various climatically-sensitive lithologies at all stages of the succession. Each of these methods of assessment is outlined below.

The distribution of coal within the succession has been studied by quantitatively assessing the percentage of total thickness of coal within each cycle (Section 6.3). Coals are highly climate-sensitive deposits and their occurrence may indicate specific climate conditions. The percentage thickness of coal was evaluated as opposed to the amount of coal since the thickness of each cycle varies a great deal throughout the succession. If just the amount of coal had been recorded this might have presented an unrealistic representation of the change in coal distribution within the succession.

The colour of both siliciclastic and carbonate sediments has been evaluated (Section 6.4). Colour relates to the mineral content of the sediment which may have been influenced by the climate conditions at time of deposition. It is necessary to distinguish between primary and secondary (diagenetic) effects as the latter would not necessarily represent the climatic conditions during deposition. A graphic representation of the results has been constructed for the siliciclastic sediments only. Carbonate results have not been plotted as the changes in colour are only slight and would be difficult to depict in graphic form.

Sandstone provenance was undertaken to assess changes in detrital grain composition on a temporal scale (Section 6.5). Sandstone provenance is useful for climatic studies as some siliciclastic grains are more prone to weathering than others under certain conditions. To avoid possible environmental-related variation, sandstones taken were of fluvial and deltaic origin only and were point-counted using the method outlined by Harwood (1988). Complete petrographic data from the sandstones can be seen in Appendix 3. Ternary plots were constructed and the scheme used by Zuffa (1985) was adopted to identify changing climatic regimes.

The amount of fine siliciclastic sediments in comparison to the amount of coarse siliciclastic sediments has been calculated as a ratio for comparison throughout the time period (Section 6.6). As fine siliciclastic sediments are generally transported as suspended load, their occurrence would be greatly influenced by climate conditions.

Coarse siliciclastics are transported by various methods, but are common in more arid climate conditions so their occurrence may be an indicator of this.

Palaeosoil analysis was incorporated into the data since interpretation of these deposits can yield valuable climatic information in order to give a complete range of climatic change proxies. The data used are directly taken from Chapter 5.

In addition to the methods outline above, literature-based research was carried out for other Carboniferous-aged outcrops at similar palaeolatitudes to investigate climate change features. These findings have been incorporated into the results.

6.3 Coal Distribution

The percentage of coal within each cycle has been plotted for both the Alston Block to the south of the study area (Figure 6-1A), the Northumberland Basin in the north of the study area (Figure 6-1B), as well as an average thickness plot for the area as a whole (Figure 6-1C). See Appendix 4 for the dataset used for these graphs.

Results

The overall trend for the three graphs (Figures 6-1A, B & C) is broadly similar with coal recorded at the start of the Asbian and no coal observed in the Early Brigantian. This is followed by an increase in the percentage of coal from the Early Brigantian to a peak in the Late Brigantian / Early Pendleian and a gradual decrease from this point until the end of the Namurian. On the Alston Block there is a significant change in the percentage of coal, with only 0.5% per cycle at the start of the Asbian to no coal in the Early Brigantian, and then an increase again up to a peak of 1.8% coal per cycle in the Late Brigantian. The Northumberland Basin begins with 1.3% coal per cycle at the start of the Asbian, then there is a decrease to no coal in the Early Brigantian and then a reversion to similar coal values of ~1.3% at the end of the Brigantian.

Interpretation

In the geological record coals are taken to indicate terrestrial humidity (Sellwood & Price 1993), and generally require poor drainage conditions which tend to occur in climates where precipitation exceeds evaporation (McCabe & Parrish 1992). Such conditions occur today in equatorial regions and at high to mid-latitudes (Parrish &

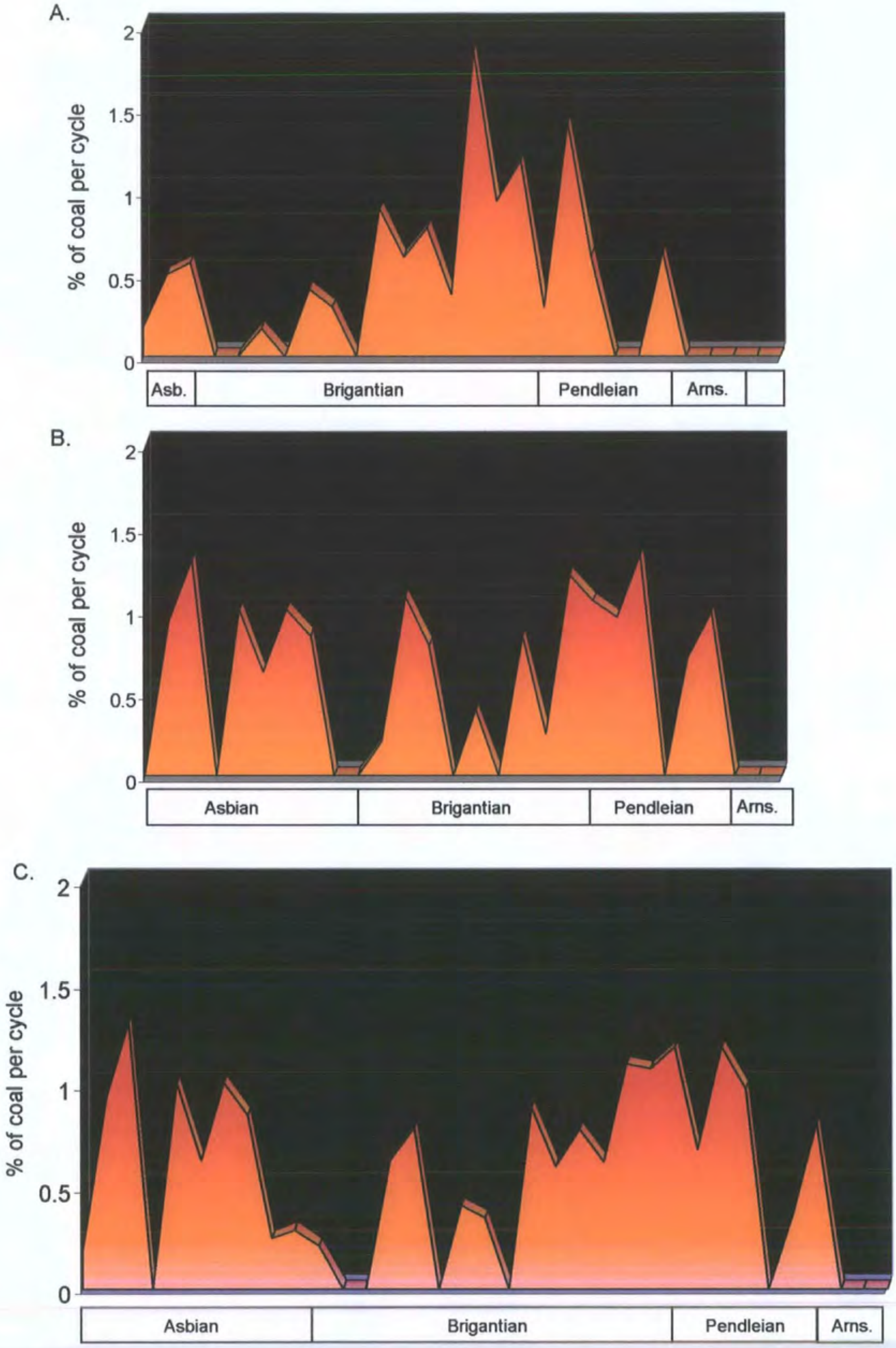


Figure 6-1 Graphs displaying the percentage of coal within each cycle. Graph A shows results from the Alston Block, Graph B shows results from the Northumberland Basin, Graph C shows the regional average results. It should be noted that the number of cycles within each structural area varies and it is impossible to correlate direct cycles.
The general trends within each time period should therefore be compared.

Barron 1986). At the present day, woody material does not generally accumulate in lower latitudes due to higher temperatures which result in rapid oxidation and breakdown by bacteria (Doyle *et al.* 1995). This would however be very much dependent on the amount of organic productivity and whether this is in excess of the amount of oxygen present. The majority of the economic Carboniferous coal deposits formed in equatorial humid, tropical climates (Besley & Fielding 1989; Cameron *et al.* 1994; Greb & Chesnut 1996). Carboniferous coals deposits that formed in equatorial humid, tropical climates are similar to deposits found in the Tasek Bera in peninsular Malaysia, a peat accumulating basin in humid, tropical conditions, which is thought to be representative of many ancient coal-forming environments (Wuest *et al.* 2002). Due to prior knowledge of the palaeolatitude (Section 2.2) of the Mid Carboniferous strata of Northumbria at equatorial latitudes, it can be assumed that the coal deposits found formed under humid, tropical conditions.

There are obvious trends in the varying percentage of coal within each cycle and from this study it is interpreted that the Mid Carboniferous Northumbrian climate changed from a tropical, humid climate at the start of the Asbian to a more semi-arid climate at the end of the Asbian / Early Brigantian and then returned to a tropical, humid climate towards the end of the Brigantian.

Coal preservation is dependent on numerous factors aside from climate change including botanical input (Eserle & Ferm 1994), changes in the depositional environmental (Jimenez *et al.* 1999) and early diagenesis (Coulson *et al.* 2005). The amount of coal within each cycle may be a result of these factors rather than climate. It is therefore stipulated that the results from this section are problematic and should only be considered in conjunction with the other results of this chapter.

The results show that although the same overall trends are seen in the Northumberland Basin and on the Alston Block, the cycles on the Alston Block contain a lower percentage of coal than those in the Northumberland Basin. There is no evidence to suggest that there were local climate changes between the two areas so it may be inferred that drainage was better on the Alston Block than in the Northumberland Basin. Today in lowland tropical areas, coal-forming environments are generally better developed than upland areas which may bear some resemblance to the differences between the Alston Block and the Northumberland Basin. Previous authors (e.g. Johnson *et al.* 1995) have however stated that there were no topographical differences between the differing structural regions of Mid Carboniferous Northumbria.

If there was no topographical difference between the structural regions of Mid Carboniferous Northumbria then the difference in percentages of coals within each cycle may be a result of the closer proximity of the major marine influence to the Alston Block than the Northumberland Basin. The major marine influence for the area lay to the south-west of the study area (Figure 2-7). The Alston Block was the closest structural region to the marine influence, resulting in more prevalent marine conditions. This may have resulted in more rapid marine flooding in this area leading to less coal accumulation.

6.4 Sediment Colour

As mentioned in Section 6.2 the colour of siliciclastic sediments are a result of mineral content which may have been directly influenced by climate at the time of deposition. Graphs have therefore been plotted to display the change in coloration of the siliciclastic sediments throughout the study period for both the Alston Block (Figure 6-2A) and the Northumberland Basin (Figure 6-2B). These graphs display the percentage of grey, buff and red siliciclastic sediments in both the Alston Block and the Northumberland Basin throughout the study period. The data for these graphs has been compiled from qualitative observations in the field.

Carbonate rocks vary a great deal from siliciclastic rocks when assessing colour. The colour of carbonate rocks is often dependent on the amount of organic matter that they contain (e.g. Tucker 2001). Organic content may be a means of assessing the organic productivity as a result of climate change but there are numerous other factors which influence the amount of organic matter and are discussed later in this section. The colour variation of limestone outcrops has therefore been evaluated but has not been presented graphically as the variations are so slight they would be difficult to depict in graphic form.

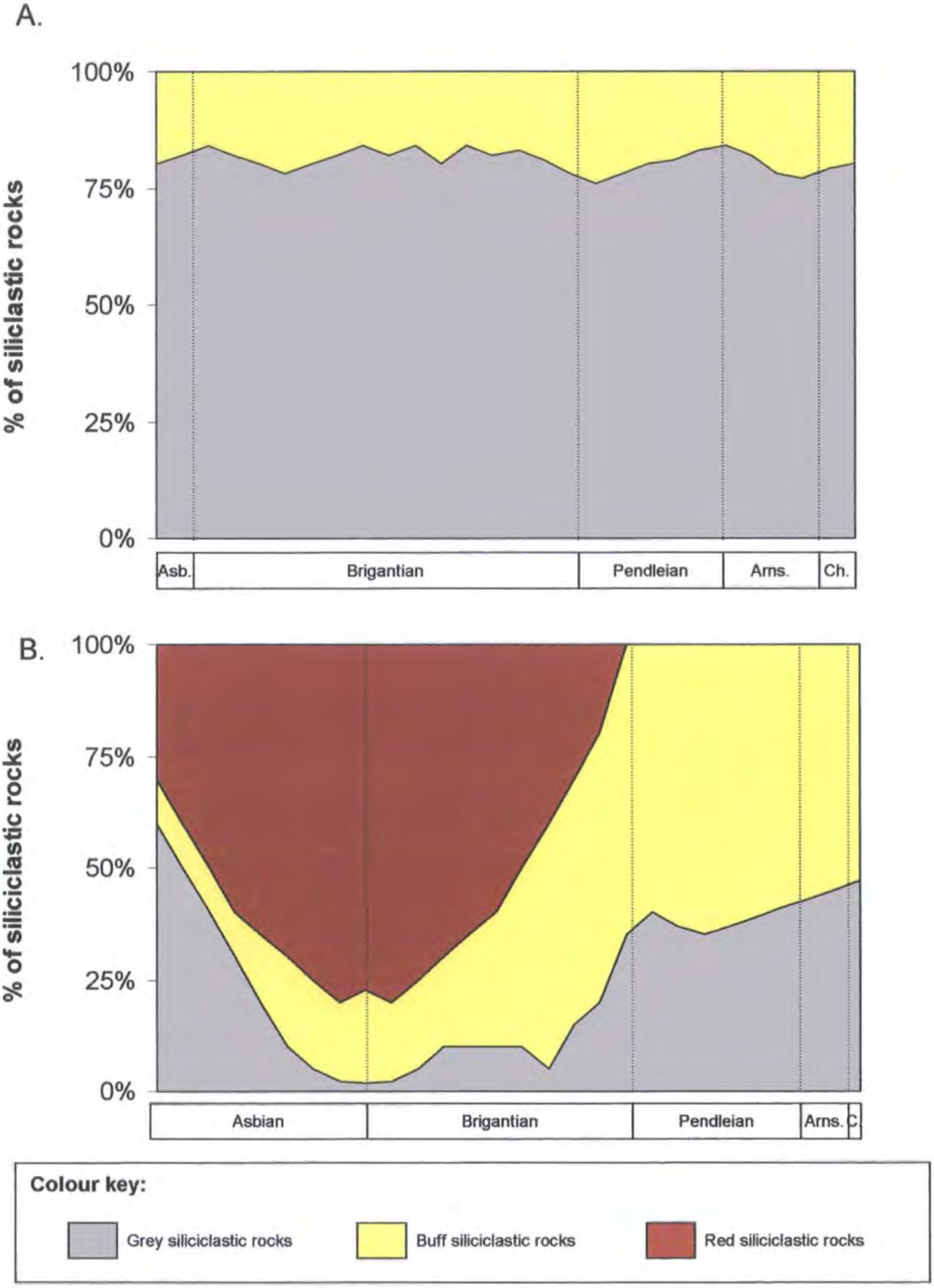


Figure 6-2 Graphs indicating the percentage of colours of siliciclastic rocks from the Asbian to Chokerian. Graph plotted using the percentage of colours of siliciclastic sediments within individual cycles. Graph A represents sediments from the Alston Block while Graph B represents sediments from the Northumberland Basin. It should be noted that the number of cycles within each time period varies between the Alston Block and the Northumberland Basin so general trends between areas have only been compared.

Results

In the Mid Carboniferous siliciclastic sediments of the Northumberland Basin there is a transition from pale grey hues at the start of the Asbian period (Figure 6-3A) to red-coloured sediments during the Mid-Asbian (See SC.1 in Appendix 2) (Figure 6-3B). In thin-section, the red coloration is seen to be due to ferric oxide rims around detrital quartz grains, which have been overgrown by later quartz cement (Figure 6-4). The period of red coloration extends until the Early Brigantian where there is a transition back to pale grey / buff hues (Figure 6-3C). This coloration extends until the end of the study period except for a short phase in the Mid-Pendleian where there is a slight change in coloration from pale grey / buff hues to warmer yellow hues. The succession from the Alston Block for the Asbian and Early Brigantian is dominated by carbonate sediments so siliciclastic coloration cannot be used from this time period; however the siliciclastic sediments from the Mid-Brigantian onwards are uniformly pale grey.

The limestones throughout the Mid Carboniferous succession display a transition from predominantly pale grey coloration to more dark grey at the end of the Asbian. The limestone coloration remains this way for the rest of the study period. This feature was also noted by Dunham (1990).

Interpretation

The grey coloration of siliciclastic sediments is usually due to the presence of organic matter which is apparent in many of the Early Asbian siliciclastic sediments. The iron present is in the ferrous state (Fe^{2+}) and generally is contained in the clay minerals shown to be the cement around grains. The presence of organic matter and Fe^{2+} would indicate a humid climate with reducing conditions during early diagenesis (Tucker 2001). As the red coloration of the siliciclastic sediments is found as ferric iron 'rims' around detrital grains and formed before quartz overgrowth cement it is likely to be a product of early diagenesis and can be related to conditions at, or shortly after deposition. Red sediments gain their coloration from the precipitation of ferric iron during oxidising conditions which are dominant during an arid / semi-arid climate (Weibel 1998) and generally suggests drier conditions (McLoughlin *et al.* 1997). However, although red coloured siliciclastic sediments form in oxidising conditions it may not be a palaeoclimatic signature because red sediments are known

Figure 6-3A Photograph of grey-coloured siliciclastic sediments at Spittal coastal section. Height of figure is approximately 1.55 m for scale.

Figure 6-3B Photograph of red-coloured siliciclastic sediments at Spittal coastal section. Height of figure is approximately 1.5m in height for scale.

Figure 6-3C Photograph of buff-coloured siliciclastic sediments at Howick coastal section. Shaft of hammer is 30cm long for scale.

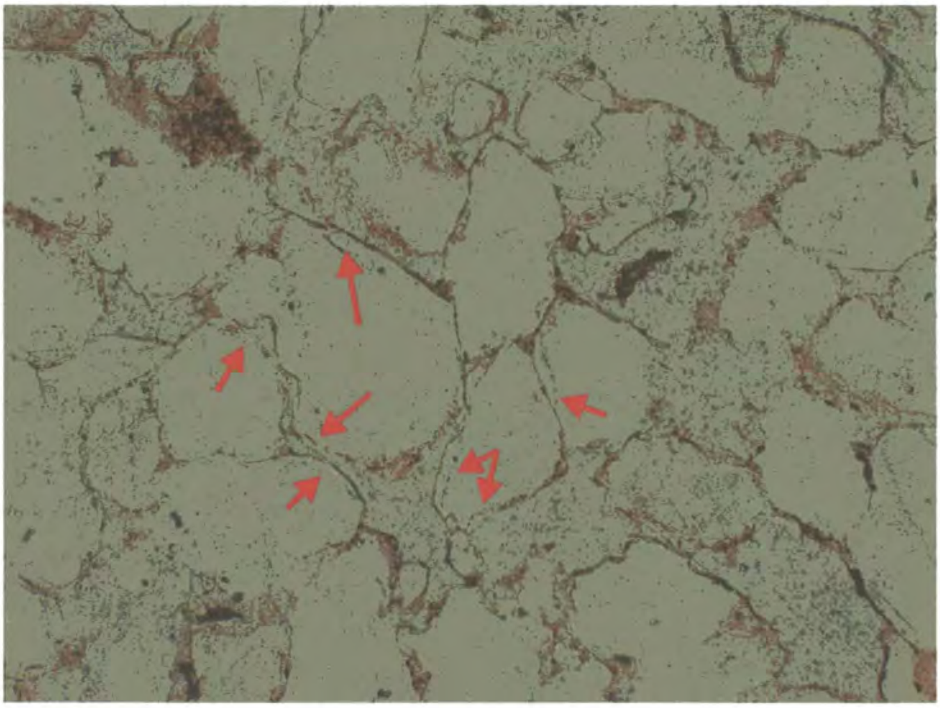


Figure 6-4 Photograph of medium-grained fluvial sandstone of Asbian age from Spittal / Scremerston showing detrital quartz grains with ferric oxide 'rims' which have been later overgrown with quartz cement (marked with red arrows). Field of view is 5mm across.

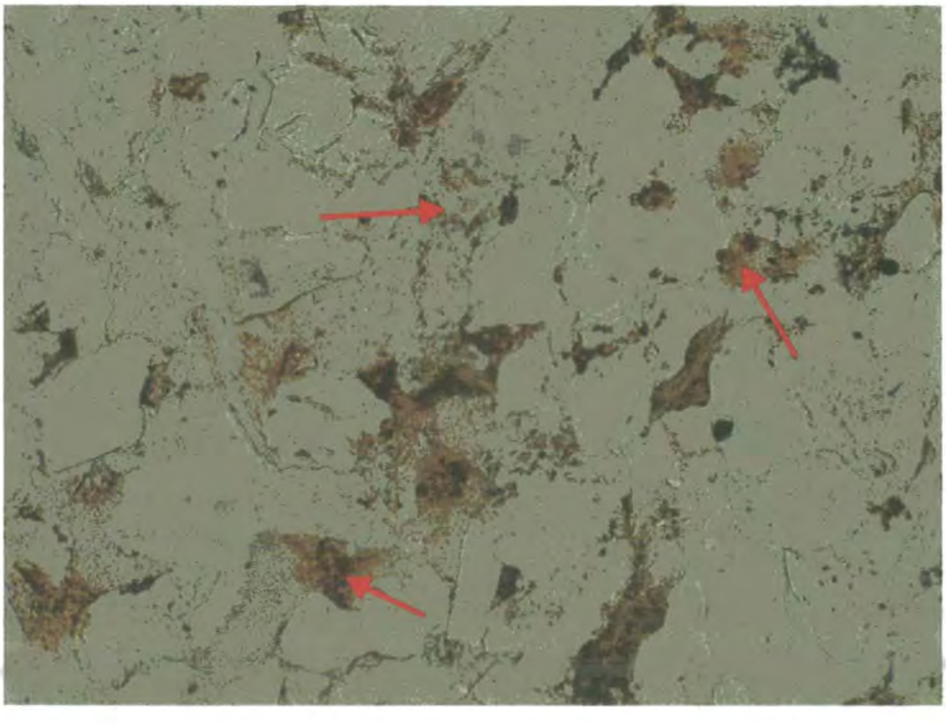


Figure 6-5 Photograph of medium-grained fluvial sandstone of Pendleian age from Howick showing goethite growth between detrital quartz grains indicating growth after deposition (marked with red arrows). Field of view is 5mm across.

to form in both arid and moist tropical climates (Besly & Turner 1983) and as a result of fluvial deposition in a variety of environments (Doyle *et al.* 1995). Yellow, brown and buff coloration of sediments is due to the presence of hydrated forms of ferric oxide (Figure 6-5) and this is often a result of recent weathering of ferrous iron minerals (Tucker 2001); this can therefore be excluded as a palaeoclimatic indicator. The interpretation of the various colours displayed within the study period would indicate that the climate at the start of the Asbian was humid and gradually changed to a more arid or semi-arid climate at the end of the Asbian / Early Brigantian, if the red coloration is due to a palaeoclimatic change. The semi-arid phase as inferred from the red coloration of sediments lasted until the Early Brigantian when humid climatic conditions resumed, as indicated by the grey coloration of the siliciclastic sediments.

As mentioned previously, grey coloration of sediments is generally due to the presence of organic matter and an increase in the organic content leads to an increasingly darker coloration (Tucker 2001). Increased organic matter in a limestone could come about in many ways including increasing anoxia which would lead to enhanced preservation of organic matter, increased productivity which could be caused by a number of reasons including upwelling or a lowering of sea level which would provide a higher nutrient supply from the exposed shelf areas (e.g. Dersch & Stein 1991) or reducing conditions during early diagenesis. A darker coloration could also be due to an increased presence of finely disseminated pyrite (Tucker 2001), or as discussed in Section 3.4, the Mid Carboniferous limestones in Northumbria are generally very nearshore, meaning that the dark colour could result from terrestrial input, both from fine-grained clays and nutrients. Increased productivity is often associated with glacial episodes as upwelling, there is also an associated significant fall in sea-level leading to exposed shelves. There is evidence of such an effect from the Pleistocene/Holocene transition, southwest Pacific (Neil *et al.* 1991). Darker grey carbonates are found from the glacial period whilst lighter carbonates are found from the interglacial period. This may be the effect that is evident in Northumbria with darker limestones seen at the end of the Asbian indicating a period of enhanced organic productivity associated with a glacial episode (Section 4.4.3.1 and Section 7.8) and also an associated fall in sea-level (Section 4.3.3).

6.5 Sandstone Provenance

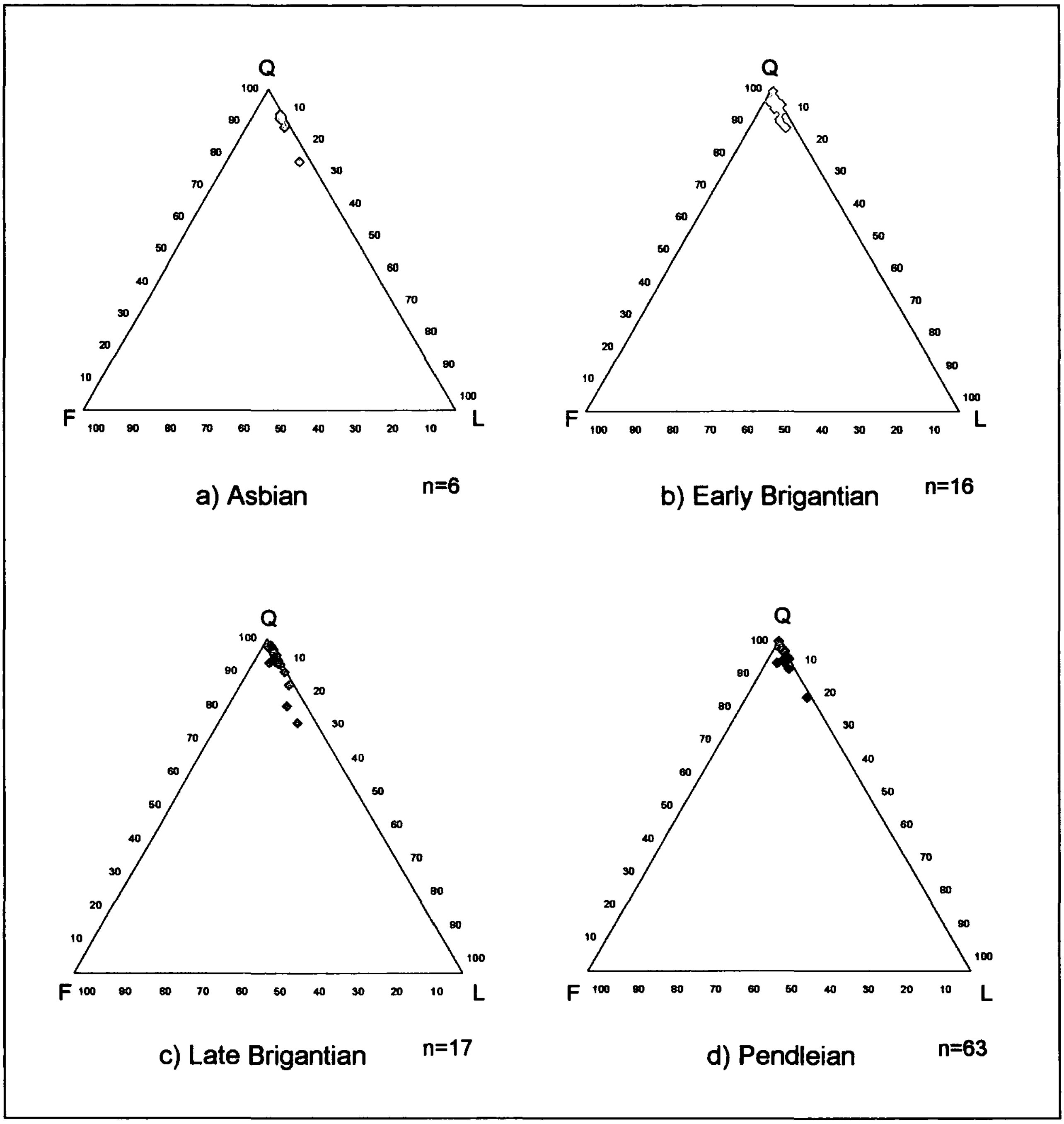
Sandstone provenance has been carried out by recording the amount of quartz, feldspar and lithic fragments as detrital grains within each sandstone thin section. Data was only recorded from fluvio-deltaic sandstones to eliminate environmental variation. Ternary graphs have been plotted for each of the following time periods: Asbian (Figure 6-6A), Early Brigantian (Figure 6-6B), Late Brigantian (Figure 6-6C) and Pendleian (Figure 6-6D). See Appendix 3 for the dataset used for these plots.

Results

The results from each of the time periods mentioned above will be discussed in turn. The Asbian data are somewhat restricted due to the lack of data available. The composition of the sandstone is varied; the maximum amount of detrital quartz is 93.2%, whilst the minimum amount is 77.4%. Feldspar grains range in abundance from 3.1% to 0.6% and lithic fragments range in abundance from 19.5% to 7%. The data from the Early Brigantian is less scattered, with detrital quartz ranging in abundance from 99.3% to 87.7%, feldspar grains from 3.3% to 0% and lithic fragments from 9.8% to 0.7%. Late Brigantian data is the most scattered dataset with detrital quartz ranging in abundance from 98.5% to 74.7%, feldspar from 5.1% to 0% and lithic fragments from 20.4% to 0.8%. The data from the Pendleian is the largest dataset, with detrital quartz ranging in abundance from 100% to 83.1%, feldspar grains from 3.7% to 0% and lithic fragments from 15.8% to 0%.

The time period with the highest amount of detrital quartz is the Pendleian (83.1% to 100%), although the Early Brigantian and the Late Brigantian both have high amounts (87.7% to 99.3% and 74.7% 98.5% to respectively). The scatter of the Late Brigantian is misleading as only 3 of the data points are below 83.7%. The detrital composition of the Asbian data is consistently low.

Feldspar compositions as a whole do not alter greatly, the time period with the highest amount of feldspar grains is the Late Brigantian, although this is a maximum of 5.1% in comparison to 3.1% to 3.7% from the other time periods. The minimum amounts of feldspar grains are 0% from the Early and Late Brigantian and the Pendleian in comparison to 0.6% in the Asbian.



a) Asbian n=6

b) Early Brigantian n=16

c) Late Brigantian n=17

d) Pendleian n=63

Figure 6-6 Ternary plots showing the composition of Asbian (Late Viséan) to Pendleian (Early Namurian) fluvio-deltaic sandstones from Northumbria. Q=Quartz, F=Feldspar, L=Lithic Fragments.

Lithic fragments are at their most abundant in the Late Brigantian dataset where they are found up to a maximum of 20.4%. If the data is looked at more thoroughly however, more than 80% of all the sample analysed contain less that 10% lithic fragments whilst only 8% have more than 15% lithic fragments. The minimum amount of lithic fragments is 0.8%. The dataset from the Asbian has a consistently high amount of lithic fragments as the maximum is 19.5% whilst the minimum is still 7%.

Interpretation

As quartz is a relatively hard mineral with no cleavage, it is mechanically very stable and can survive considerable attrition during transport, so if there is weathering under a hot and humid climate, quartz will most likely be the only mineral transported. An increase in annual precipitation from 37cm (semi-arid) to 120cm (humid) can result in a 140% increase in the amount of quartz (Blatt & Tracy 1996). The time periods that display large proportions of detrital quartz (i.e. Pendleian and Early and Late Brigantian) are inferred to have had a humid climate. The Asbian period is inferred therefore as having a less humid climate.

Feldspars have a strong cleavage and are subject to dissolution, therefore a humid climate in the source area promotes feldspar destruction due to chemical weathering (Tucker 2001). By comparison, in arid areas, fresh feldspars survive the dominantly physical weathering. The feldspar composition of the sandstones does not alter greatly; there is a higher minimum amount of feldspar in the Asbian than any other period which may infer a slightly more arid climate but the difference is minimal between this and other time periods. Feldspar abundance may be influenced by other factors: if there is rapid erosion, such as in an area of rapid relief, ample time will not provided for the destruction of feldspar grains in spite of a humid climate and feldspar dissolution can also take place during diagenesis. The climate interpretation based on the proportion of feldspar should be evaluated with care.

Lithic fragments are most abundant in the Asbian period which would indicate a more arid climate. Humid climates may result in a difference of two-thirds more lithic fragments than those in arid climates (Blatt & Tracy 1996). This feature results from the generally weak intercrystalline or intergranular bonds within lithic fragments which are more easily broken down during sediment transport (Tucker 2001).

The sandstone provenance indicates that there was a more arid climate in the sediment source area during the Asbian period inferred from the presence of abundant lithic fragments and the reduced amount of quartz. The climate from the rest of the study period is inferred as being more humid in the source area due to the lack of lithic fragments and abundant quartz within each sandstone.

The results achieved from the sandstone provenance analysis are perhaps slightly tentative. The ternary plots (Figure 6-6) have yielded very tight datasets meaning that they have similar characteristics with only the slightest change in composition being interpreted as evidence for climate change and are therefore by no means conclusive. This may be because the scale of the fluvial transport system into Mid Carboniferous Northumbria was vast and much of the sediment brought in would have been far-travelled and mature (Tyrell *et al.* 2006) regardless of the climatic regime.

6.6 Fine versus coarse siliciclastic sediments

As each cycle is composed of varying amounts of fine and coarse siliciclastics, a ratio of the two components has been calculated for each cycle throughout the time period. Coarse siliciclastic sediments are sand-sized fractions and upwards (0.25mm+) while fine siliciclastic sediments are anything below this. The results from the Alston Block have been plotted (Figure 6-7A) separately from the Northumberland Basin (Figure 6-7B) to try and eliminate tectonic effects on siliciclastic sediment supply. A regional average has also been calculated (Figure 6-7C). See Appendix 4 for the dataset used for these graphs.

Results

The overall trend is very similar for both the Alston Block and the Northumberland Basin. There is a large decrease in the amount of fine sediment in each cycle from the Early Asbian to the Early Brigantian to a low of 20%. Following this, there is a significant increase in the amount of fine sediment in each cycle towards the end of the Brigantian to a peak of 70%. The amount of fine siliciclastics in each cycle

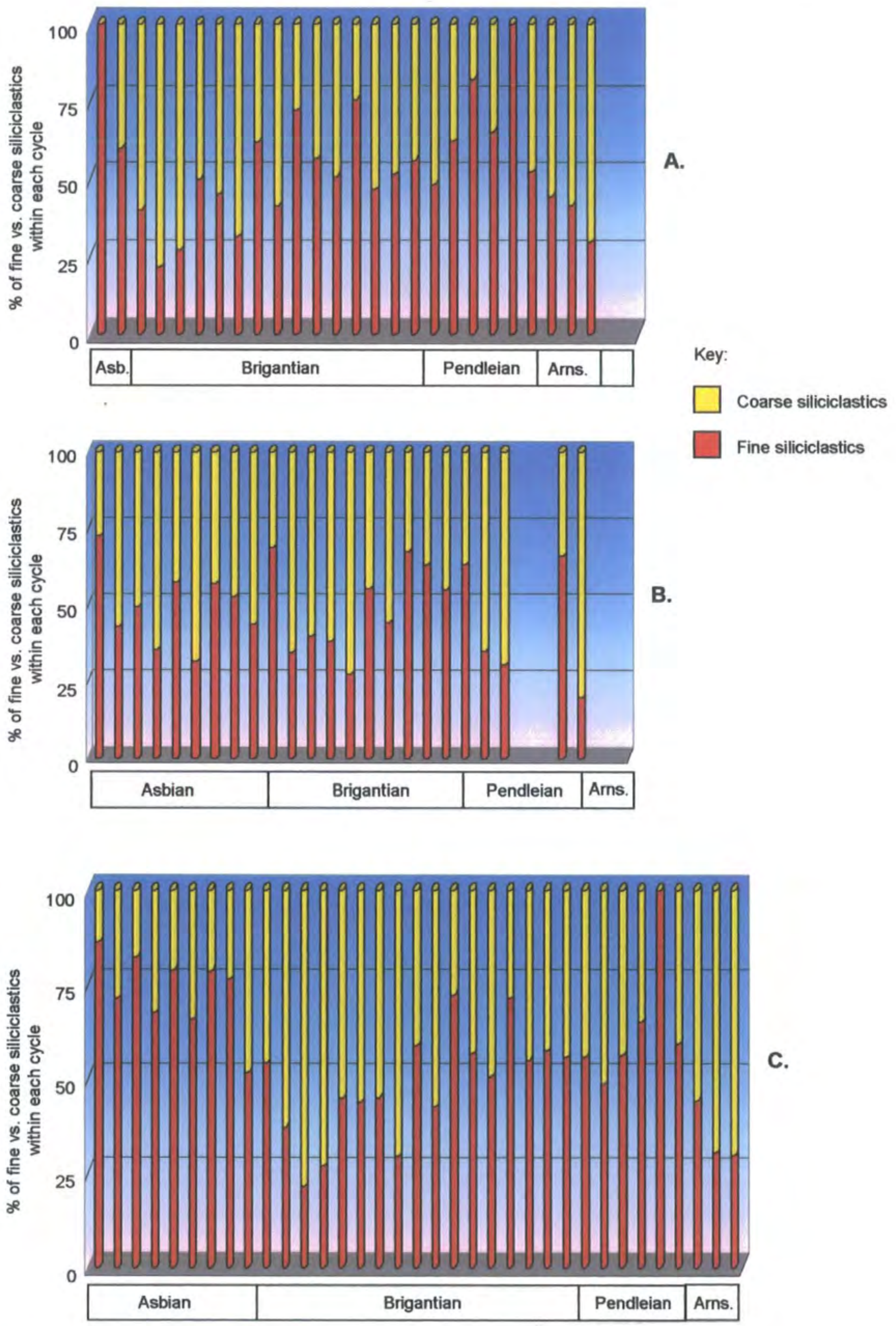


Figure 6-7 Graphs representing the ratio of fine vs. coarse siliciclastics within each cycle. Graph A shows results from the Alston Block, Graph B shows results from the Northumberland Basin, Graph C shows the regional average.

decreases again slightly in the Early to Mid-Pendleian and then reaches a small peak towards the end of the Pendleian, tailing off towards the Arnsbergian.

The main deviation from this trend is found in the Northumberland Basin (Figure 6-7B) where there is trough reached on the graph as the amount of fine siliciclastic sediment per cycle decreases to 20% in the Mid-Asbian and then reaches a small peak of ~40% as it increases once again at the Asbian-Brigantian boundary. The overall trend is the same as that of the regional average.

Apart from the minor variation mentioned the only difference between the two specified areas is that there are generally more coarse siliciclastic sediments in each cycle in the north of the study area than in the Alston Block cycles to the south.

Interpretation

The overall trend in the ratio of fine to coarse siliciclastics within each cycle is the same and this would suggest that the controlling factor is at least regional in scale and not local. The fact that the same pattern is displayed in different tectonic areas would suggest that the main controlling factor was not tectonic-related.

In fluvially-dominated environments, the grain size of siliciclastic sediments is often related to stream power and hence will respond to climate change. A decrease in fine siliciclastic sediment is generally attributed to a decrease in the amount of surface run-off as there would be little water for transport of fine sediment suspension (Dersch & Stein 1991). This suggests a period of semi-arid or arid climate.
An increase in coarse siliciclastic sediment supply would also be consistent with a semi-arid climate phase as the potential for water transported siliciclastics is restricted to catastrophic flood events (Cecil 1990). An increase in coarse siliciclastic sediment and a decrease in fine siliciclastic sediment were common during glacial phases in the Quaternary. For example, on the Makran continental slope in the Arabian Sea, an increase in fluvial and aeolian detritus was recorded (Prins *et al.* 2000) as fine sediment was transported away from the continental slope by wind action and deposited in deep basins. Increased coarse sediment supply during glacial times is due to intensified atmospheric and oceanic circulation, lowered sea-level and decreased vegetation cover (Dersch & Stein 1991). This often occurs in association

with a decrease in the clay content and an increase in the feldspar / quartz ratios of coarse sediments suggesting aridification of the source area (Dersch & Stein 1991). The major change in the ratio of fine to coarse siliciclastic sediments therefore would imply that there was a change from more humid climate conditions at the start of the Asbian to more semi-arid or arid conditions from the Late Asbian to the Early Brigantian. After this semi-arid or arid phase, humid climatic conditions returned for the remainder of the study period

An increase in stream power may also be attributed to a change in base-level, so the greater amounts of coarse siliciclastic sediment may not have been a result of climate change. Large changes in regional base-level have been noted from a similar time period as the proposed semi-arid / arid phase described within the study area (Section 4.3.2.1) and could have been associated with the onset of glaciation in the southern hemisphere (Section 4.3.3).

The small increase in the amount of coarse siliciclastic sediments during the Mid Brigantian in the Northumberland Basin may be controlled by local tectonics and was probably not associated with a major climate change. If climate change was involved it is only likely to have been a local change. During this time the area was undergoing differential subsidence with the Northumberland Basin subsiding faster that the adjoining Alston Block, and this could have led to variations in sediment supply and so small local changes in the amount of fine and coarse siliciclastic sediment.

The variation in the amount of coarse siliciclastic sediments within each cycle between the Alston Block (Figure 6-7A) and the Northumberland Basin (Figure 6-7B) could be due to an increase in seasonality which is a major cause for increase in siliciclastic sediments as it restricts vegetative cover in upland areas (Cecil 1990). This feature may be environment-related as there is generally a higher amount of fine-grained lithofacies on the Alston Block due to the proximity to the marine source. The Alston Block is also further from the sediment source land to the north-east of the study (Figure 2-7), which would mean that there would be less coarse siliciclastic sediments the further away from the source area that sediment is deposited.

6.7 Palaeosoil Analysis

For a full description of the variation in palaeosoil types in the study area during the Mid Carboniferous see Chapter 5. The palaeosoils throughout the study area provide a near-continuous record of the pedogenic conditions during the Mid Carboniferous and show significant temporal variation.

Results

At the start of the Asbian, gleysols and podzols are the dominant palaeosoil type with the incoming of pedogenic and groundwater calcretes (See PS.1 in Appendix 2) towards the end of the Asbian and start of the Brigantian. There is a reversion back to gleysols (See PS.3 in Appendix 2) and podzols (See PS.2 in Appendix 2) throughout the rest of the study period with palaeosoils displaying vertic features at the end of the Brigantian and Early Pendleian. This is explained in more detail in Section 5.3.1.

Interpretation

Gleysols are generally not diagnostic of any particular climatic regime although they do require waterlogged conditions which occur more readily in tropical to low Mid-latitudes (Section 5.2.3). Podzols form in cool, wet environments where rainfall exceeds 450mm per annum, although they also develop on well-drained siliceous substrates under warmer climatic regimes (Section 5.2.2) (Fitzpatrick 1993; Sellwood & Price 1993). Calcretes form in conditions of low rainfall and high evaporation which are most commonly achieved in semi-arid / arid conditions (Strong *et al.* 1992), and generally form in areas with mean annual temperatures of 16 to 20°C with low (100 to 500mm) rainfall (Section 5.2.5) (Goudie 1983). However, calcite has been reported from Mississippi River flood-plain soils that are currently forming in a humid climate, which indicates that calcic palaeosoils do not always represent semi-arid or arid climates (Aslan & Autin 1998). Vertisols are found in climatically diverse areas but are most common in warm-temperate to tropical climates with 4 to 8 dry months each year (Sellwood & Price 1993); they are indicative of strong seasonality (Section 5.2.4) (Wright *et al.* 1991; Wright 1992).

The interpretations of the various soil types provide evidence that the climate in the Early Asbian was probably humid and then changed to arid or semi-arid in the Late Asbian. This arid or semi-arid phase lasted until the Early Brigantian when soils that formed in humid conditions returned. In the Late Brigantian to Early Pendleian although humid soils are present, seasonal conditions were also present. This is summarised fully in Section 5.5.

6.8 Cyclic climate change

The cycles found within the Mid Carboniferous of Northumbria contain climate-sensitive lithologies and can be interpreted in terms of climate change in association with glacio-eustatic changes.

Results

The main components of each cycle are displayed in Figure 6-8. Each cycle contains three main climatically-sensitive lithologies; shelf carbonates, deltaic clastics and then coal at the top of the cycle.

Interpretation

The deposition of calcium carbonate as limestone can be used to indicate a warm climate (Figure 6-9) as the solubility of $CaCO_3$ decreases as temperature increases and so higher temperatures tend to lead to more limestone (Doyle *et al.* 1995). Most marine carbonate is of organic origin and organic productivity generally increases from higher to lower latitudes in connection with solar illumination (Sellwood & Price 1993). However, this depends on whether Carboniferous carbonate producers were light dependent, a topic on which there is currently under considerable debate (e.g. McGee & Whalen 2002; Aretz & Herbig 2003). It should also be stated that many shelf limestones are also associated with periods of rising sea-level which occurred repeatedly in the Mid Carboniferous succession of Northumbria a subject that has been discussed in detail in Section 4.4.2. The repeated occurrence of shelf carbonates may be more likely to be attributed to the frequent oscillations of sea-level rather than repeated climate change. Although sediment supply is controlled by a variety of geographical and climatic factors (Van der Zwan 2002), siliciclastic input into a sedimentary basin is at its optimum when there is seasonal rainfall because such seasonality restricts vegetation cover in upland areas (Cecil 1990).

The ideal conditions for peat / coal accumulation are during relatively wet climates (Figure 6-9) where siliciclastic sediments and dissolved sediment loads are at a

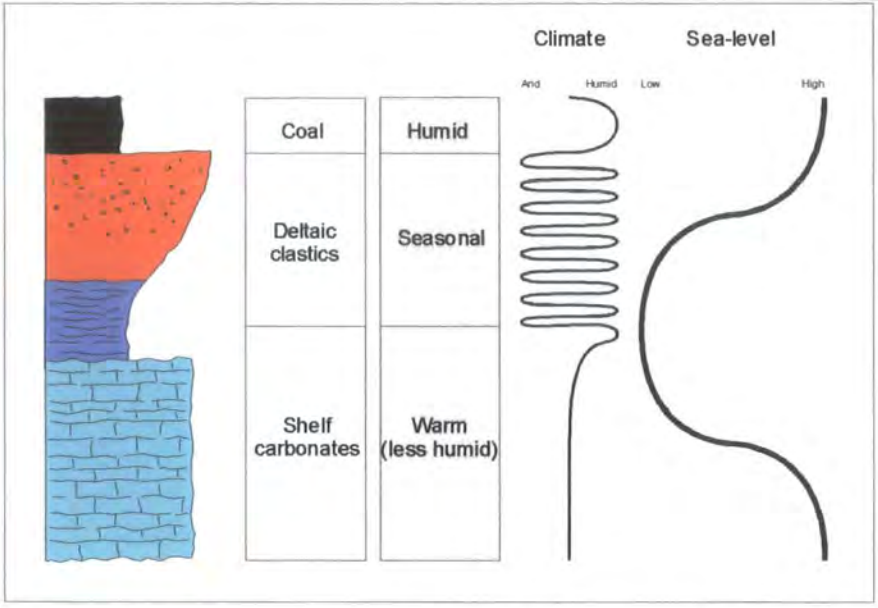


Figure 6-8 Cycle components and their corresponding climate units and associated change in sea-level. Adapted from, Tucker (*pers comm.*).

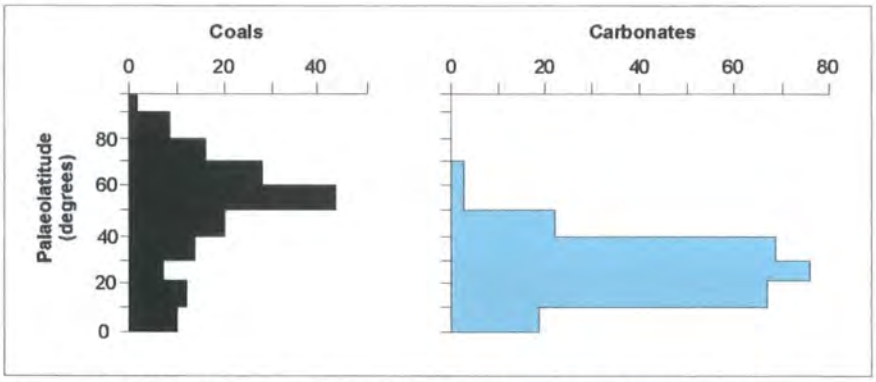


Figure 6-9 Palaeolatitudinal zonation of coals and carbonates. Each histogram shows the frequency of deposits against palaeolatutude. From, Scotese & Summerhayes (1986).

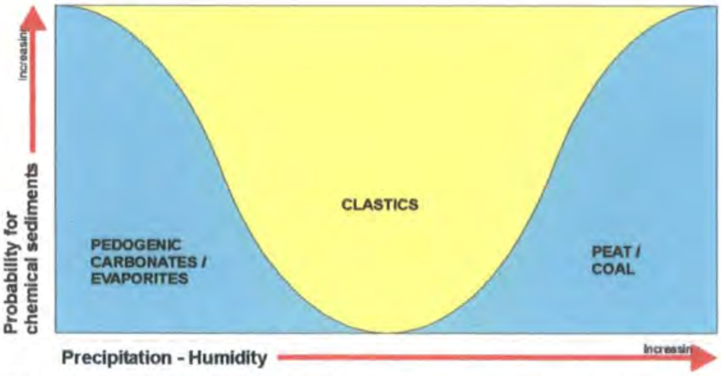


Figure 6-10 Conditions for formation of chemical sediments in response to climate wetness. Adapted from, Cecil (1990).

minimum (Figure 6-10) due to leached soils, maximum vegetation cover and / or sediment denuded upland areas (Cecil 1990). As mentioned previously however, the principal requisite for coal formation is poor drainage and this may even occur in semi-arid areas providing there is a high water-table (Doyle *et al.* 1995).

Although the Mid Carboniferous cycles found with the study area do contain climate-sensitive lithologies within each cycle as described, such lithologies can form independently of climate conditions. Each cycle within the study area represents a shallowing-upward sequence and would therefore be evidence of such sea-level change as opposed to climate change. Similar cycles have been described from areas of similar palaeolatitudes which would indicate that sea-level change was eustatic as opposed to relative. Cyclic climatic change associated with each depositional cycle on the scale of approximately 200,000 years (Section 4.3.1) is therefore highly unlikely.

6.9 Long-term climate change

The different lines of evidence when evaluated together are interpreted as showing that within the Mid Carboniferous there is a prolonged period of aridity / semi-aridity from the Late Asbian to the Mid Brigantian lasting approximately 1Ma. The remainder of the study period is consistent with a tropical, humid climate. The evidence for long-term climate change is summarised in Table 6-1. Climate change on a scale of 1Ma or more that may or may not be cyclic, is regarded as long-term climate change (Cecil 1990).

6.9.1 Comparison with areas of similar palaeolatitude

It is proposed that the long-term climate change witnessed during the Mid Carboniferous is global in scale as opposed to local or regional as there is evidence to suggest that a similar arid / semi-arid phase can be found in areas of similar palaeolatitude during this time. Andrews & Nabi (1998) have described the Asbian of the Cockburnspath Outlier of East Lothian and North Berwickshire as being largely warm and humid although there seems to have been a brief return to semi-arid conditions in the Late Asbian. This is known from the presence of nodular calcrete similar to those found at Spittal / Scremerston. The Upper Viséan Aghagrania Formation of Leitrim and Cavan, Eire, contains evaporitic beds within a limestone,

	Long-term Climate Change	
	Evidence	**Interpretation**
Coal Distribution	Coal recorded within cycles at start of Asbian but no coal present at Asbian/Brigantian boundary. Increase of coal within each cycle from Early Brigantian.	Change from tropical, humid climate to semi-arid at Asbian/Brigantian boundary. Change back to tropical, humid climate at end Brigantian
Sediment Colour	Transition from pale grey hues to red-coloured sediments in Mid Asbian. Period of red coloration extends until Early Brigantian, then transition to pale grey / buff hues.	Humid climate with reducing conditions at start of Asbian. Drier conditions from Mid Asbian to Early Brigantian. Humid climate from Early Brigantian onwards.
Sandstone Provenance	Abundant lithic fragments and reduced amounts of quartz during Asbian period. Remaining time of study period has few lithic fragments and abundant quartz.	More arid climate in sediment source area during Asbian. For rest of study period, a humid climate prevailed in sediment source area.
Fine vs. Coarse Siliciclastic Sediments	Decrease in amount of fine siliciclastic sediments from Early Asbian to Early Brigantian. Increase in amount of fine siliciclastic sediment from Early Brigantian onwards.	Arid or semi-arid climate from Early Asbian to Early Brigantian. Increasingly humid climate from Early Brigantian onwards.
Palaeosoil Analysis	Gleysols and podzols predominant soils at start of Asbian. Pedogenic and groundwater calcretes dominate towards end of Asbian and start of Brigantian. From Early Brigantian onwards variety of soils present.	Climate in Early Asbian was humid but changed to arid or semi-arid in the Late Asbian. This phase lasted until the Early Brigantian, when humid conditions returned.

Table 6-1 Summary table of evidence for long-term climate change within the Mid Carboniferous strata of Northumbria.

dolomite, shale and sandstone succession. The evaporite beds have been compared to present-day tidal flats and their associated shallow lagoons (West *et al.* 1968) and formed during an arid / semi-arid period. The Upper Mississippian Macumber Formation of the Maritimes Province, Canada accumulated at similar palaeolatitudes to deposits in the U.K. during the Mid Carboniferous and displays cyclic carbonates and evaporites within red, terrigenous siliciclastic sediments. The interpretation of this formation is of shoreline carbonates analogous to the modern-day Arabian Gulf (Schenk 1967) indicating an arid / semi-arid phase at approximately the same time as that found here. One other area which was not at a similar palaoelatitiude to deposits in the U.K. but provides evidence of major climate change during this time is that of eastern Australia. There is evidence of cooling in the Late Viséan known from changes in Carboniferous brachiopod zones (Roberts 1981). There is a lowering of faunal diversity and increased levels of endemism indicating not only a cooling period but a corresponding eustatic drop in sea level (Roberts 1981).

6.9.2 Proposed mechanisms for long-term climate change

The origin of the global change in climate experienced during the Mid Carboniferous is a topic of considerable debate, with three main factors suggested as causal mechanisms: changes in atmospheric CO_2 levels (Moore 1983; Crowley *et al.* 1987; Berner 1990; Crowley & Baum 1992); Gondwana glaciation (e.g. Crowley *et al.* 1987; Powell & Veevers 1987; Wright & Vanstone 2001); the changing continental configuration and docking of Gondwana and Laurasia (e.g. Van der Zwan *et al.* 1985; Wright 1990), or a combination of all of the above factors.

Changing atmospheric CO_2 levels play a fundamental role in climatic variations (Crowley & Baum 1992), with very low values of atmospheric CO_2 present from the Late Palaeozoic (Figure 6-11; Crowley *et al.* 1987; Berner 1990; Crowley & Baum 1992). The reason for such a decrease is most likely the expanding vegetation of the Devonian / Carboniferous world which would have placed a demand upon the atmospheric CO_2 to build the vegetation biomass (e.g. Moore 1983). Perhaps one of the most important effects resulting from a decrease in atmospheric CO_2 was that it may have led to glacial expansion or even caused the formation of the Gondwanan ice sheets (Crowley *et al.* 1987).

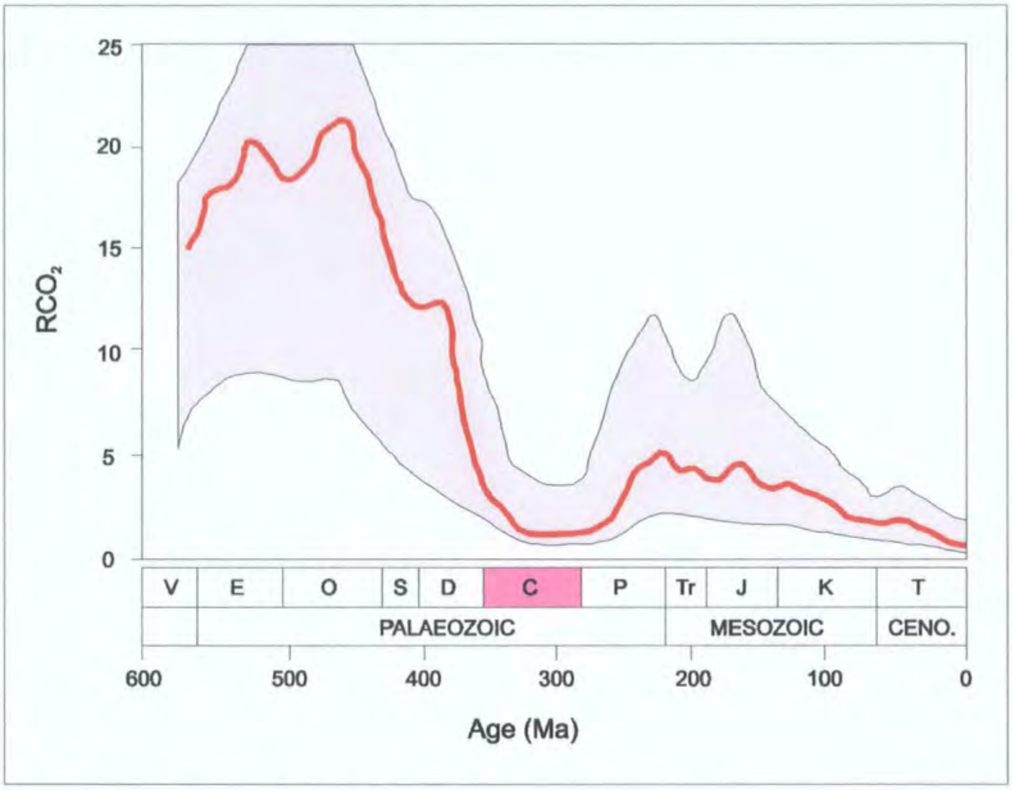


Figure 6-11 Atmospheric CO_2 versus time. The parameter RCO_2 is the ratio of the mass of CO_2 in the atmosphere at some time in the geological past to the present. The Carboniferous period has been highlighted in pink. Adapted from, Berner (1997).

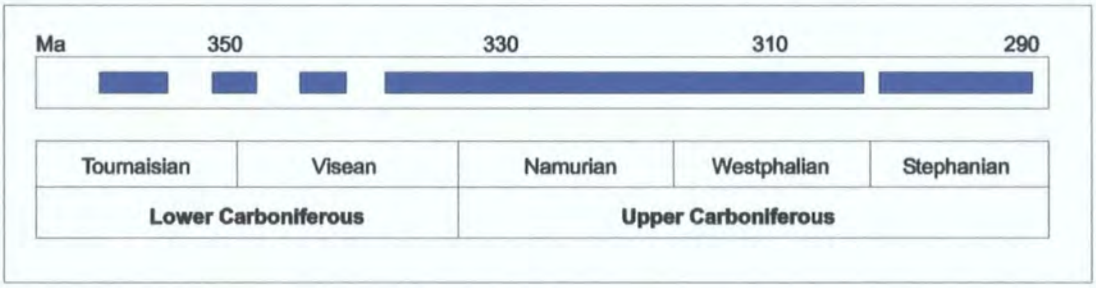


Figure 6-12 Records of glaciation for Europe from the geological record. Blue line represents glacial occurrence. Adapted from, Bruckschen *et al.* (1999).

The gradual northwards shift of the whole of the Laurasian continent would have had a profound effect on climatic zones during the Mid Carboniferous. Today, major climatic belts are more or less sub-parallel to the equator (Figure 2-8) with the Doldrum belts being between 5°S and 5°N containing lush rainforest and a wet, tropical climate. To the south and north of this the climate is more frequently dry, with extended evaporites on land and along shallow seas (Bless *et al.* 1984). It is thought that the same situation existed through geological time (Bless *et al.* 1984), therefore a northward drift of the Laurasian continent could have produced a shift in climatic zones (Van der Zwan 1985). It has been postulated, however, that the palaeoclimatic equator was offset northwards during the Carboniferous possibly due to a difference in the heat budget because of the larger size of the Gondwanan landmass (Van der Zwan *et al.* 1985); such an offset could have produced a drier climatic zone over present-day Western Europe. Another effect of the changing continental configuration was caused by the rotation of the Gondwanan supercontinent leading to the presence of more land in higher latitudes and increasing the area in which snow could accumulate and thereby increasing the size of the Gondwanan icesheet (Crowley & Baum 1992).

Perhaps the most dramatic factor affecting and resulting from climate change during the Mid Carboniferous was that of the Gondwanan glaciation. Various phases of glacial activity have been recognised during the Carboniferous (Figure 6-12). Bruckschen *et al.* (1999) suggested that glacial episodes were present from the Late Tournaisian and the Mid to Late Viséan and that they were short sharp glacial episodes prior to the a longer term cooling leading to the main Gondwanan glaciation (Figure 6-12). One of these short sharp glacial episodes may be recorded within the Mid Carboniferous of Northumbria. The duration of the long-term climate change within the Mid Carboniferous described within this Chapter and the occurrence of this phase in the Mid to Late Viséan (Asbian) would support this proposal. With such periods of glaciation came major fluctuations in eustatic sea-level and climate, although Isbell *et al.* (2003) are doubtful as to whether glaciation was indeed responsible for such major fluctuations in sea-level.

Evidence for a significant fall in eustatic sea-level is presented elsewhere in this thesis in Section 4.3.3, and has also been suggested in Section 6.1, and indicates that at approximately the same time as the proposed arid / semi-arid phase, sea-level fell by a substantial amount. Since the change in climate occurred in association with a eustatic sea-level fall it is therefore consistent with glacial-related climate change. Aridity is a common effect of the onset of a glaciation and is most commonly recorded from equatorial regions. During the last glacial maximum the Kalahari Desert was subject to a major increase in size and the rainforests of the Congo and Guinea saw a marked reduction (Dawson 1992). Other evidence of aridity in equatorial regions is found from aeolian detritus in deep-sea sediments from the last glacial maximum, and a change from a warmer, wetter climate in equatorial West Africa towards a drier climate was recorded in pollen records from ODP core from the preliminary stage of the last glaciation (Leroy & Depont 1997).

Other periods of aridity have been recorded from earlier in the Carboniferous (Wright 1990; Vanstone 1991). Wright (1990) described a semi-arid climate intermittent with humid periods from the start of the Carboniferous in southern Britain. There was a gradual change to a more humid climate later in the Viséan, then during the Asbian and Brigantian, frequent if not continuous phases of aridity (Wright 1990). The reasons presented for such arid phases include a palaeoclimatic equator offset producing a drier climate zone over Western Europe, and the presence of monsoonal circulation during Tournaisian equatorial Laurasia. The occurrence of more than one arid phase during the Early Carboniferous could be associated with phases of glacial activity, a phenomenon also recorded during the last glaciation (Leroy & Duport 1997).

6.10 Seasonal climate during the Mid Carboniferous

Increased seasonality in the Late Brigantian and Early Pendleian is seen throughout the region but has not been correlated elsewhere. The effects of seasonality are found within the siliciclastic component of each cycle making it extremely difficult to correlate between horizons. The only assumption that can be made therefore is that this effect is at least regional in scale.

6.10.1 Causal mechanisms for seasonal climate

Seasonality can be caused by various factors such as monsoonal circulation and the affects of Milankovitch cycles. Monsoonal circulation is thought to have ceased by the Early Namurian (Falcon-Lang 2000) which is where most of the evidence for seasonality is found in Northumbria, so is probably not the controlling factor on the seasonality at this stage. Obliquity cycles of the earth's orbit determine the degree of seasonality and precessional cycles of the earth's orbit control the timing of seasons (Weedon 1993). These cycles could have been enhanced during this period due to the presence of Gondwanan ice sheets and therefore produced enhanced seasonality.

6.11 Summary

Long-term climate change is found within the study area as climate changes from a tropical humid climate to a semi-arid/arid climate before returning again to a tropical humid climate. The semi-arid/arid period lasts approximately 1Ma, and starts in the Late Asbian and lasts until the Mid Brigantian. The proposed causal mechanism for such a long-term climate change could be changes in CO_2 levels, changing continental configuration or Gondwanan glaciation and although all three mechanisms are intricately linked, Gondwanan glaciation is inferred here to be the most likely control on climate change. The main reason for this conclusion is the comparison with equatorial regions during the last glaciation which also display a pronounced aridity. Other evidence includes the major fall in eustatic sea-level which would be associated with the onset of a major glaciation.

In addition to long-term climate change there is also evidence of seasonality within the siliciclastic component of some cycles, concentrated within sediments of Late Brigantian and Early Pendleian age. Seasonality can be produced by various factors such as monsoonal circulation and glacio-eustasy associated with Milankovitch. Gondwanan glaciation has already been seen to have had a profound impact on the mid Carboniferous climate it is therefore possible that it could have had a further influence on climate by producing enhanced seasonality.

Many of the results and interpretation presented within this Chapter such as coal distribution (Section 6.3), sediment colour (6.4) and sandstone provenance (6.5) are tentative and inconclusive on their own. It should be highlighted however that the majority of the results indicate a similar period of long-term climate change, and that by combining the results within this Chapter a worthwhile and conclusive dataset has been produced.

Chapter Seven

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Chapter 7 - Stable Isotope Geochemistry of the Marine Limestones

7.1 Introduction

The Mid Carboniferous cyclic deposits contain approximately 20% carbonate rocks generally formed as a result of shallow-marine deposition on a carbonate platform (Section 3.4). The carbonate component of each 'Yoredale cycle' enables the use of carbon and oxygen geochemical analysis, a technique often used to assess variations in palaeoceanography and / or palaeoclimate.

Carbon isotopes in carbonates are recorded as the precipitation of various carbonate minerals, either by organisms or inorganically, which involves a fractionation of carbon isotopes relative to total dissolved carbon. Carbonate minerals can be used to monitor changes in the carbon isotopes of total dissolved carbon in the solutions from which they precipitate (Anderson & Arthur 1983) and are essentially used to look at levels of productivity and to identify times when the storage of organic material is particularly enhanced (e.g. Saltzman *et al.* 2004).

The study of oxygen isotopes is useful since oxygen isotope fractionation in carbonates is temperature dependent (e.g. Anderson & Arthur 1983) and has been used as a proxy to document many more recent climatic and palaeoceanographic events.

Variations in carbon and oxygen isotopic ratios can yield valuable information regarding palaeoclimate and palaeoceanography but their uses in rocks of Palaeozoic age and older have been restricted. Oxygen isotopes are particularly susceptible to post-depositional repartitioning due to the high water / rock ratios of diagenetic systems in terms of their oxygen budget (e.g. Banner & Hanson 1990). Carbon isotopes are by comparison much less susceptible, but their reliability in rocks of this age and older is still tentative.

The aims of this chapter are therefore not only attempt to assess the variations in carbon and oxygen isotope ratios in relation to palaeoceanography and palaeoclimate, but also to evaluate any post-depositional alteration on such isotope values.

7.2 Sample Collection

More than 120 samples of brachiopods or brachiopod-bearing limestone distributed throughout the study area were collected, ranging in age from Early Asbian to Late Pendleian (Figure 7-1). Brachiopod samples were collected as they are composed of low-Mg calcite which is the most stable form of marine $CaCO_3$ (Al-Aasm & Veizer 1982) and therefore less susceptible to diagenetic alteration. Whole-rock limestone samples were collected from very fine-grained argillaceous marine limestones, once again to minimise the possibility of diagenetic alteration. Samples were collected from both outcrop and borehole material. The locations of samples collected have been marked on the sedimentary logs in Appendix 2. A database of the geochemical results can be seen in Appendix 6. Whole-rock limestone results can be seen in A6.1 and the brachiopods results can be seen in A6.2. In each case the results are further subdivided into localities of where samples were collected.

7.3 Methodology

Brachiopod shells were identified to species level where possible. Thin sections of the brachiopod shells of ~30μm thickness were made and examined for preservation of shell structure and luminescence using a petrographic microscope and a cathodoluminescence stage. Those shells with well preserved microstructure (Figure 7-2) and non-luminescent shells were selected for further analysis as they displayed little or no signs of diagenetic alteration (Figure 7-3). Care was taken to remove any adhering cement and / or matrix by scraping clean each selected brachiopod shell with a scalpel under a binocular microscope. The clean shell was then powdered using a mortar and pestle.

Whole rock limestone samples were visually assessed for the presence of excessive organic material by examining the overall colour of the limestone. Those with a very dark grey to dark grey coloration were interpreted as containing excessive levels of organic material. Samples with excessive levels of organic material were immersed in 5% NaOH.Cl overnight to remove any organic material that may influence the isotopic results by reflecting the isotopic values of organic carbon as opposed to marine carbon. All samples, whole-rock limestone with and without excessive organic material, were powdered using a mortar and pestle.

Figure 7-1 Map of sample collection sites for stable isotope analyses.

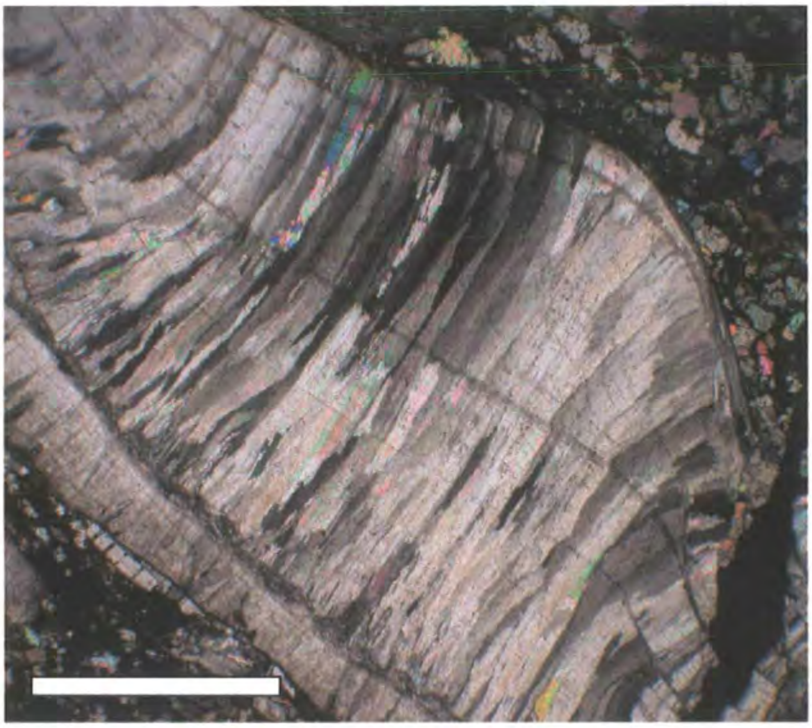


Figure 7-2 Photomicrograph of longitudinal section of Productid shell, displaying well-preserved prismatic structure. Scale bar is approximately 2mm.

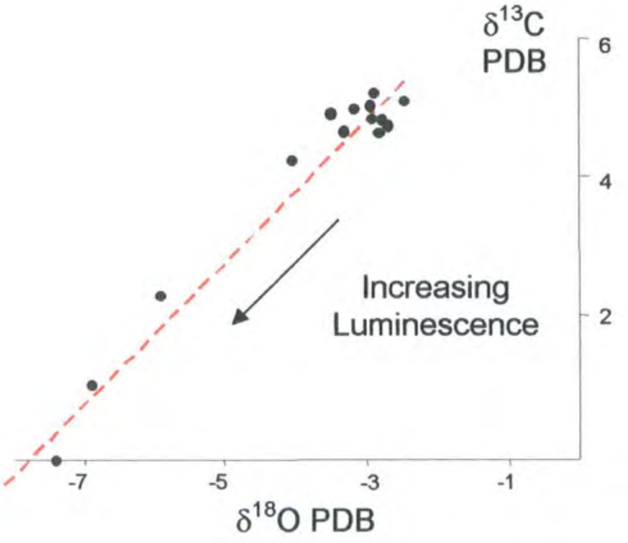


Figure 7-3 Graph showing relationship between $\delta^{18}O$ & $\delta^{13}C$ with luminescence of brachiopod shells. After, Given & Lohmann (1985).

An aliquot of powdered sample (c. 10mg) was time reacted with anhydrous phosphoric acid in vacuo at 16°C for 2 hours. This low temperature / short reaction dissolves the calcite but leaves any dolomite present unreacted. The CO_2 liberated was separated from water vapour and collected for analysis.

Measurements were made on a VG Optima mass spectrometer. Overall analytical reproducibility for the samples was normally better than 0.1 for $\delta^{13}C$ and $\delta^{18}O$. Isotope values are reported as per mil deviations of the isotopic ratios ($^{13}C/^{12}C$ and $^{18}O/^{16}O$) from standards (VPDB for carbonates).

All geochemical analyses were carried out at the NERC Isotope Geoscience Laboratory (NIGL).

7.4 Stable Isotope Analysis

The results of carbon and oxygen stable isotope analysis are presented in Figures 7-4 to 7-8. Figure 7-4 shows the results of brachiopod shell analysis. Figures 7-5, 7-6 and 7-7 show the results of whole-rock limestone analysis from each Mid Carboniferous time period, Asbian, Brigantian and Pendleian respectively, from the study area. In the case of Figures 7-5, 7-6 and 7-7, red data points represent analyses from the Alston Block whilst blue data points represent analyses from the Northumberland Basin (including the Tweed Basin and Cheviot Block). Figure 7-8 shows the combined results from all of the time period represented. In each case $\delta^{18}O$‰ results have been plotted against $\delta^{13}C$‰.

7.4.1 Brachiopod shell data

Brachiopod shell isotope values are displayed in Figure 7-4. Brachiopod shell $\delta^{13}C$ values lie within the range 3.7‰ to -2.8‰ and $\delta^{18}O$ values in the range -4.1‰ to -9.7‰.

There is no clear compositional difference between those samples taken from the Alston Block (five analyses) and those from the Northumberland Basin (fourteen analyses).

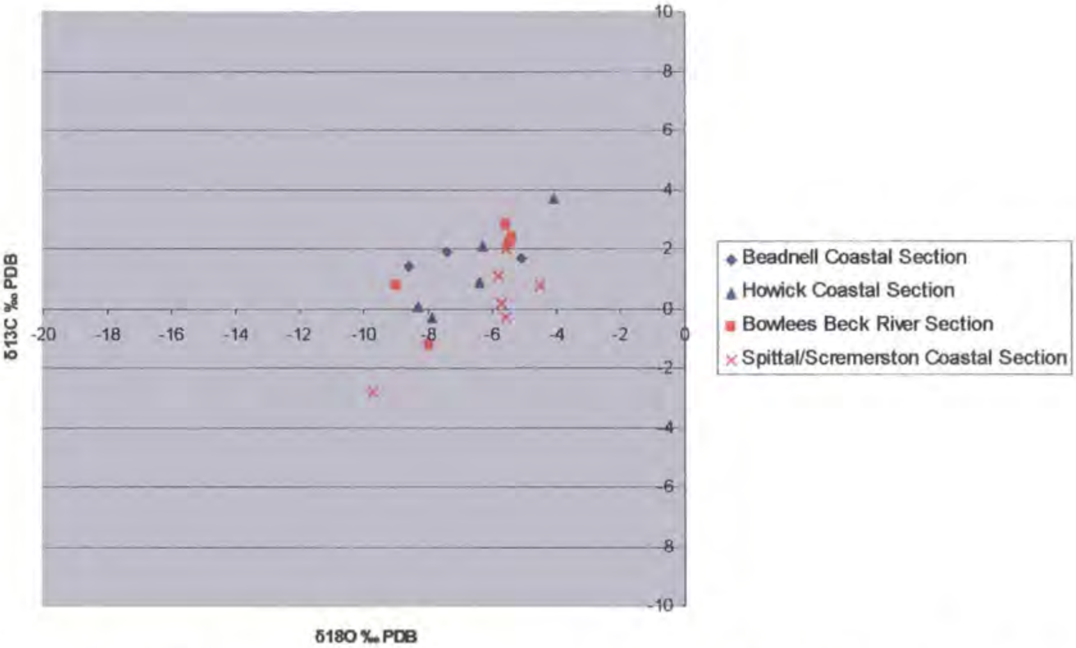


Figure 7-4 Bivariate plot of Productid brachipod shell $\delta^{18}O$ and $\delta^{13}C$ values from the Mid Carboniferous succession of Northumbria. A key has been provided to indicate which locality samples have been collected from. Samples in blue are from the Northumberland Basin whilst those in red are from the Alston Block.

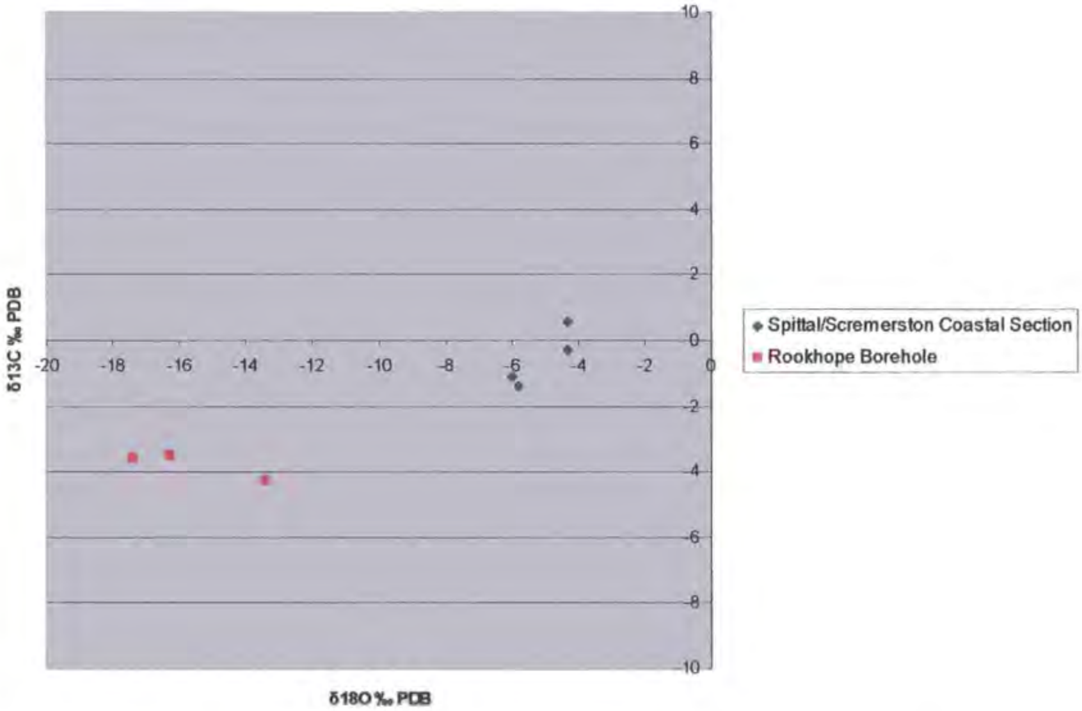


Figure 7-5 Bivariate plot of Asbian whole-rock limestone $\delta^{18}O$ and $\delta^{13}C$ values from the Mid Carboniferous succession of Northumbria. A key has been provided to indicate which locality samples have been collected from. Samples in blue are from the Northumberland Basin whilst those in red are from the Alston Block.

The range of isotopic values is much less than those of the whole-rock limestone analyses. Both the brachiopod shell $\delta^{13}C$ and $\delta^{18}O$ values are the heaviest of the entire data set.

7.4.2 Asbian whole-rock limestone data

The Asbian whole-rock limestone results ate displayed in Figure 7-5. Asbian $\delta^{13}C$ values for whole-rock limestone lies within the range 0.6‰ to -4.3‰ and $\delta^{18}O$ values in the range -4.3‰ to -14.6‰ (six analyses).

There is a significant variation between the Alston Block and the Northumberland Basin. The $\delta^{13}C$ values for the Alston Block lie within the range -3.5‰ to -4.3‰ (three analyses) and the range for the Northumberland Basin lie within the range -13.4‰ to -17.4‰ (three analyses).

The isotopic values from the of the Asbian Alston Block whole-rock limestones show relative ^{13}C-depletion and the $\delta^{18}O$ values are exceptionally light. The isotopic values for the Asbian Northumberland Basin whole-rock limestones however are still $\delta^{18}O$ light but not to the same extent and they are not ^{13}C-enriched.

The Asbian Alston Block whole-rock limestone $\delta^{13}C$ and $\delta^{18}O$ compositions are comparable with those of the Brigantian Alston Block whole-rock limestones. The $\delta^{13}C$ and $\delta^{18}O$ values for the Asbian Northumberland Basin are comparable to those of the Brigantian Northumberland Basin and to the brachiopod samples for the entire study area.

7.4.3 Brigantian whole-rock limestone data

The Brigantian whole-rock limestone results are displayed in Figure 7-6. Brigantian $\delta^{13}C$ values for whole-rock limestone lie within the range 2.8‰ to -6.9‰ and $\delta^{18}O$ values in the range -4.3‰ to -16.7‰ (fifty-one analyses).

There is some variation between the Alston Block and the Northumberland Basin. The $\delta^{13}C$ values for the Alston Block lie within the range 1.2‰ to -6.9‰ (twenty-five analyses) with the range of values for the Northumberland Basin lying between 4.8‰ and -2.6‰ (twenty-six analyses). The $\delta^{18}O$ values for the Alston Block lie within the

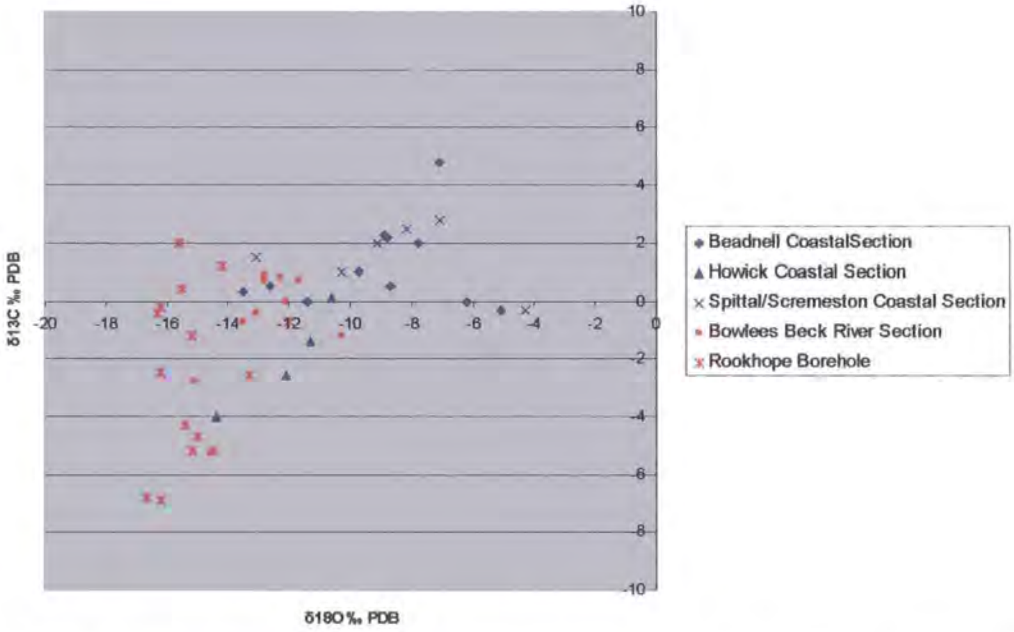


Figure 7-6 Bivariate plot of Brigantian whole-rock limestone $\delta^{18}O$ and $\delta^{13}C$ values from the Mid Carboniferous succession of Northumbria. A key has been provided to indicate which locality samples have been collected from. Samples in blue are from the Northumberland Basin whilst those in red are from the Alston Block.

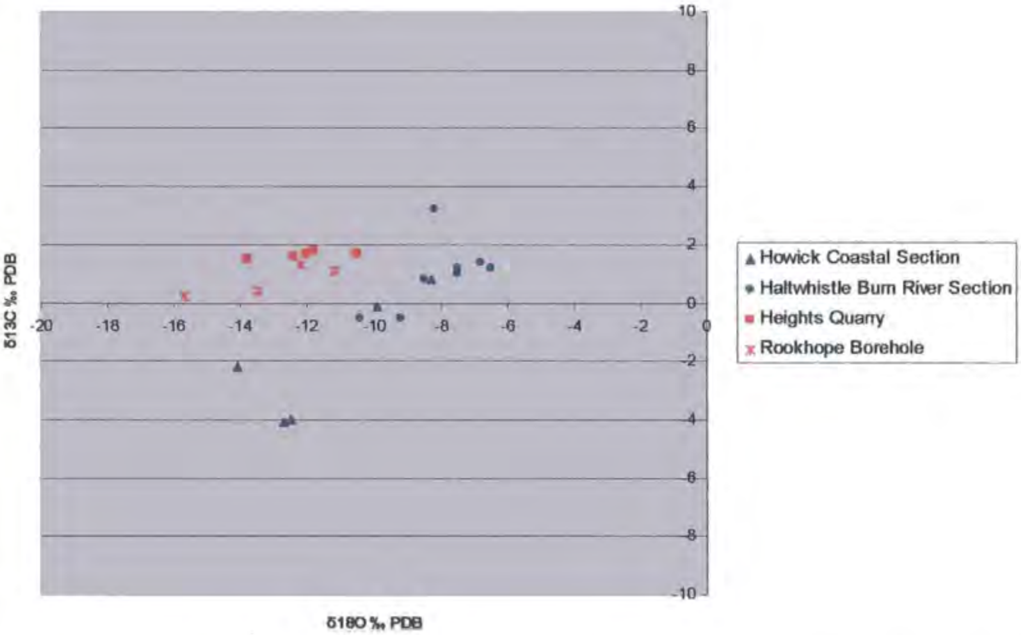


Figure 7-7 Bivariate plot of Pendleian whole-rock limestone $\delta^{18}O$ and $\delta^{13}C$ values from the Mid Carboniferous succession of Northumbria. A key has been provided to indicate which locality samples have been collected from. Samples in blue are from the Northumberland Basin whilst those in red are from the Alston Block.

range -10.3‰ to -16.7‰ whilst the values for the Northumberland Basin lie within the range -4.3‰ to -14.3‰.

The $\delta^{13}C$ values for the Alston Block show much more ^{13}C-depletion than the Asbian whole-rock limestone for the Alston Block. Those with the greatest ^{13}C-depletion were obtained from the Rookhope Borehole dataset. The $\delta^{18}O$ values are also exceptionally light but are comparable with those from the Asbian Alston Block whole-rock limestone analyses. With the exception of the Howick Coastal Section samples, the Northumberland Basin analyses show little ^{13}C-depletion and the $\delta^{18}O$ values are slightly heavier than those of the Brigantian Alston Block whole-rock values. The Brigantian Northumberland Basin whole-rock limestone values are comparable with the $\delta^{13}C$ and $\delta^{18}O$ values for the Asbian Northumberland Basin whole-rock limestones and with the brachiopod shell values for the whole study area.

7.4.4 Pendleian whole-rock limestone data

The Pendleian whole-rock limestone results are displayed in Figure 7-7. Pendleian $\delta^{13}C$ values for whole-rock limestone lie within the range 3.2‰ to -4.1‰ and $\delta^{18}O$ values lie within the range -6.5‰ to -15.7‰ (twenty-seven analyses).

There is little variation between the Alston Block and the Northumberland Basin. The $\delta^{13}C$ values for the Alston Block lie with the range 1.8‰ to 0.2‰ (nine analyses) with the range of values for the Northumberland Basin lying between 3.2‰ to -4.1‰ (eighteen analyses). The $\delta^{18}O$ values for the Alston Block lie within the range -10.5‰ to -15.7, with the range of values for the Northumberland Basin lying between -6.5‰ and -14.1‰.

The $\delta^{13}C$ values for the Alston Block show no ^{13}C-depletion in the Pendleian whole-rock limestone dataset. The Northumberland Basin samples have a much greater $\delta^{13}C$ range, but the values are generally much more ^{13}C-depleted than those of the Alston Block. The $\delta^{18}O$ values for both the Alston Block and the Northumberland Basin are particularly light but the Northumberland Basin values being relatively heavier. The exceptions of this are three samples from Howick Coastal Section and four samples from Haltwhistle Burn River Section.

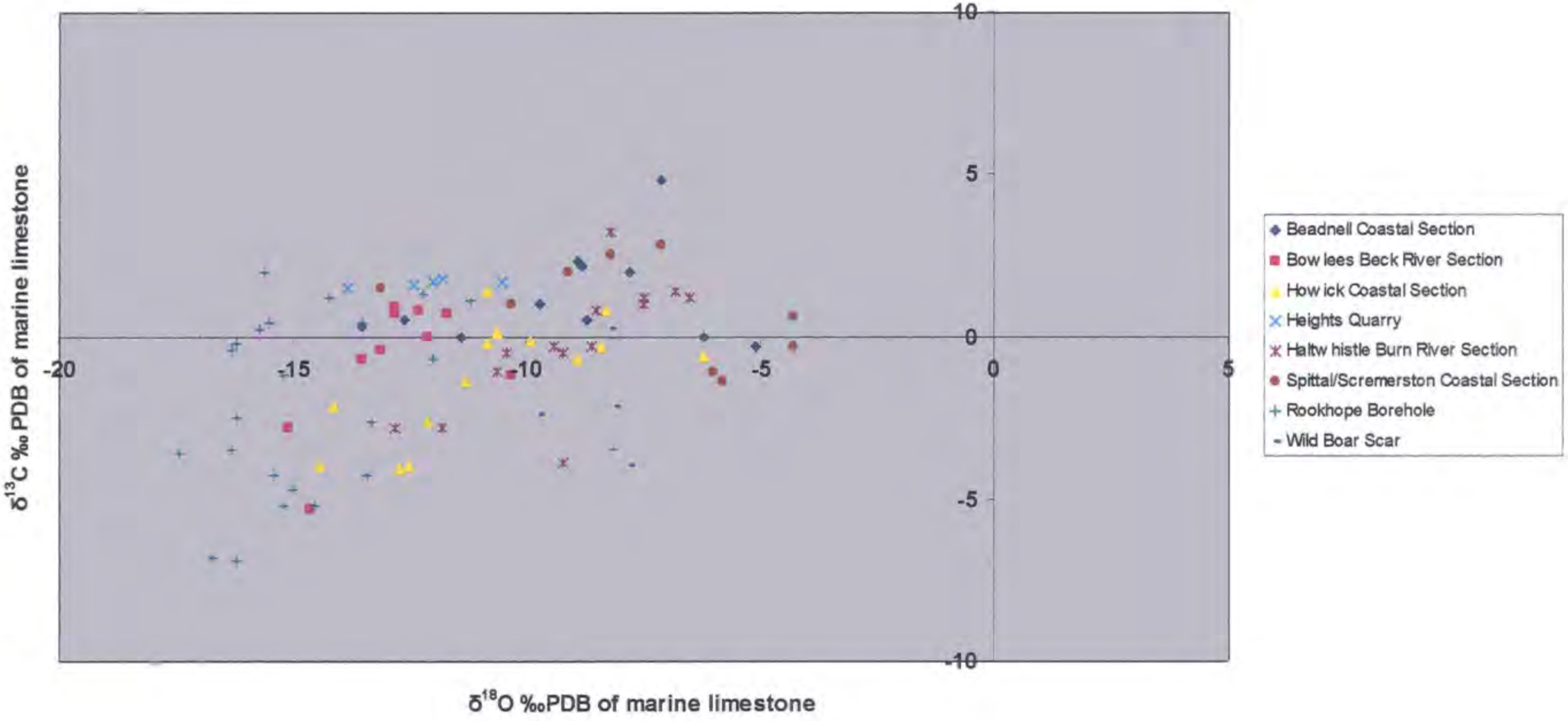


Figure 7-8 Bivariate plot of whole-rock limestone $\delta^{18}O$ and $\delta^{13}C$ values from the Mid Carboniferous succession of Northumbria. A key has been provided to indicate which locality samples were collected from.

The Pendleian Northumberland Basin whole-rock limestone $\delta^{13}C$ and $\delta^{18}O$ compositions are comparable to those of the Brigantian Northumberland Basin whole-rock limestones.

7.5 Stable Isotope Interpretation

The oxygen and carbon stable isotope analyses of the Mid Carboniferous limestone of Northumbria generally show remarkably light $\delta^{18}O$ values. The $\delta^{13}C$ values vary greatly. In order to assess whether these results can be used to gain any useful palaeoclimate / palaeoeceanography information then it would be useful to look at the original source of these fluids, the Mid Carboniferous seawater.

7.5.1 Brachiopod shells and Mid Carboniferous sea water composition

The brachiopod shells analysed and presented in Figure 7-4 were selected as they were apparently unaltered and should therefore yield original seawater isotopic values. The shells were non-luminescent but this method of testing for alteration may be unreliable (Walkden & Williams 1991).

The heaviest and therefore the least altered $\delta^{18}O$ values from the brachiopod shells is -4.1‰. Similar studies have derived values of -1.5‰ to -2‰ (Brand 1982) and -1.5‰ (Meyers & Lohmann 1985) although the $\delta^{18}O$ values of Mid Carboniferous sea water may be as low as -6‰ (Dickson & Coleman 1980). The $\delta^{18}O$ values of brachiopod shells from the study area may therefore be close to original seawater composition.

The heaviest and once again least altered $\delta^{13}C$ value of the brachiopod shells is 3.7‰ and suggests slightly heavier values than the original marine Mid Carboniferous signal suggested as being approximately 1.5‰ (Neilsen *et al.* 2000).

7.5.2 Asbian whole-rock limestone

The $\delta^{18}O$ and $\delta^{13}C$ values of the Asbian Alston Block whole-rock limestones deviate substantially from the original Mid Carboniferous seawater signal (Section 7.5.1), as they are significantly lighter. Such light $\delta^{18}O$ and $\delta^{13}C$ values are consistent with those obtained from limestone subjected to interaction with fluids at elevated temperatures during burial (e.g. Dickson *et al.* 2001).The $\delta^{18}O$ and $\delta^{13}C$ values from the Asbian Northumberland Basin whole-rock limestones appear to be consistent with those of original Mid Carboniferous seawater composition.

It should be noted that there were only three analyses from each of the Alston Block or the Northumberland Basin and therefore the results are tentative for this time period due to lack of data.

7.5.3 Brigantian whole-rock limestone

Brigantian Alston Block whole-rock limestone values vary greatly from the original Mid Carboniferous seawater composition described in Section 7.5.1 and the majority of the samples have light $\delta^{13}C$ and $\delta^{18}O$ compositions. These values are consistent with interaction with fluids at elevated temperatures associated with deep burial as were those values from the Asbian Alston Block whole-rock limestone (Section 7.5.2).

Brigantian Northumberland Basin whole-rock limestone values reveal light $\delta^{18}O$ values but enriched ^{13}C values. These values differ from those in the Alston Block and may therefore not suggest alteration by deep burial. There is little alteration of $\delta^{13}C$ from the original seawater composition so these results may have preserved the original signal, but the light $\delta^{18}O$ values certainly reflects interaction with fluids at elevated temperatures (Walkden & Williams 1990).

7.5.4 Pendleian whole-rock limestone

Pendleian Alston Block whole-rock limestone $\delta^{13}C$ values are similar to those of the original Mid Carboniferous seawater signal (Section 7.5.1) but the $\delta^{18}O$ values are very light and could indicate the influence of fluids at elevated temperatures.

Pendleian Northumberland Basin whole-rock limestone values are very scattered and they indicate two signals recorded within the rocks; there are samples with very light $\delta^{13}C$ and $\delta^{18}O$ values indicating the influence of elevated temperatures associated with deep burial, and there are samples that fall within the meteoric diagenesis signal values. Those with a meteoric diagenesis signal value are those that are depleted in both ^{13}C and ^{18}O but to a lesser extent than burial (Nielsen et al. 2000). The light $\delta^{13}C$ values in meteorically-altered limestones are attributed to the effects of soil-derived

CO_2, whilst the light $\delta^{18}O$ values are too light to suggest precipitation from seawater and reflect growth within an ^{18}O-depleted fluid such as meteoric water (e.g. Allan & Matthews 1982).

7.5.5 Interpretation Summary

The brachiopod shells analysed from the study area show the least alteration out of all the samples and their $\delta^{13}C$ and $\delta^{18}O$ are similar to those for original Mid Carboniferous seawater composition. Asbian whole-rock limestone values are also similar to those of original Mid Carboniferous seawater composition but the small dataset from this period makes it impossible to comment further.

Samples analysed from the Alston Block during both the Asbian and Brigantian periods show evidence of interaction with fluids associated with deep burial. There is some evidence for this in Pendleian Northumberland Basin whole-rock limestone samples also.

Elevated temperatures not necessarily associated with deep burial have also had an influence on the isotopic compositions of the whole-rock limestones. Brigantian Northumberland Basin whole-rock limestones and Pendleian Alston Block whole-rock limestones both reveal this signal.

There is evidence of meteoric diagenesis from some samples from the Pendleian Northumberland Basin whole-rock limestones.

7.6 Influencing factors

The age of the rocks within the study area mean that the numbers of influencing factors regarding carbon and oxygen stable isotopic compositions are numerous. In this section various hypotheses are outlined regarding the isotopic values obtained from the study area.

7.6.1 Palaeoclimate / palaeoceanography variations

Although some of the samples analysed have shown little alteration from the original Mid Carboniferous seawater composition there are too few to construct any kind of chemostratigraphy plot which would be necessary to investigate variations in palaeoclimate / palaeoceanography. Future work would be beneficial in this field with sample collection being restricted to brachiopod samples but using a much larger dataset.

7.6.2 Elevated temperatures due to burial

Petrographic and vitrinite reflectance studies of Mid Carboniferous coals have been used to examine the heat flow on the Alston Block. Such studies have revealed that rejuvenation of the Weardale granite occurred at depth, perhaps in response to the Hercynian Orogeny, when temperatures were in excess of 185° (Creaney 1980). Ferguson (1984) also supported this idea, as studies of the anomalous amounts of methane gas in Mid Carboniferous limestones on the Alston Block may be a consequence of the prolonged existence of a high geothermal gradient in the area. Increased vitrinite reflectance has been shown to positively correlate with decreasing $\delta^{18}O$ values during the Upper Frasnian and Lower Fammenian (Figure 7-9), which may be what is seen on the Alston Block.

Deep burial of Mid Carboniferous sediments would mean that they would have been subjected to the increased temperatures caused by rejuvenation of the Weardale granite. As the Weardale Granite is found beneath the Alston Block this may explain why the isotopic values are different between the Alston Block and the Northumberland Basin.

Fission track analysis of the Carboniferous strata of Northern England has displayed annealing leading to partial overprinting, or a complete resetting of the fission track record. This has been attributed to some form of thermo-tectonic event, either due to residence at temperatures in the range of 70 to 125°C over many 10's of Ma, or due to a short –lived heat pulse associated with an event such as the Tertiary Igneous Province which occurred to the North-West (Green 1986). Fission track analysis carried out in Eastern Ireland has suggested that heat advection by gravity driven ground water flow followed the Tertiary Uplift about 60Ma, with fluid flow that produced local remagnetisation of the Palaeozoic basement and the overlying Carboniferous limestones (McCulloch 1994). As this study was carried out on the

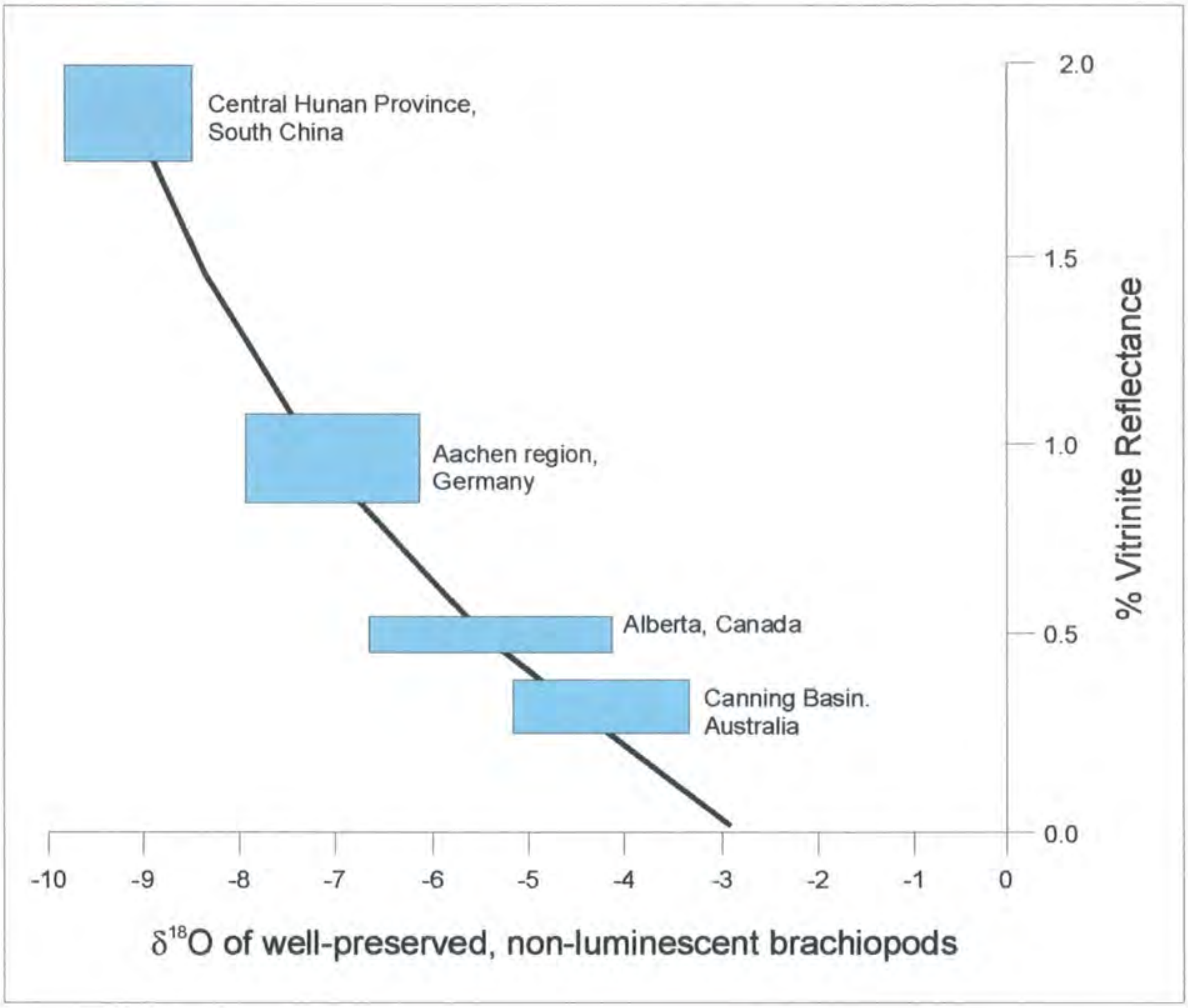


Figure 7-9 Vitrinite reflectance values against $\delta^{18}O$ values for well-preserved, non-luminescent brachiopods of Upper Frasnian to Upper Famennian age from various localities as marked. From, Stephens (2002).

Iapetus Suture Zone transect, which the Northumberland Basin is also thought to overlie (Section 8.2), perhaps this event could have also affected the Mid Carboniferous strata of Northumbria.

7.6.3 Elevated temperatures

The Whin Sill complex was intruded into the Mid Carboniferous country rock during the Late Carboniferous (Johnson & Dunham 2001) and this would undoubtedly have had an influence on fluid flow throughout the area may have produced an elevated heat flow. Studies of the effects of the Whin Sill upon surrounding country rocks have indicated that heat flow only affected those rocks immediately adjacent to the intrusion (Creaney 1980).

The Whin Sill and the associates Whin Dykes are found throughout the study area at various localities and at a range of horizons (Figure 7-10), but are not continuous across the area. This could account for not only the isotopic values indicating interaction with fluids associated with elevated temperatures but also for the lack of restriction of this feature to one particular time period or area. One particular area which displays isotopic values indicating interaction with fluids of elevated temperatures is that of Howick Coastal Section. This is of particular interest as the Whin Sill is found at this outcrop (marked on Figure 7-10) where it is referred to as Cullernose Point (Grid Ref.: NU 263188).

Crinoid fragments commonly display the effects of thermal alteration in the form of neomorphic degradation (Folk 1965), a term used when the single plate of calcite that usually forms each crinoid ossicle fragments into many smaller calcite plates. As there are many crinoid fragments within the Mid Carboniferous marine limestones, these were examined in thin section to assess the effects of low-grade metamorphism on the rocks. Numerous crinoid fragments were found to be composed of numerous small calcite plates (Figure 7-11) but as there was no spatial or temporal restriction to such occurrences suggesting that there was either no significant regionwide low-grade metamorphic event or else no variation has been recorded associated with a low-grade metamorphic event.

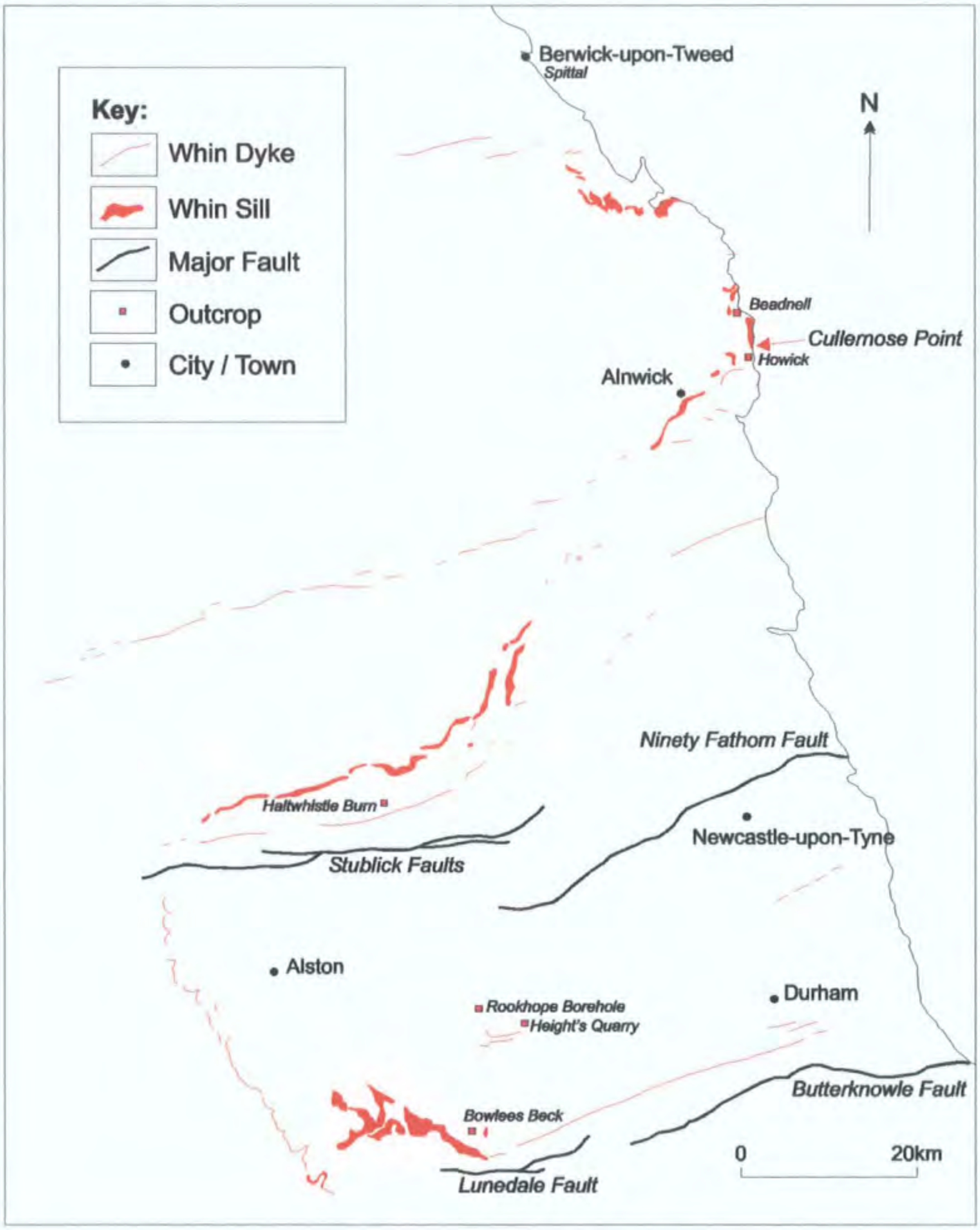


Figure 7-10 Map showing the outcrop of the Whin Sill and associated dykes in Northumbria. Outcrop localites and major faults have also been indicated. After, Randall, (1995).

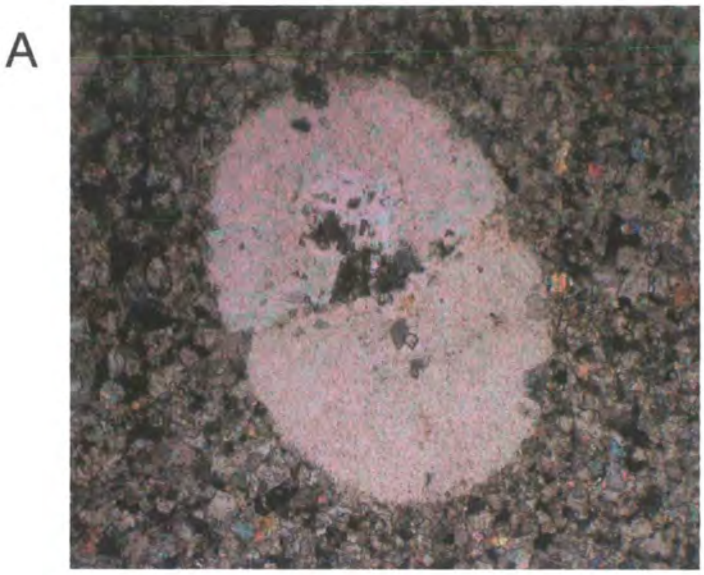
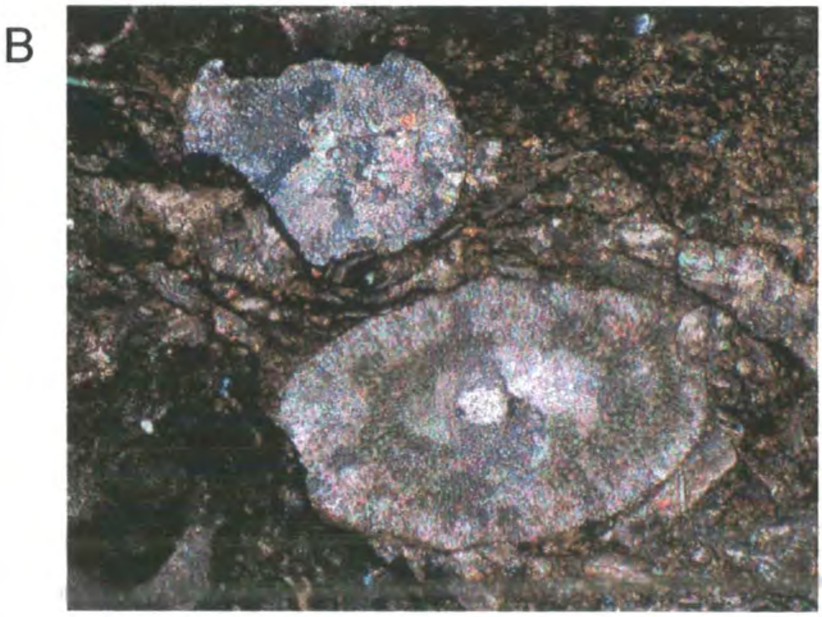


Figure 7-11 Photomicrographs of unaltered crinoid ossicle (A) and altered crinoid ossicle (B). Photomicrograph A is from Scar Limestone (Brigantian) at Bowlees Beck, width of crinoid ossicle is approximately 0.7mm. Photomicrograph B is from Sandbanks limestone (Brigantian) from Beadnell, width of crinoid ossicle is approximately 0.5mm.



7.6.4 Meteoric diagenesis

Meteoric diagenesis only occurs in samples from the Pendleian Northumberland Basin whole-rock limestones. Meteoric diagenesis normally occurs very shortly after diagenesis and is therefore commonly overprinted by later fluid flow (Nielsen *et al.* 2000).

The Pendleian period is characterised by larger amounts of terrestrial siliciclastic material than both the Asbian and Brigantian periods and less carbonate production. These limestones could therefore indicate a greater meteoric influence wither by rainwater or freshwater influx occurring shortly after deposition.

7.7 Summary

The marine limestones of Mid Carboniferous Northumbria have yielded valuable information from analysing their oxygen and carbon stable isotopes. Although one of the primary aims of this study was to assess variations in palaeoclimate / palaeoceanography it has not been possible to do so due to the presence of numerous highly altered samples and a lack of unaltered samples.

The majority of the $\delta^{18}O$ samples have been altered and are very light indicating that they are not the original Mid Carboniferous seawater values and they are apparently reset by later fluid flow.

Information has been gained in fluid flow through the area which appears to have been dominated by elevated burial temperatures. This is especially seen in values of the Alston Block where the effects of rejuvenation of the Weardale Granite seem to have heavily influenced the isotopic values of the limestone.

The flow of heated fluids has also undoubtedly been influenced by the intrusion of the Whin Sill complex in the Late Carboniferous. Its lack of restriction to any particular area and horizon means that it could have altered any of the limestones in the area, especially those that are very close to the intrusions.

There is evidence of fluids associated with meteoric diagenesis which have been tentatively been attributed to increasing terrestrial input during the Pendleian period.

It is very clear that this study of carbon and oxygen stable isotopes has surrendered much information on the various fluids affecting the area both during deposition and subsequent to it. It is also clear however that there is still a lot more work that could be carried out within the study area in this field including a detailed diagenetic analysis of the limestones and also a details analysis of the unaltered brachiopods to help investigate any changes in palaeoclimate / palaeoceanography.

Chapter Eight

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Chapter 8 – Tectonic-influenced sedimentation

8.1 Introduction

Investigated in this chapter is the influence that tectonism had upon sedimentation during the Viséan and Namurian periods in Northumbria. The effects of tectonism upon sedimentation during each of the time periods is assessed through studying variations in cycle thickness (Section 8.3.1) and lithofacies variations throughout the region (Section 8.3.2). Local affects of tectonism upon sedimentation are investigated by evaluating the control of local faulting on lithofacies distribution (Section 8.4.1).

8.2 Northern Britain Extensional Province

As stated in Section 2.4, basin formation in Northern Britain was initiated in the Late Devonian to Early Carboniferous (Turner *et al.* 1995). Various theories for basin initiation have been suggested including; megashear resulting from a wide zone of dextral transcurrent faulting which affected the majority of Europe during the Early Carboniferous (Haszeldine 1984), rifting and ocean spreading between Europe and Greenland and the formation of the proto-Atlantic leading to E-W to SW-NE crustal tension (Haszeldine 1989). Most authors have generally accepted the theory of Bott (1976) and Leeder (1982), who inferred that basin formation was a result of tension induced by the closure of the Rheno-Hercynian seaway through northerly migration of a subduction zone located to the south of Britain (Turner *et al.* 1995). The main plate-margin process controlling this development was the formation of a collision type orogenic belt in the Iberia-Armorica-Massif Central region of the Hercynides (Fraser & Gawthorpe 1990). Extension was widespread within the back-arc system with the Northern England extensional province being located some 500km north of the main Rheno-Hercynian back-arc (Fraser & Gawthorpe 1990).

A complex series of extensional basins developed in Northern England with marked asymmetry (Fraser *et al.* 1990), and these exerted a strong structural control on sedimentation (Gawthorpe *et al.* 1989). The location of the basins is attributed to inherited Caledonian weaknesses (Turner *et al.* 1995) with a major crustal shear or thrust zone beneath Northern England (Chadwick & Holliday 1991; Figure 2-4). The largest Carboniferous 'basin bounding' faults lie above and synthetic to this shear zone resulting in the E-W trend of the Northern England Basins (Chadwick & Holliday 1991).

As discussed in Section 2.4 (Figure 2-5), the major basins within the region comprise the Tweed basin to the north, the Northumberland Basin and its westerly continuation to the Solway Basin and the Stainmore Basin to the south (Figure 8-1). The intervening block structures are the Cheviot Axis to the north, the Lake District and Alston Block, and the Askrigg Block to the south. Each of these block structures is underlain by a buoyant low density granite mass, the Cheviot Granite, the Lake District-Weardale Batholith and the Wensleydale Granite respectively (Bott 1983). The presence of such structural features exerted a strong control on sedimentation throughout the Carboniferous period.

8.3 Regionwide effects of tectonics

The study area comprises the Alston Block in the farthest south which is bounded to the south by the Butterknowle Fault. This also marks the boundary with the Stainmore Basin (Bott *et al.* 1984). The Northumberland Basin is immediately north of the Alston Block, the bounding fault between the two structural units is the Stublick-90 Fathom Fault line (Johnson 1984). The northern margin of the Northumberland Basin is much less well defined, but it does lie to the south of the Cheviot Block (Bott *et al.* 1984). Further west, the boundary of the Northumberland Basin is the unconformity between the Carboniferous outcrops and the Silurian greywacke outcrop of the Southern Uplands Basement (Johnson 1984). The Cheviot Block occurs as a distinct shelf between the Northumberland Basin in the south and the Tweed Basin in the north (Figure 8-1). The size of the study area allows assessment of the regionwide effects of tectonism on the Mid-Carboniferous strata. The two main aspects concentrated on are the thickness and lithofacies variations across the region. Each of these features is investigated within each of the relevant Carboniferous time periods (Asbian, Brigantian and Pendleian / Arnsbergian) to assess the temporal variation of tectonic control on sedimentation. The effect of tectonics on Mid-Carboniferous cyclicity is discussed briefly in Section 4.4.

The data for this section have been compiled from a variety of sources. The main source of information is borehole data from the British Geological Survey which are

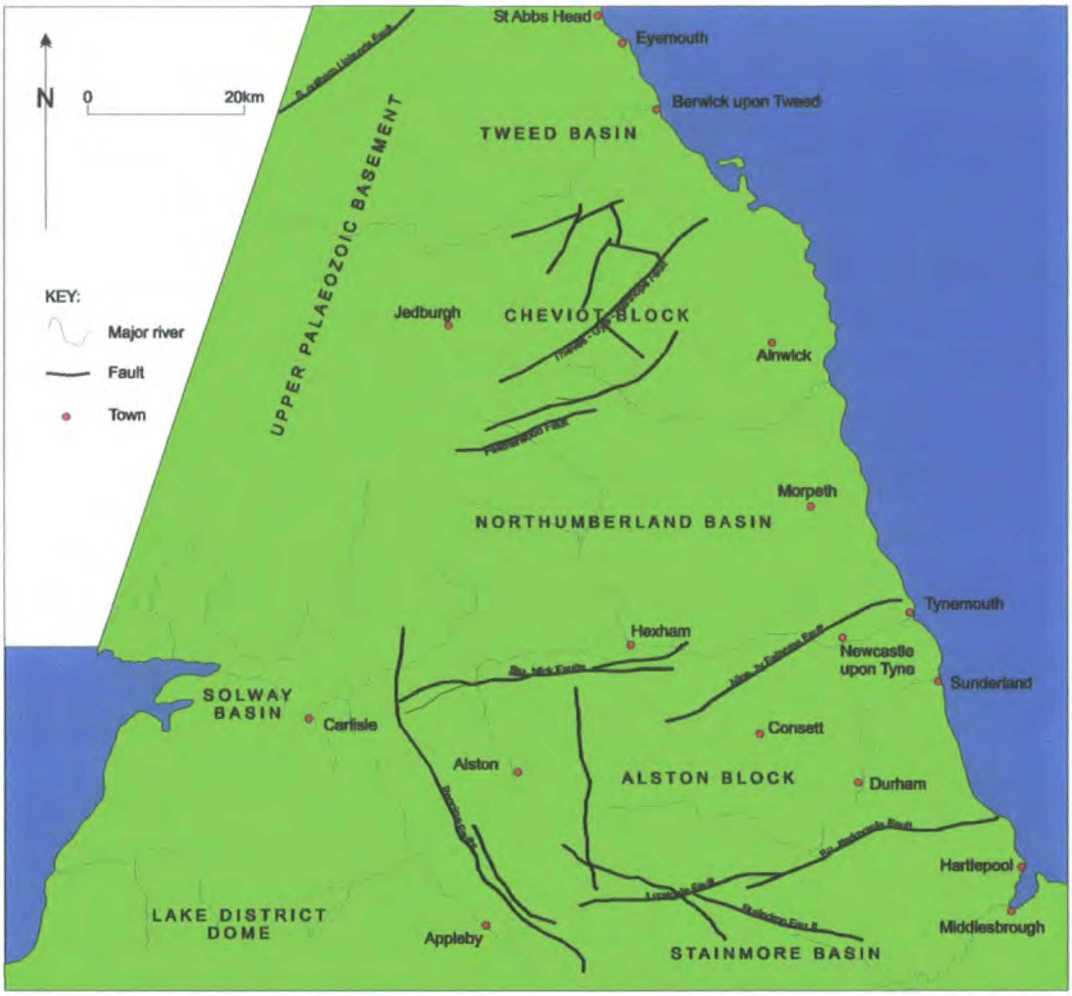

Figure 8-1 Map of Northern England indicating the location of major faults and their relationship to sedimentary basins. Major rivers and towns have also been marked on the map. Modified from Turner *et al.* (1995).

Figure 8-2 Map of study area with location of boreholes and outcrops used throughout this chapter marked.

listed fully in Appendix 1. Borehole records from the study area are numerous due to the coal and mineral exploitation of the region and many date from the latter part of the 19th Century. A total of 28 individual borehole records have been used for this study, each of which has had to be converted into metric measurements where necessary. A great deal of time was spent deciphering some of the colloquial mining terminologies used with regards to rock type, sedimentary structures and limestone names, but a great deal of information has been gained including thickness data for this study and an improved limestone correlation chart (Figure 4-2).

Detailed sedimentary logging throughout Northumbria provided both thickness data and lithofacies information. A small amount of information has been gleaned from published borehole data yielding mostly thicknesses but in a few cases lithofacies information as well. Figure 8-2 presents a map of all boreholes and outcrop locations used in this Chapter.

8.3.1 Thickness Variations

As mentioned in the previous Section (Section 8.3) the information gathered for this study is from BGS borehole data and from field outcrop data. This data has been plotted as basic stratigraphic columns for each Mid Carboniferous time period studied; Asbian, Brigantian and Pendleian/Arnsbergian (Figures 8-4, 8-5 & 8-7). Only siliciclastic and carbonate material has been presented to make it visually easier to identify regional changes in thickness. A basic cross-section of the study area has been provided in Figure 8-3 so that the underlying structure of the area and its effect on regional sedimentary thickness can be visualised.

8.3.1.1 The Asbian Period

The greatest variation in thickness is observed during this period with the thickest succession being some 330m thick and the thinnest succession a mere 26m thick (Figure 8-4). There are no data during this period for the Cheviot Block but nevertheless there is still a noticeable variation between the thickness of strata between the Tweed Basin to the north and the Northumberland Basin to the south. The thickness of the Tweed Basin is 252m in comparison to the 330m of the Northumberland Basin. The thickest succession found is that of the Longhorsley borehole at 330m, near the centre of the Northumberland Basin although there are few

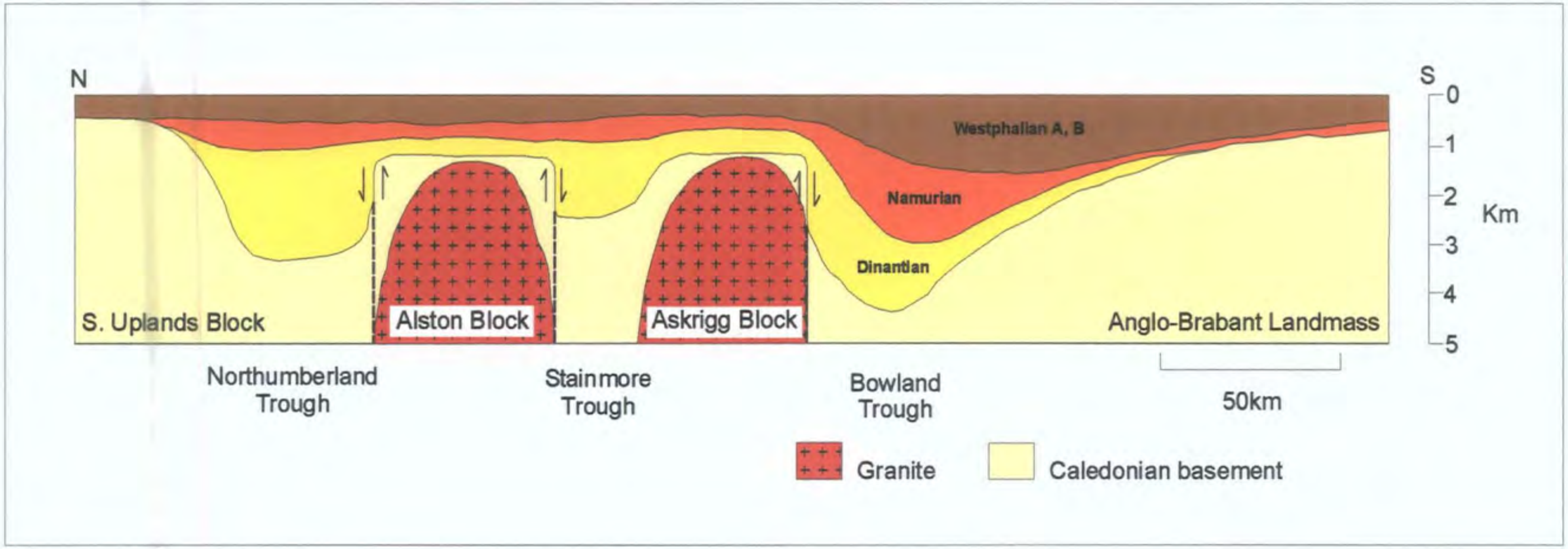

Figure 8-3 Sketch cross-section of the basin and block structure of the study area. The general thickness variations of the stratigraphy across the area are also shown. After, Leeder (1982).

Key for figures 8-4 to 8-7

Limestone names

3YL	Three-Yard limestone
4FL	Four Fathoms limestone
5YL	Five-Yard limestone
AL	Acre limestone
BCL	Buccleuch limestone
BHL	Bankhouses limestone
BLDL	Belsay Dene limestone
CL	Crag limestone
CBL	Catsbit limestone
CRL	Corbridge limestone
CSL	Cockleshell limestone
DL	Dun limestone
DML	Denton Mill limestone
EWL	Eelwell limestone
FLL	Fourlaws limestone
GL	Great limestone
GBL	Grainbeck limestone
GFL	Gunnerton Fell limestone
GPL	Gastropod limestone
GWL	Greengate Well limestone
HKL	Howick limestone
IPL	Iron Post limestone
ISL	Iron Scars limestone
JL	Jew limestone
LL	Little limestone
LBHL	Lower Bankhouses limestone
LCL	Lower Camphill limestone
LDL	Lower Demesne limestone
LFL	Lower Felltop limestone
LPHL	Lower Peghorn limestone
LTPL	Lower Tipalt limestone
MBHL	Middle Bankhouses limestone
MSL	Melmerby Scar limestone
NL	Naworth limestone
NTL	Newton limestone
OXL	Oxford limestone
OWL	Oakwood limestone
PTL	Penton limestone
RL	Robinson limestone
RDL	Redesdale limestone
SL	Scar limestone
SBL	Sandbanks limestone
SML	Smiddy limestone
SPL	Single Post limestone
SSL	Sugar Sands limestone
TL	Tynebottom limestone
THL	Thornborough limestone
TSL	Tombstone limestone
UBHL	Upper Bankhouses limestone
UDL	Upper Demesne limestone
UFL	Upper Felltop limestone
UPHL	Upper Peghorn limestone
WEL	Woodend limestone
WHL	Whitehouse limestone

🟨	Siliciclastics
🟦	Carbonate
🟥	Igneous intrusion (Whin Sill)
----	Correlation line
– –	Time-period boundary
∿	Contorted bedding
🟧	Sections mentioned in text

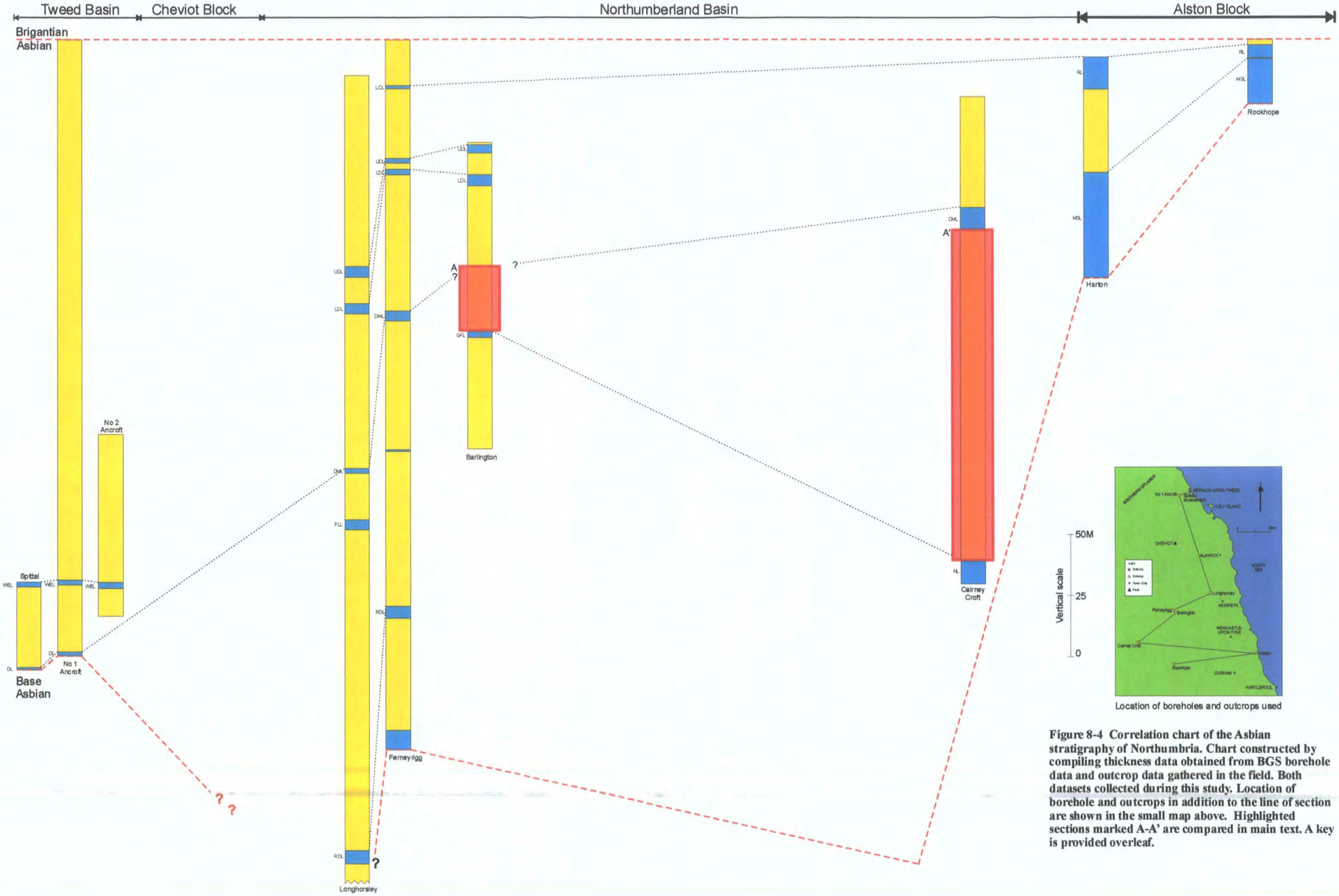

Figure 8-4 Correlation chart of the Asbian stratigraphy of Northumbria. Chart constructed by compiling thickness data obtained from BGS borehole data and outcrop data gathered in the field. Both datasets collected during this study. Location of borehole and outcrops in addition to the line of section are shown in the small map above. Highlighted sections marked A-A' are compared in main text. A key is provided overleaf.

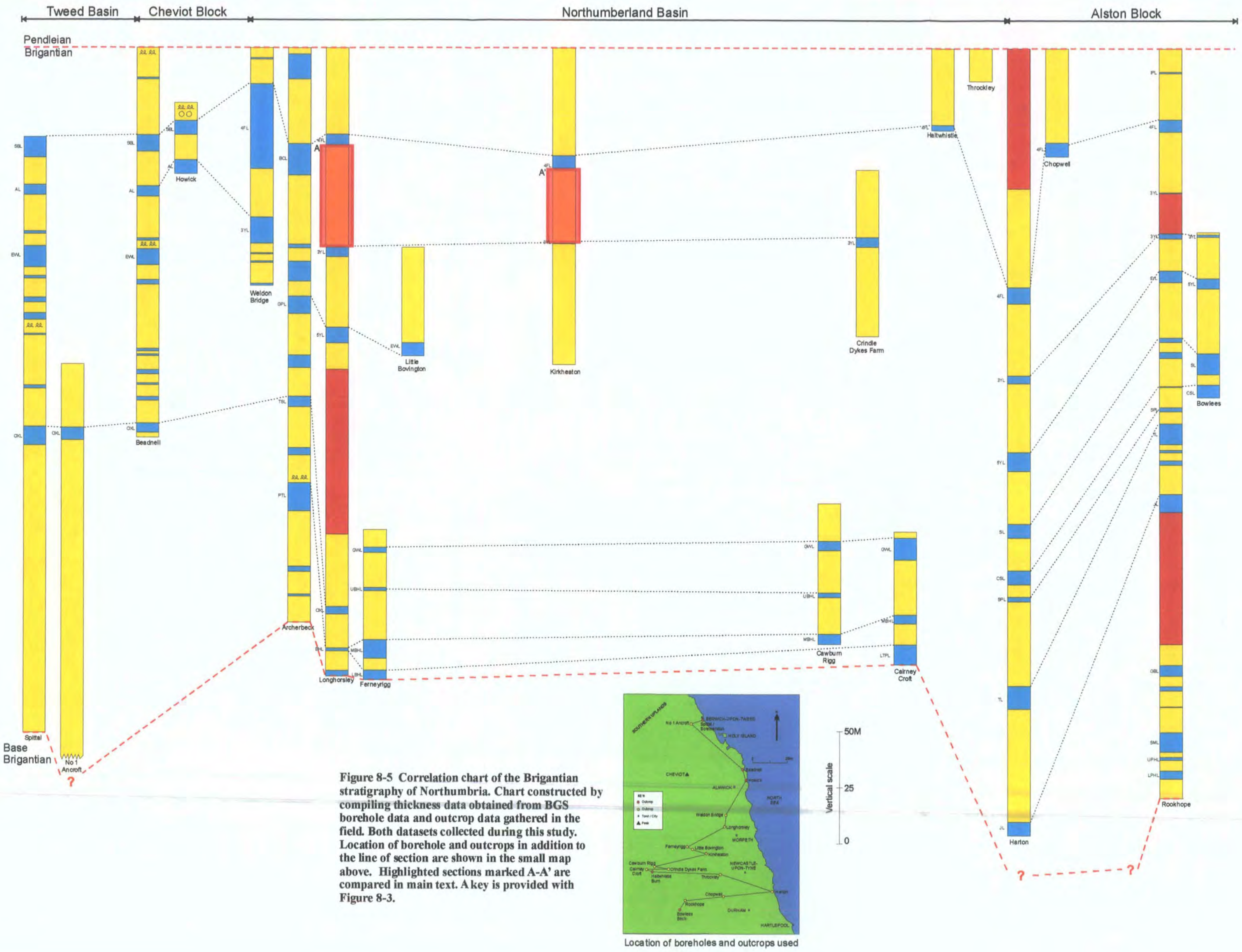

Figure 8-5 Correlation chart of the Brigantian stratigraphy of Northumbria. Chart constructed by compiling thickness data obtained from BGS borehole data and outcrop data gathered in the field. Both datasets collected during this study. Location of borehole and outcrops in addition to the line of section are shown in the small map above. Highlighted sections marked A-A' are compared in main text. A key is provided with Figure 8-3.

complete successions. A major thickening is seen towards the southern margin of the basin, evident between the horizon of the Denton Mill limestone and the Gunnerton Fell / Naworth limestone of the Barlington borehole and the Cairney Croft borehole where the siliciclastic component of each cycle increases from 27m to 144m (Figure 8-4 (Section A-A')). The greatest variation in thickness is seen between the Northumberland Basin and the Alston Block where the thickness of the succession in the latter area reaches a minimum of 26m. Siliciclastic material is not abundant in the Alston Block with the Melmerby Scar limestone taking the place of six siliciclastic / carbonate cycles found elsewhere in the region (Figure 4-7). The total thickness of the period changes from 90m at the northern margin of the Alston Block to 26m in the middle of the block.

The amount of thickness variation within the Asbian period is an indication of the varying tectonic rates throughout the region during this time. As the Tweed Basin and the Northumberland Basin contain noticeably different succession thicknesses it is inferred that accommodation space was controlled by differential subsidence during this time. The Alston Block and the Northumberland Basin have an extremely different succession thickness and virtually all siliciclastic sediments are absent from the Alston Block, once again suggesting differential rates of subsidence between these two areas. The thickness changes however are not instantaneous and seem to occur gradationally between the two areas as seen by the thinning of sediments farther towards the centre of the Alston Block. The succession of the Northumberland Basin thickens towards the southern margin of the basin which would indicate that it was an asymmetric or half-graben style basin (e.g. Gawthorpe *et al.* 1989).

8.3.1.2 The Brigantian Period

There is a small change in thickness from the Tweed Basin where the succession is some 325m thick, to the northern boundary of the Northumberland Basin as seen at the Archerbeck borehole in the north-west of the basin where the succession is only 255m thick (Figure 8-5). Although there is information available from the Cheviot Block for this time period, no major thickness changes are observed between it and the Tweed Basin to the north and the Northumberland Basin to the south. The thickness of the succession in the Northumberland Basin remains fairly uniform throughout. However, some thickening of 'cycles' occurs, for example between the

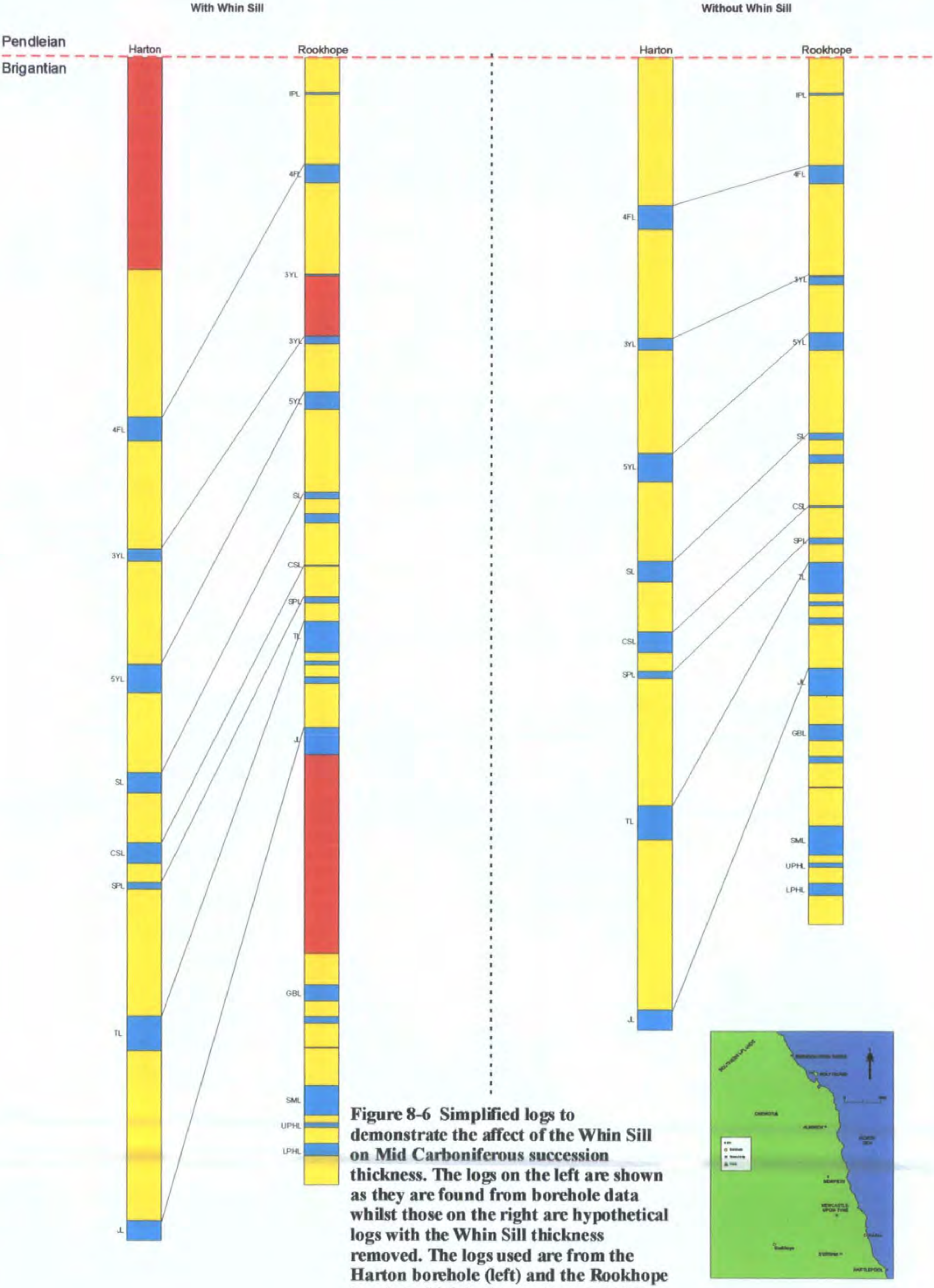

Figure 8-6 Simplified logs to demonstrate the affect of the Whin Sill on Mid Carboniferous succession thickness. The logs on the left are shown as they are found from borehole data whilst those on the right are hypothetical logs with the Whin Sill thickness removed. The logs used are from the Harton borehole (left) and the Rookhope borehole (right), the location of which are marked on the small map to the right.

horizons of the Four Fathom limestone and the 3-Yard limestone of the Longhorsley borehole (43m) in comparison with the same horizon of the Kirkheaton borehole (31m)(Figure 8-5 (Section A-A')).

There is an apparent thickening of the succession across the boundary between the Northumberland Basin and the Alston Block and it should be noted that the Whin Sill, a quartz dolerite sill-like intrusion of Upper Carboniferous age (Johnson & Dunham 2003) is present in such successions. A reconstruction of the succession without the presence of the Whin Sill has been done, and when compared with the succession with the Whin Sill still present, this does make a significant difference to the total thickness. The succession without the Whin Sill present (Figure 8-6) indicates that there is no significant thickening of succession between the Alston Block and the Northumberland Basin. The Whin Sill was intruded in the Upper Carboniferous, well after the deposition of the Mid-Carboniferous sediments of the study area, this suggests that the intrusion of such an igneous body has 'jacked up' the succession.

The overall minor change in succession thickness between the Tweed and Northumberland Basin during the Brigantian period marks the onset of the amalgamation of the two basins into one single Northumberland Basin, suggesting that regional subsidence began during this time (Turner *et al.* 1995). Further corroboration comes from the lack of any major changes in thickness over the intervening Cheviot Block, especially from the Oxford limestone horizon upwards. The rate of differential subsidence seems to be slowing down during the Brigantian period as there is a relatively uniform thickness throughout the area especially in the Upper Brigantian period. The addition of the Whin Sill into the strata of the southern part of the area during the Upper Carboniferous seems to have augmented the thickness of the succession in the Alston Block (e.g. Johnson & Dunham 2001), but if this is removed the thickness remains relatively constant between the Alston Block and the Northumberland Basin.

The presence of localised thickening is indicative of intra-basinal faulting produced by synthetic and antithetic faults.

8.3.1.3 The Pendleian / Arnsbergian Period

There are no data available for this time period from the Tweed Basin. There is no complete Pendleian / Arnsbergian for the Cheviot Block but from the limited information that is available there appears to be a uniform thickness of succession across the Cheviot Block and the Northumberland Basin (Figure 8-7). Some minor thickness variations are seen, such as between the horizons of the Little limestone and the Crag / Oakwood limestone at Haltwhistle Burn (46m) and the Black Heddon borehole (78m) (Figure 8-7 (Section A-A')). There is some variation seen across the boundary of the Alston Block and the Northumberland Basin, i.e. between the Throckley borehole and the Chopwell borehole but it should be noted that the succession contains a component of Whin Sill and may be an exaggerated thickness. As a whole, thickness variations between the Alston Block and the Northumberland Basin are small, with the thickness of the succession at the southern margin of the basin being 237m at the Throckley borehole and the comparative thickness on the Alston Block being 163m.

The uniform thickness across the entire area during the Pendleian is indicative of regionwide thermal subsidence continuing to be more important that differential subsidence as proposed by Mackenzie's thermal subsidence model (1978). The only exception to this is the localised thickening of the succession once again due to a small amount of minor faulting attributed to intrabasinal synthetic and antithetic fault movement.

8.3.2 Lithofacies Variations

Information for regionwide lithofacies variation is limited but a brief description and interpretation of the variations is made in this section.

During the Asbian period there was a very broad pattern of lithofacies distribution with upper delta plain and lower delta plain lithofacies restricted to the north of the area in the Tweed Basin and the Northumberland Basin, while farther south on the Alston Block carbonate platform lithofacies dominated as discussed previously in Sections 3.4 & 4.3.2.1. The same pattern exists for the Lower Brigantian period with upper delta plain and lower delta plain lithofacies being the dominant lithofacies in the Tweed Basin and Northumberland Basin. Lithofacies of the Upper Brigantian

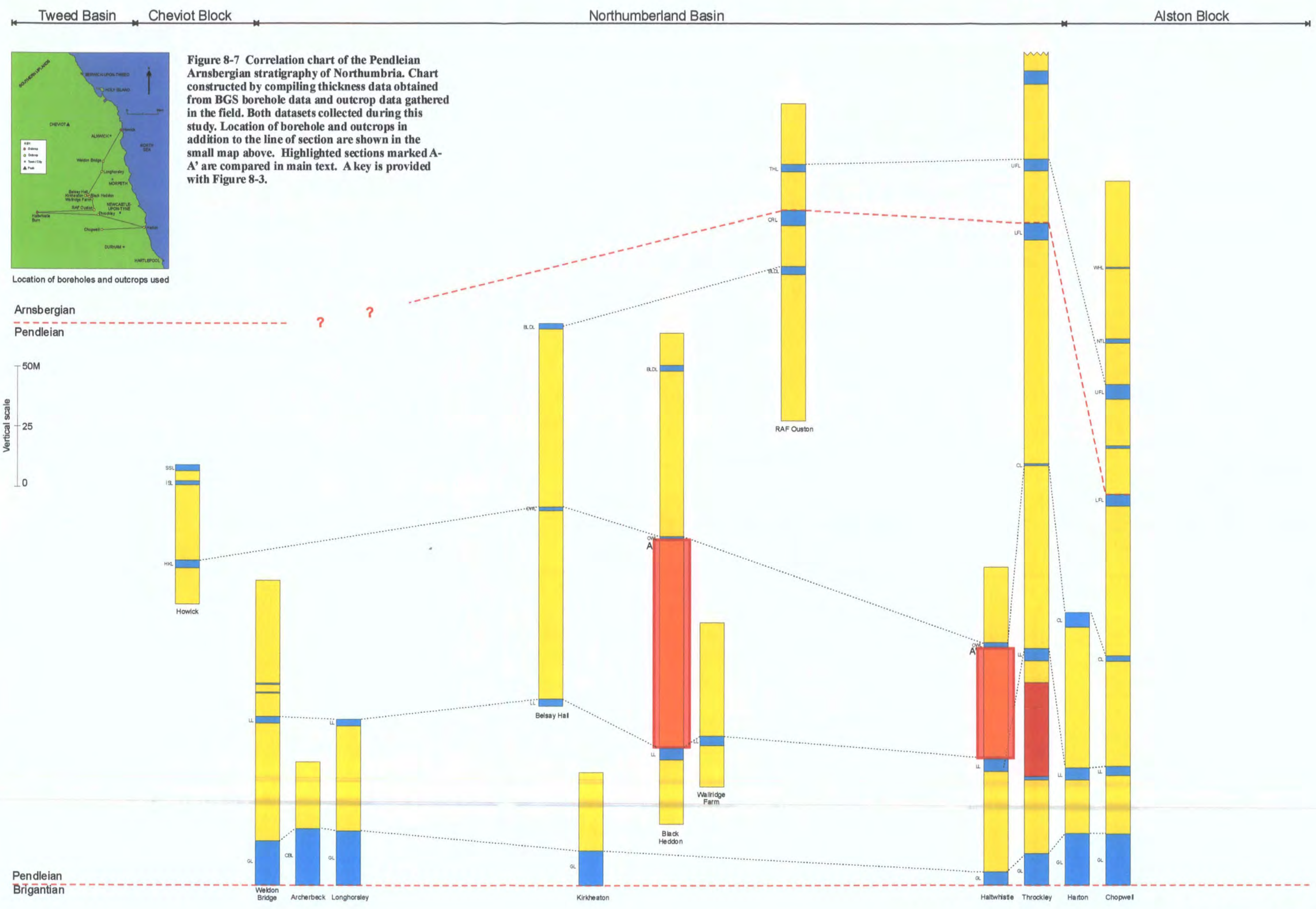

Figure 8-7 Correlation chart of the Pendleian Arnsbergian stratigraphy of Northumbria. Chart constructed by compiling thickness data obtained from BGS borehole data and outcrop data gathered in the field. Both datasets collected during this study. Location of borehole and outcrops in addition to the line of section are shown in the small map above. Highlighted sections marked A-A' are compared in main text. A key is provided with Figure 8-3.

Location of boreholes and outcrops used

however are much more varied with a gradual increase in the amount of other lithofacies such as marine shoreline lithofacies and transgressive shoreline lithofacies occurring throughout the region. Lower delta plain lithofacies are also observed further south in the Alston Block during this time. The Pendleian was a time of extremely varied lithofacies with no spatial restriction of any one particular lithofacies. All of the information provided in this section is summarised in Table 8-1.

	Alston Block	Northumberland Basin	Cheviot Block	Tweed Basin
Asbian	Carbonate Platform Llithofacies dominate	Delta Plain Lithofacies dominate		
Lower Brigantian	Carbonate Platform Lithofacies dominate	Delta Plain Lithofacies dominate		
Upper Brigantian	Delta Plain Lithofacies common, but Marine Shoreline Lithofacies, Transgressive Shoreline Lithofacies are also present. Carbonate Platform Lithofacies is increasingly less common.			
Pendleian	All siliciclastic lithofacies are widespread throughout the region. Carbonate Platform lithofacies is uncommon.			

Table 8-1 Table summarising the spatial and temporal lithofacies variations seen throughout the study area

8.3.2.1 Interpretation

The different rates of subsidence that existed into the Early Brigantian period referred to in Section 8.3.1.2, have had a fundamental control on sedimentation. The main sediment source of siliciclastic material as inferred from the position of deltas and from published provenance analysis appears to be coming from the north-east (Cliff *et al.* 1991). The transport pathways and deposition of the sediments seems to have been controlled and hindered by the rift topography (Johnson *et al.* 1995). During the syn-rift phase of deposition, tectonic subsidence generally exceeded the rate of sediment supply to the basins since siliciclastic material remained confined to the north of the region (Fraser & Gawthorpe 1990). With the transition to post-rift deposition in the Brigantian, deposition became regionally widespread less restricted distribution (e.g.

Fraser *et al.* 1990). It should be noted that during the Mid Carboniferous the distribution of sediments was dependent on a number of factors including climate change as summarised in Section 6.12, eustatic sea-level changes as summarised in Section 4.5, as well as regional and local tectonic movements.

8.4 Outcrop evidence of tectonic activity

There are many features within the Mid-Carboniferous strata that are indicative of syn-sedimentary tectonic activity. The main features concentrated on in this section are the effects of tectonics on fluvial channel formation.

Although many of these features appear to be localised in extent it should be noted that any information gleaned is from outcrops only since borehole data do not usually record such occurrences. There is also a lack of appropriate correlatable boreholes and spatial variations inferred from outcrops alone are problematic.

8.4.1 Tectonic control on fluvial channel formation

Fluvial channels are abundant within the study area with the majority of channel sandstone bodies reaching a maximum thickness of 20 metres and with a predominant palaeoflow direction towards the south-west as outlined in Section 3.2.3.5. There are however localised 'anomalous' channel sandstones with different characteristics and these have been examined to assess whether tectonics influence fluvial channel formation.

8.4.1.1 Howick Channel Sandstone

A major feature of the coastal outcrop at Howick is the presence of a large channelised sandstone body (Figure 8-8). The channel itself has been interpreted as resulting from the deposition of a major braided river system as described in Section 3.2. The thickness of the sandstone body reaches a maximum of 25 metres while the cross-sectional width is approximately 750 metres. Although the thickness of the channel is anomalous, this is discussed further in Section 4.2.2.4 (Table 4-1) where its formation is interpreted as an incised palaeovalley. The palaeocurrent direction, gained from abundant cross-bedding within the sandstone body, is to the east (Fig 8-9), which as is somewhat different to the regional palaeoflow direction to the south-west stated in Section 3.2.3.5.

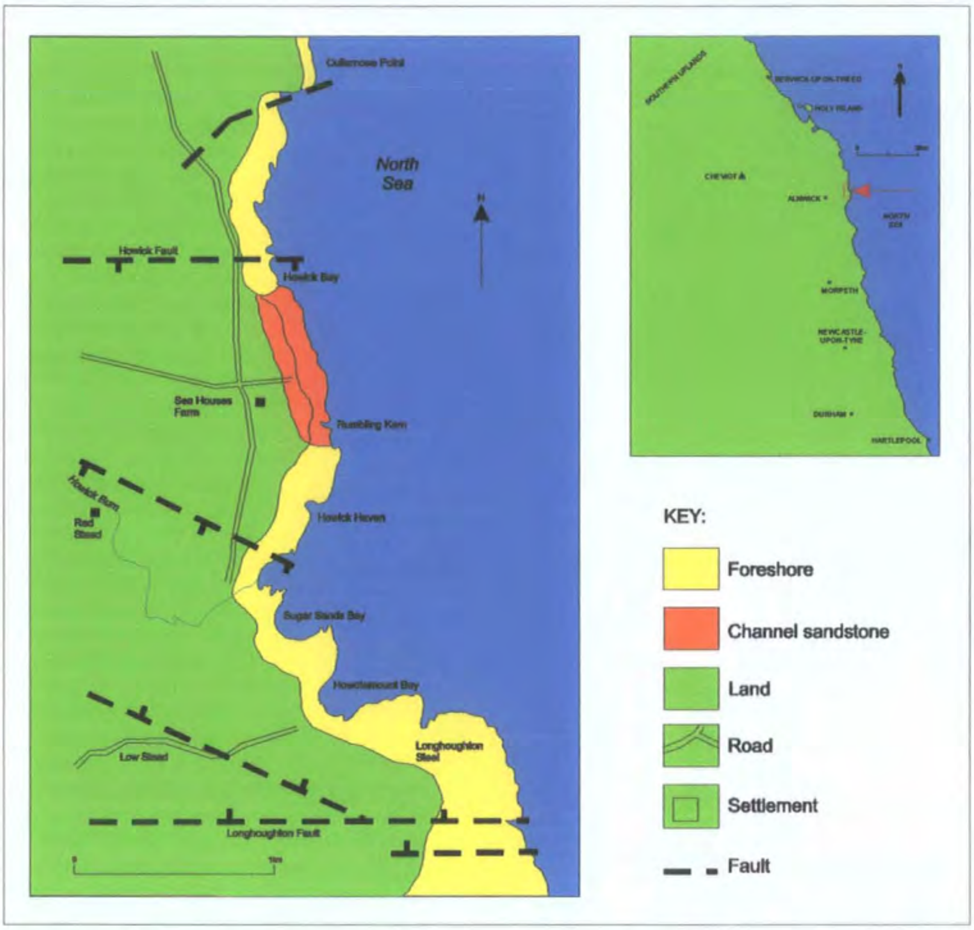

Figure 8-8 Simplified map of Howick Coast section showing large channel sandstone body. Position of map within study area is shown in smaller map in upper right corner. After, Tucker (2004).

Figure 8-9 Photograph of cross-bedding within fluvial channel sandstone at Howick Coast section (see map above for location). Palaeocurrent direction is towards the East as shown in rose diagram in top left-hand corner of photograph. Shaft of hammer is 30cm for scale.

8.4.1.2 Spittal Channel Sandstone

Exposed along the Spittal / Scremerston coastline is an unusually thick fluvial sandstone body overlying the Woodend Limestone at the Asbian / Brigantian boundary. The sandstone body is composed of medium-grained red sandstone and is 49 metres thick (Figure 8-10); this is much greater than even the average 30 metres of a complete Yoredale Cycle thickness. The channel sandstone has 'removed' the Watchlaw Limestone and its associated cycle which is found elsewhere throughout the region. The unit contains abundant cross-bedding with south-west palaeocurrent indicators and is therefore consistent with the regional palaeoslope. The other major sedimentary structure found within the unit is abundant deformed bedding which will be described further in Section 8.4.2.1, found concentrated in the lower half of the unit. The location of the unusually thick fluvial sandstone along the Spittal / Scremerston is visible on Figure 8-11.

8.4.1.3 Shaftoe Grits

The Shaftoe Grits are described by Young & Lawrence (1998) from the interval between the Oakwood and Newton Limestones (Arnsbergian) in a restricted area between Shaftoe Crags and Low Angleton. They comprise of 100 metres of coarse-grained sandstones and have been interpreted as being deposited in a low sinuosity fluvial environment. The exposure of the Shaftoe Grits is confined between the South Middleton – Malsk fault to the north and the Hallington Reservoir fault to the south (Figure 8-12). As in the Spittal sandstone body the unusual thickness of the unit has been achieved by removal of the cycles; in this case the removal of the Belsay Dene, Corbridge and Thornborough Limestone cycles.

8.4.1.4 Interpretation

The fluvial channel at Howick was initially created as a result of a dramatic fall in sea-level as previously discussed in Section 4.2.2.4. However, based on the palaeocurrent being sub-perpendicular to the regional palaeocurrent direction, this could indicate that fault activity controlled the location of the channel. A similar channel is found in the Namurian of the Silesian Coal Basin, Poland where incised valley systems occur abundantly in the vicinity of bounding faults (Van der Belt 2002). Although the Howick channel is an incised valley-fill, the position and orientation of faulting could have controlled the lateral distribution of the channel.

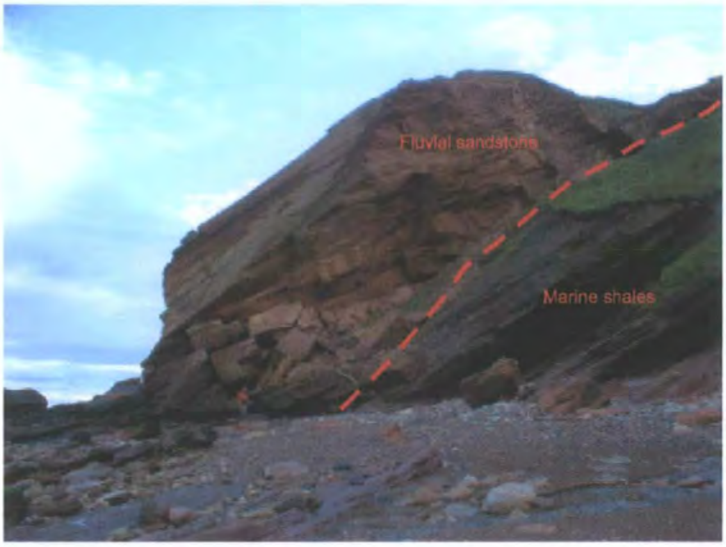

Figure 8-10 Photograph of thick fluvial sandstones seen at Spittal Coast section (see text for further details). Height of figure is 1.55m for scale.

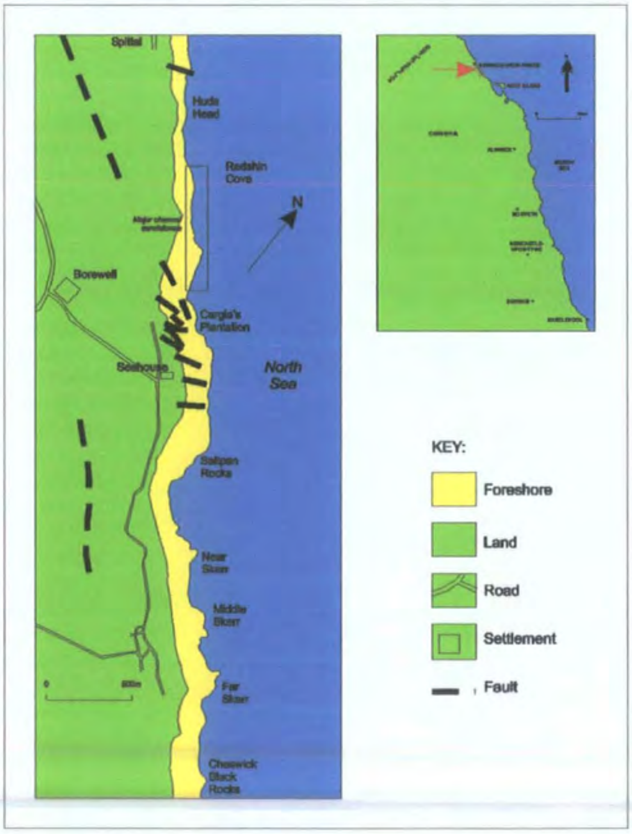

Figure 8-11 Outcrop map of Spittal / Scremerston coast section. Location of main map within study area is seen on smaller map in upper right hand corner. The location of faults in the area are marked on the map in addition to the occurrence of major channel sandstone bodies as mentioned in main text. After, Turner & Scrutton (2004).

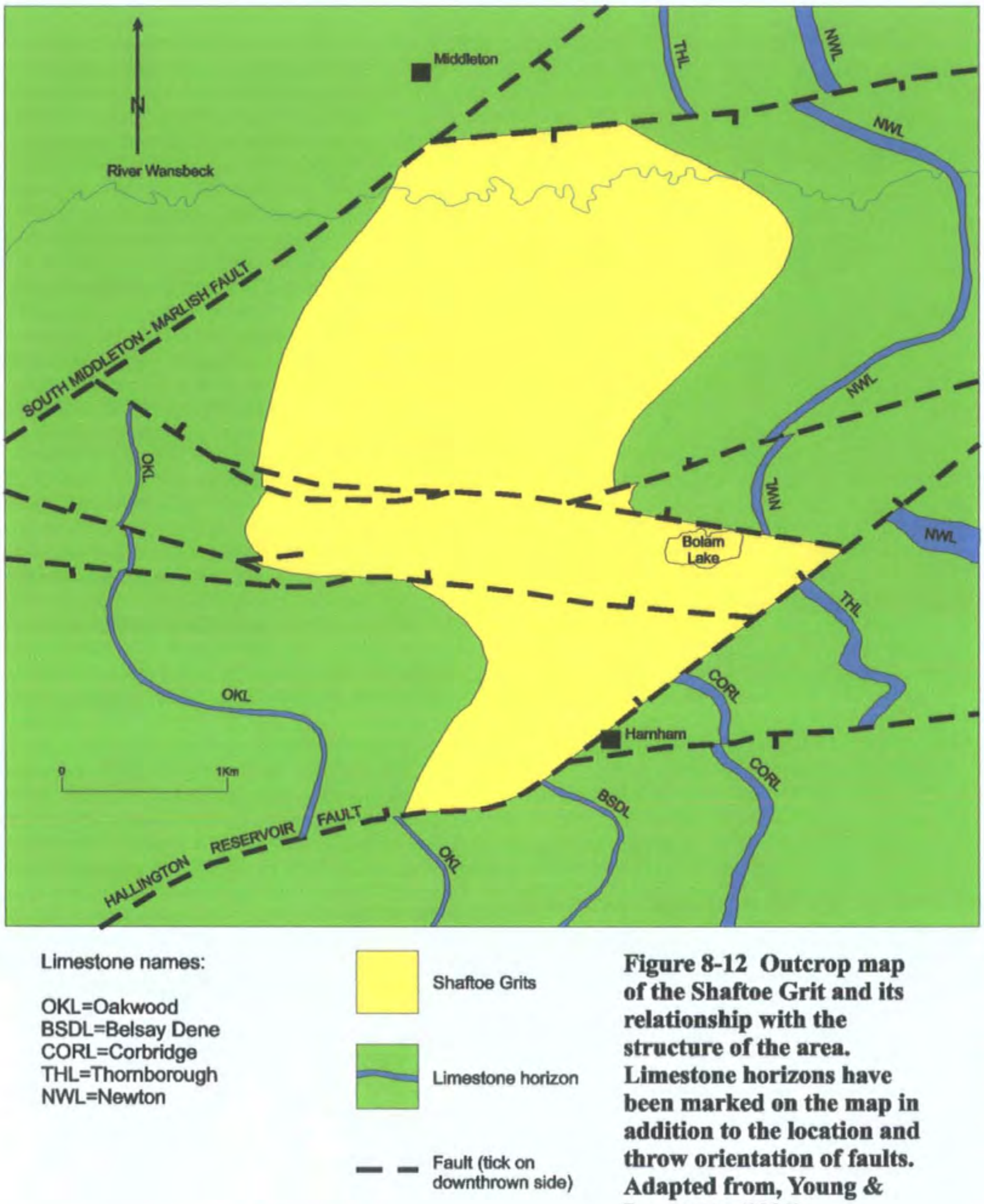

Figure 8-12 Outcrop map of the Shaftoe Grit and its relationship with the structure of the area. Limestone horizons have been marked on the map in addition to the location and throw orientation of faults. Adapted from, Young & Lawrence (1998).

The contorted bedding within the Spittal channel could have been formed from a number of processes usually linked to dewatering processes such as fluidisation and liquefaction (e.g. Merriam & Foerster 2002). Such processes could be the result of wave action on a shoreline but in the case of fluvial channels on the delta plain this is highly unlikely. More realistic processes that cause contorted bedding are natural bank collapse, which is perfectly plausible given that this outcrop is within distributary channel lithofacies (Section 3.2.3.1), and earthquake induced shocks often associated with syn-sedimentary movements of faults (Tucker 2001). The interpretation of contorted bedding as being produced by earthquake induced shocks may be reinforced as the major change in channel thickness would require a significant increase in accommodation space which could have been produced by fault movement. This particular horizon can be correlated with the Ancroft borehole where a conglomeratic horizon is found which may indicate close proximity to a fault that was active during deposition. The Spittal Channel can be interpreted to have been formed in response to a dramatic increase in accommodation space which could be attributed to a major drop in sea-level, but based on the abundance of contorted bedding and the laterally equivalent conglomerate beds it is suggested that the creation of accommodation space was tectonically-induced.

Young & Lawrence (1998) inferred that the geographical restrictions of the Shaftoe Grits was because the course of the major channel system was determined by movement along the NE – SW trending bounding faults (Young & Lawrence 1998) . Although the initiation of the Shaftoe Grits channel was different to Howick in that the channel does not appear to have been created in response to a major fall in sea-level (Section 4.2.2.4), the control on its location was very similar.

Fluvial channel systems whose courses are ultimately controlled by tectonic activity are well documented. The Yaluzangby River of the Tibetan Plateau has its downstream course determined by strike-slip faulting during the Miocene (Zhang 2001), while the Lower Negro River in Amazonas State, Brazil is controlled by a NW – SE trending tectonic lineament linked to the major tectonic transcurrent dextral megasystem of the Amazon Basin (Wroblewski 2002). Redirection of fluvial systems such as that found at Howick is also well documented with examples such as the redirection of the early Palaeocene fluvial systems in the Hanna Basin of southern Wyoming (Wroblewski 2000).

8.5 Carboniferous tectonics is other parts of the British Isles

The closure of the Rheno-Hercynian seaway not only initiated basin formation in Northern England, but also throughout the majority of the British Isles (Figure 2-3). Asymmetric tilt-blocks / half-grabens, with a NE-SW orientation were produced throughout Northern England; in the Bowland Basin (e.g. Gawthorpe 1987), the Stainmore Basin (e.g. Gawthorpe et al. 1989; Collier 1991), and the Craven-Askrigg area (e.g. Martinsen 1993). Similar basins were also produced in southern Scotland in the Midland Valley (e.g. Fielding *et al.* 1988) and in the Solway Basin (e.g. Ord *et al.* 1988). The underlying Caledonian basement structures that formed as a result of the Iapetus suture site of the main orogenic collision (Fraser & Gawthorpe 1991) directly influenced the positioning and orientation of these basins.

The westerly continuation of the Iapetus suture zone has also acted as a locus for the formation of Carboniferous extensional basins. The Dublin Basin shares many similarities with extensional basins from Northern England; granite-cored fault blocks, basinwide extensional faulting beginning in the Early Dinantian and subsequent differential subsidence (Pickard *et al.* 1994). The Munster Basin also lies along the westerly extension of the Iapetus suture zone and is the result of Carboniferous extensional activity (Williams *et al.* 1994).

The Carboniferous extensional basins of South Wales formed due to the closure of the Rheno-Hercynian seaway. This produced similar asymmetric tilt-blocks / half-graben structures, with deposition being controlled by movements on the basement faults (Ramsay 1991).

There are many other extensional basins in the British Isles, some of which are listed in Table 8-2. All of the basins share a common casual mechanism in that they were formed as a result of extensional stress fields produced by the closure of the Rheno-Hercynian seaway. The position and orientation of each of these basins was directly influenced by inherited basement structures, most commonly being a direct result of the closure of the Iapetus Ocean in the Devonian. Similar patterns of subsidence are seen within each basin; the initial extensional phase of active rifting in the Early Dinantian which is followed by a period of thermal relaxation or 'sag' in the Late Dinantian to Namurian.

Area of study	**Reference**
Bowland Basin (N. England)	Gawthorpe (1987)
Midland Valley Basin (Scotland)	Fielding *et al.* (1988)
Solway Basin (SW Scotland)	Ord *et al.* (1988)
Stainmore Basin (N. England)	Collier (1991)
Craven – Askrigg Area	Martinsen (1993)
Dublin Basin (Ireland)	Pickard *et al.* (1994)
South Wales	Ramsay (1994)
South Munster Basin (Ireland)	Williams *et al.* (1994)

Table 8-2 Summary table of references to tectonic activity from the Carboniferous period within the British Isles

8.6 Summary

Synsedimentary faulting began in Northumbria in the Early Dinantian (e.g. Turner *et al.* 1995), with a series of independent basins developing parallel to major fault trends. The basins are interpreted as having formed due to the reactivation of crustal scale Caledonian thrust zones beneath both the Northumberland Basin and the Tweed Basin (Chadwick et al. 1993).

Extensional faulting was initiated as a result of closure of the Rheno-Hercynian seaway in the Late Devonian (e.g. Turner *et al.* 1995), which led to the formation of a series of E-W trending tilt block / half-graben structures in Northern Britain. Fault-controlled subsidence was rapid in the Early to Mid Dinantian, but had begun to slow down by the Late Dinantian (Chadwick *et al.* 1993). The Stublick-90 Fathom Fault was active from the Early Dinantian right up until the end of the Asbian, with the movement of the fault keeping pace with the sedimentation of the basin (Johnson 1984).

During the Asbian period, the primary control on the thickness of sediments accommodation space developed through regional subsidence and relative sea-level changes, but regional variations in thickness developed due to differential subsidence (e.g. Turner *et al.* 1995). The presence of Lower Palaeozoic granitic bodies beneath the Alston Block and the Cheviot Block resulted in the uplift of structurally positive areas (e.g. Johnson *et al.* 1995). Hinge line faults developed on the margins of the uplifted basins, dropping down the adjacent Northumberland Basin and Tweed Basin resulting in reduced accommodation space and thinner sediment cover across the more buoyant blocks (e.g. Turner *et al.* 1995).

The period of differential subsidence produced half-graben structures in the form of the Tweed and Northumberland Basins known from the accumulation of a prism of sediment which thickens towards active fault-bounded margins of the basins (Gawthorpe *et al.* 1989).This phase of deposition can be referred to as the syn-rift succession (e.g. Fraser & Gawthorpe 1990). The syn-rift succession accommodated by along axis thickening is also observed in other contemporary basins of Northern Britain and Ireland such as the Devono-Carboniferous Munster and South Munster Basins of south-west Ireland mentioned previously in Section 8.5. The absence of alluvial fan deposits and the abundance of low relief environments of deposition such as marine or marginal marine, indicates that little relief was created as a result of differential subsidence. This would suggest that high rates of sedimentation outpaced subsidence which led to the suppression of basin margin relief (Williams *et al.* 1994).

The end of the Asbian period also marked the demise of the Tweed Basin which up until then had acted as two independent basins. The Cheviot Block lost its independence and sedimentation became more uniform and continuous (Johnson 1984).

This marked the onset of post-rift sedimentation with extensional faulting much reduced and sedimentation becoming gradually more uniform (Chadwick & Holliday 1993). Differential subsidence still existed for example on the Alston Block as it still subsided more slowly than the adjacent basins although this was somewhat more reduced. This persisted during the Brigantian and Namurian and even right through into the Wetsphalian (Johnson 1984).

From the end of the Asbian onwards, the effect of differential subsidence became much less pronounced as the blocks separating the basins also began to subside (e.g. Johnson *et al.* 1995). The effect of such a switch was by no means instantaneous but occurred rather as a gradual transition. The change to a generally consistent deltaic palaeoenvironment is the result of this decline in the rate of subsidence.

The abundance of post-depositional sedimentary structures attributed to tectonic activity at the end of the Brigantian suggests that localised tectonic activity was common during this time. This occurred as differential subsidence decreased and uniform regionwide subsidence became dominant. Limited extensional faulting occurred into at least Namurian times, with localised fault-related thickening (Chadwick *et al.* 1993). Intrabasinal faulting, both anti- and synthetic to the main bounding faults, locally trapped axial drainage systems encouraging the development of vertically-stacked, fault-bounded sand bodies (Turner *et al.* 1995), examples of which are seen within the study area.

During the Pendleian period of sediments accumulated during regional subsidence since sediment thicknesses became uniform across Northern England (e.g. Fraser & Gawthorpe 1990). By this period, active extension ceased, which led to a predominantly unfaulted thermal subsidence phase (Turner *et al.* 1995).

Figure 8-13 displays the varying subsidence rates throughout the study period on the Northumberland Basin and the Alston Block, whilst Figure 8-14 summarises the tectonic activity throughout Northumbria during both the Carboniferous and Permian periods.

Tectonic activity had a profound effect on sedimentation during the Mid Carboniferous resulting in major regional thickness changes, lithofacies variations and localised deformation. It is beyond the range of this work to provide a conclusive study of the effects of fault activity during this period and it should be emphasised that there is scope for considerable further work in this field.

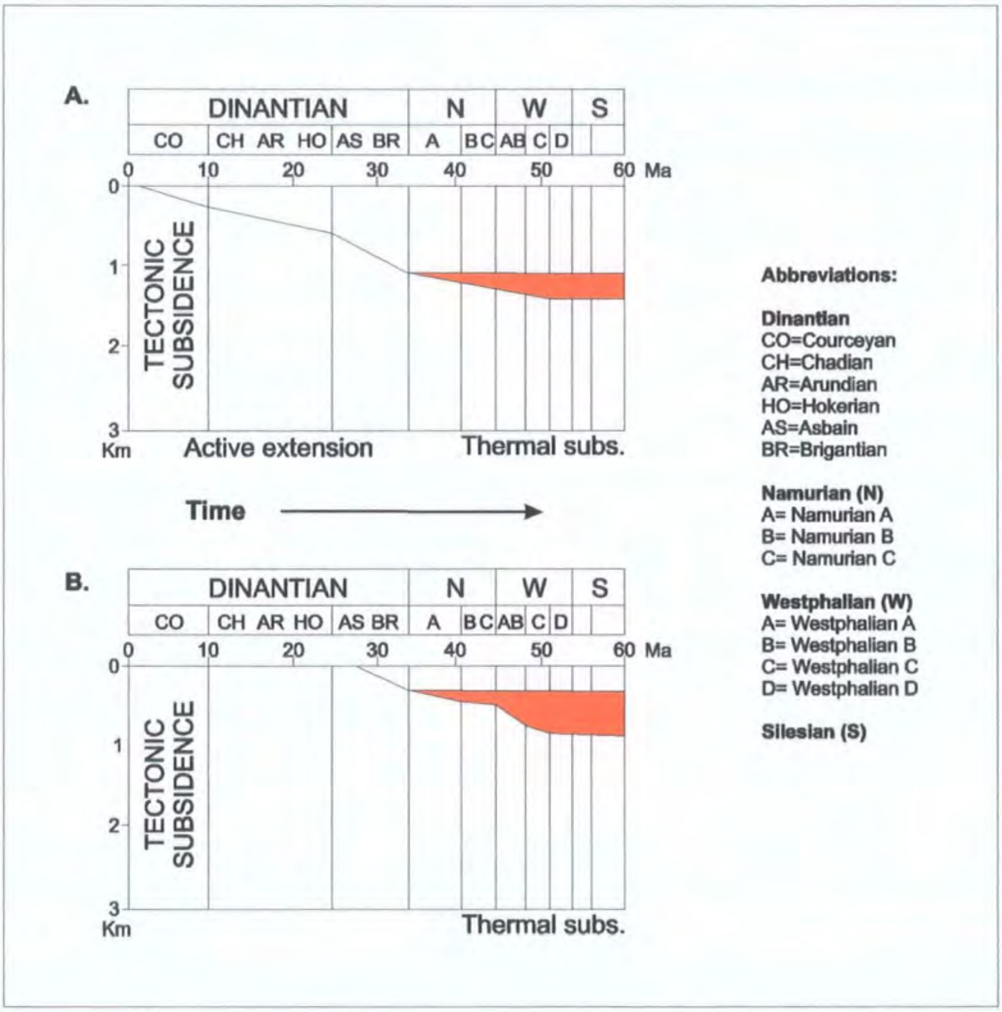

Figure 8-13 Graphs displaying the subsidence rates of both the Northumberland Basin (A) and the Alston Block (B). After, Leeder 1988.

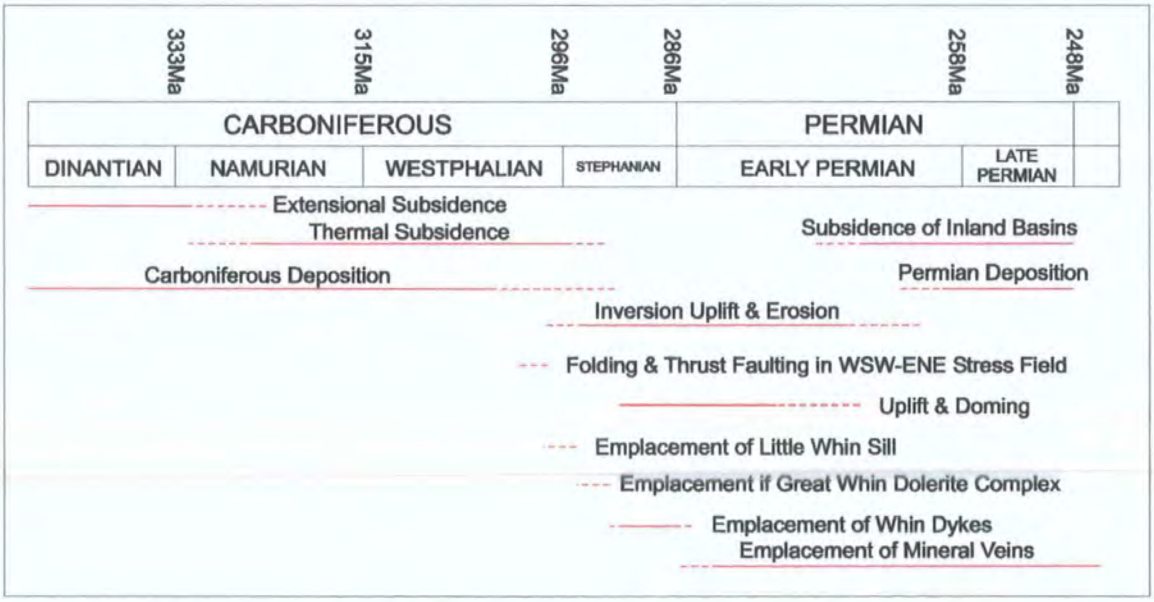

Figure 8-14 Summary diagram of Carboniferous and early Permian history of tectonic activity and igneous emplacement in northern England. From, Johnson & Dunham 2001.

Chapter Nine

9. SYNTHESIS AND CONCLUSIONS 243

9.1 Climatic, eustatic and tectonic effects on the Mid Carboniferous Strata 243

9.2 Summary of conclusions 244

Chapter 9 – Synthesis and conclusions

This thesis has presented the results of fieldwork and laboratory work to determine the effects of climate, eustasy and tectonics on the Mid Carboniferous (Viséan and Namurian) strata of Northumbria. This chapter synthesises the information and provides a summary of the conclusions found throughout the thesis.

9.1 Climatic, eustatic and tectonic effects on the Mid Carboniferous strata

The causal mechanism for cyclicity in Northumbria and indeed at similar palaeolatitudes during the Mid Carboniferous has been widely accepted as being glacio-eustasy. Glacio-eustasy has affected the Mid Carboniferous strata in the form of both climate change and eustatic sea-level fluctuations. There is one other factor, not linked to glacio-eustasy, which has had a profound influence of the Mid Carboniferous strata, and that is the effect of regional tectonic activity.

Climate, which is intricately linked with eustasy, has had a major effect on the Mid Carboniferous strata. Climate change appears to have occurred on an individual cycle scale, and also on a long term scale. This information is apparent from palaeosoil analysis, stable isotope analysis and lithological evidence. As all of these climate changes are apparent in areas of similar palaeolatitude during the Mid Carboniferous in area as far afield as Canada, it can be assumed that such climate changes were on a global scale. Climate change has therefore been interpreted as primarily being the result of the Gondwanan glaciation in the southern hemisphere.

Eustasy is the overriding control on the formation of each cycle and occurs within the same order of magnitude as Milankovitch eccentricity cycles. The occurrence of such cycles at other areas of similar palaeolatitude would once suggest that these were global events and such regularity would indicate that fluctuating ice sheets in Gondwana produced such oscillations in sea-level. Third-order sea-level change has also been identified which can be correlated with the Carboniferous eustatic sea-level curve. This scale of sea-level change coincides with the onset of the Gondwanan glaciation and would result from the formation of major ice sheets.

Tectonic activity was abundant in the Mid Carboniferous and was a time of major basin formation throughout Britain. The major effect that tectonic activity had upon the Northumbrian Mid Carboniferous sediments was that it created accommodation space. This was created at various rates at first as differential subsidence dominated, but gave way to uniform subsidence. Tectonic activity was a regional effect on sedimentation as opposed to climate and eustasy which were very much a global effect on sedimentation

9.2 Summary of conclusions

- The Mid Carboniferous was a time of major climatic change. These changes were brought about by the changing continental configuration onset of the Late Palaeozoic glaciation in the southern hemisphere.

- Using sedimentological information, a lithofacies scheme could be devised for the Viséan and Namurian of Northumbria. Twenty-six lithofacies could be identified, which would be divided into seven groups, and three major lithofacies associations. The deltaic lithofacies association was represented by a diverse range of siliciclastic sediments and contained very few if any fossils. The deltaic lithofacies association represented a predominantly non-marine environment, although some tidal influences were recognised. The marine lithofacies association was characterised by siliciclastic sediments and had a diverse range of trace fossils. The carbonate platform lithofacies was dominated by open-marine limestone and contained abundant marine body fossils.

- The vertical associations in lithofacies and their cyclic nature have been interpreted to represent fluctuations in relative sea-level.

- A Basic Cycle has been interpreted using sequence stratigraphic terminology with the base of each cycle i.e. limestone, representing the transgressive systems tract. Two further cycle variations have been interpreted; Cycle Variant A was used to describe those cycles that contained an incised valley-fill, and Cycle Variant B was used to describe those cycles that have an IFS that varied from the Basic Cycle.

- The duration of each cycle was calculated as being approximately 200,000 years which represents a fourth-order sea-level cycle.

- Fischer plots were used to recognise third-order cyclicity of approximately 4Ma duration, ongoing simultaneously with fourth-order cyclicity. The cause of the third-order was unknown but it was suggested that glacio-eustatic fluctuations and/or tectonic activity could be the causal mechanism.

- Using pedological and sedimentological analysis, a palaeosoil facies scheme was devised. Nine palaeosoil facies and subfacies were recognised which were grouped into six palaeosoil facies. Each palaeosoil was used to glean information on the palaeoenvironment in which they formed. Histosols were interpreted to be formed when precipitation exceeds evaporation, typical of equatorial or mid-latitudes. Podzols were interpreted as representing well-drained conditions in humid climates. Gleysols were interpreted as forming in all climatic regions. Vertisols were interpreted as forming in a climate zone with a strong seasonal climate. Aridisols were interpreted as forming in an arid or semi-arid environment, and the groundwater calcrete was also interpreted as forming in an arid or semi-arid environment.

- The palaeosoil facies also displayed vertical relationships which have been recognised on two scales: firstly, indicating a marine transgression immediately prior to the deposition of a marine limestone, and secondly, indicating fluctuations in base-level on a much smaller fifth-order scale.

- Fluctuations in sea-level had a profound influence on the formation of palaeosoils, but so too did tectonic activity. Tectonics would have affected local sedimentation, the sediment source and may also have impeded drainage.

- Palaeosoils are a useful tool for palaeoclimatic interpretation in the Mid Carboniferous of Northumbria. By studying the palaeosoils, a semi-arid phase has been recognised close to the Asbian/Brigantian boundary, similar to that described by other authors from other Mid Carboniferous strata. Such a change in climate has been attributed to a major worldwide regression.

- Various scales of climate change have been identified from fieldwork and laboratory fieldwork. Long-term climate change has been identified indicating a prolonged period of aridity / semi-aridity from the Late Asbian to Early Brigantian, with changes in atmospheric CO_2, Gondwanan glaciation and changing continental configuration all being proposed mechanisms. As this long-term period of aridity also coincides with a significant fall in eustatic sea-level it can be assumed that Gondwanan glaciation was the primary mechanism responsible for climate change. Within individual cycles, seasonal climate change was identified from the Mid Carboniferous, most common during the Late Brigantian and Early Pendleian. Seasonal climatic variations have been associated with a monsoonal climate, with the seasonal nature of such climate being particularly enhanced during an ice age.

- No valid palaeoclimatic / palaeoceanographic data was retrieved for the Mid Carboniferous period from stable isotope analysis.

- Isotope values from the Mid Carboniferous of Northumbria were unusually light for the type of limestone and age. These values have been suggested to have been caused by various factors (or a combination thereof) including high levels of heat flow during deep burial especially in those rocks found overlying the Weardale Granite, and the intrusion of the Whin Sill complex in the Late Carboniferous that may have caused a hydrothermal heat flow.

- Extensional basin formation in Northumbria during the Mid Carboniferous had a profound effect on sedimentation. Differential subsidence dominated during the Asbian resulting in variations in sediment thickness across the area. Differential subsidence gradually decreased throughout the Brigantian, giving way to thermal relaxation and uniform deposition across the area.

- Tectonically-influenced fluvial channels represented localised tectonic activity still ongoing during the Brigantian.

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Appendix One

A1. BOREHOLE LOCATIONS 277

A1. Borehole locations

The following table provides the borehole number and/or the grid reference of all boreholes used within this thesis.

Borehole Name	Borehole Number	Grid Reference
Allenheads No. 1	-	NY 8604 4539
Allenheads No. 2	-	NY 8715 4505
Ancroft	NT 94 NE / 8	NT 9950 4601
Archerbeck	-	NY 4163 7824
Barlington	NY 98 SW / 1	-
Barrock Park	-	NY 4613 4660
Belsay Hall	NZ 07 NE / 4	NZ 0687 7729
Black Heddon	N7 07 NE / 11	NZ 0763 7539
Brandy Well Hall	NZ 07 NE / 1	NZ 0570 7876
Cairney Croft	NY 66 NE / 2	NY 6626 6700
Cawburn Rigg	NY 76 NW / 2	NY 7397 6811
Chopwell	NZ 15 NW / 46	-
Crindle Dykes Farm	NY 76 NE / 7	NY 7815 6739
Ferneyrigg	NY 98 SE / 13	NY 9579 8364
Harton	NZ 36 NE / 80	NZ 4396 5656
Healycote Colliery	NV 10 SW / 8	-
Kyloe House	NZ 17 SW / 4	NZ 1067 7036
Little Bovington	NY 97 NE / 3	-
Longhorsley	NZ 19 SW / 16	NZ 1444 9255
No. 2 Ancroft	NT 94 NE / 6	-
Weldon Bridge	NZ 19 NW / 4	NZ 1380 9898
Wallridge Farm	NZ 07 NE / 6	NZ 0522 7693
RAF Ouston	N7 07 SE / 12	NZ 0788 7000
Roddymoor	NZ 13 NE / 2	-
Rookhope	-	NY 9375 4278
Stonehaugh	NY 77 NE / 2	NY 7899 7619
Stoop Rigg Farm	NY 87 SW / 13	NY 8459 7276
Throckley	NZ 16 NW / 28	-

Appendix Two

A2. DETAILED SEDIMENTARY LOGS.. 278

A2.1 Beadnell coast section... 279

A2.2 Bowlees Beck river section.. 289

A2.3 Haltwhistle Burn river section... 293

A2.4 Howick coast section (south of Howick Fault).. 303

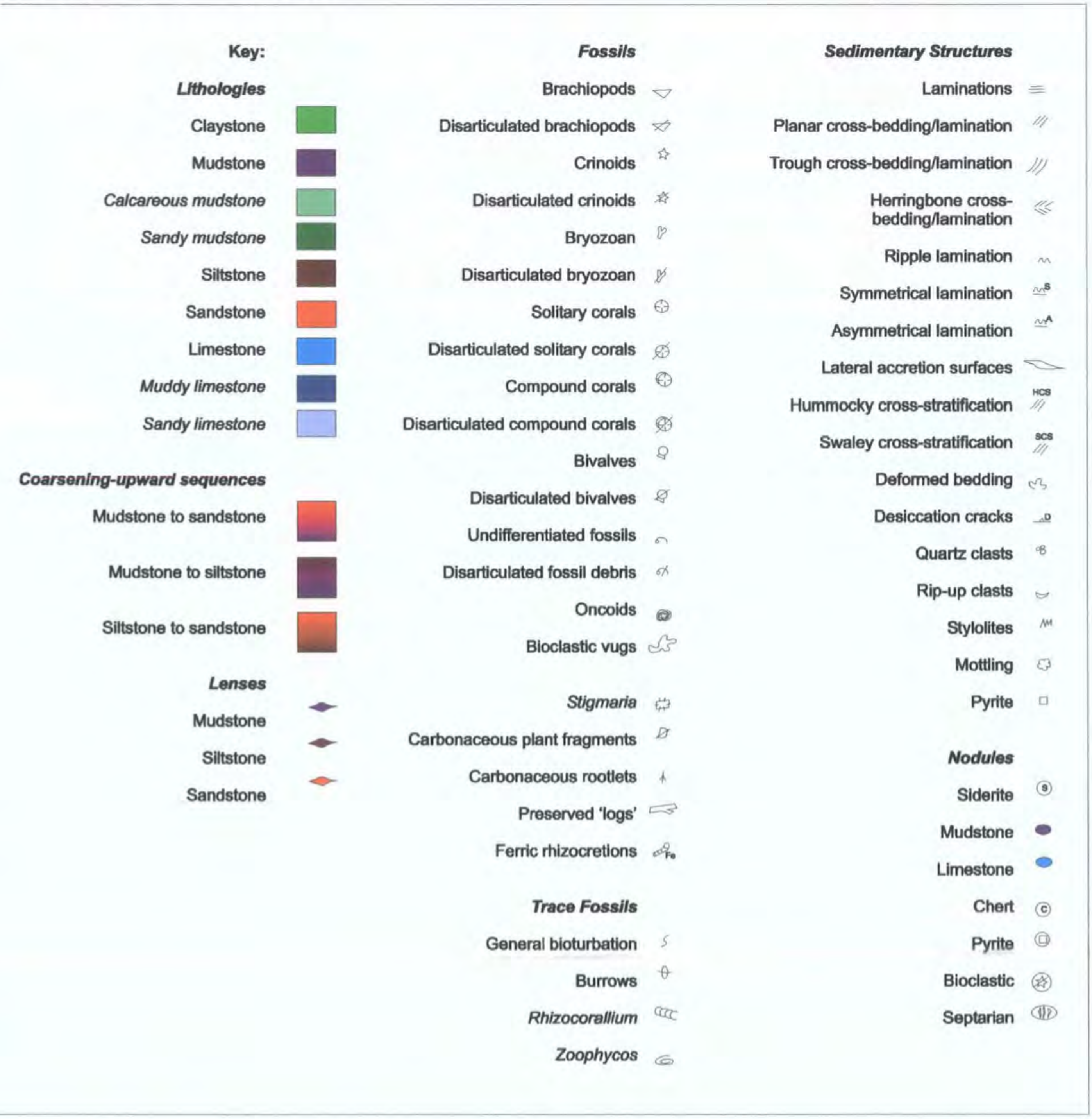
A2.5 Howick coast section (north of Howick Fault)... 307

A2.6 Spittal / Scremerston coast section.. 309

A2. Detailed sedimentary logs

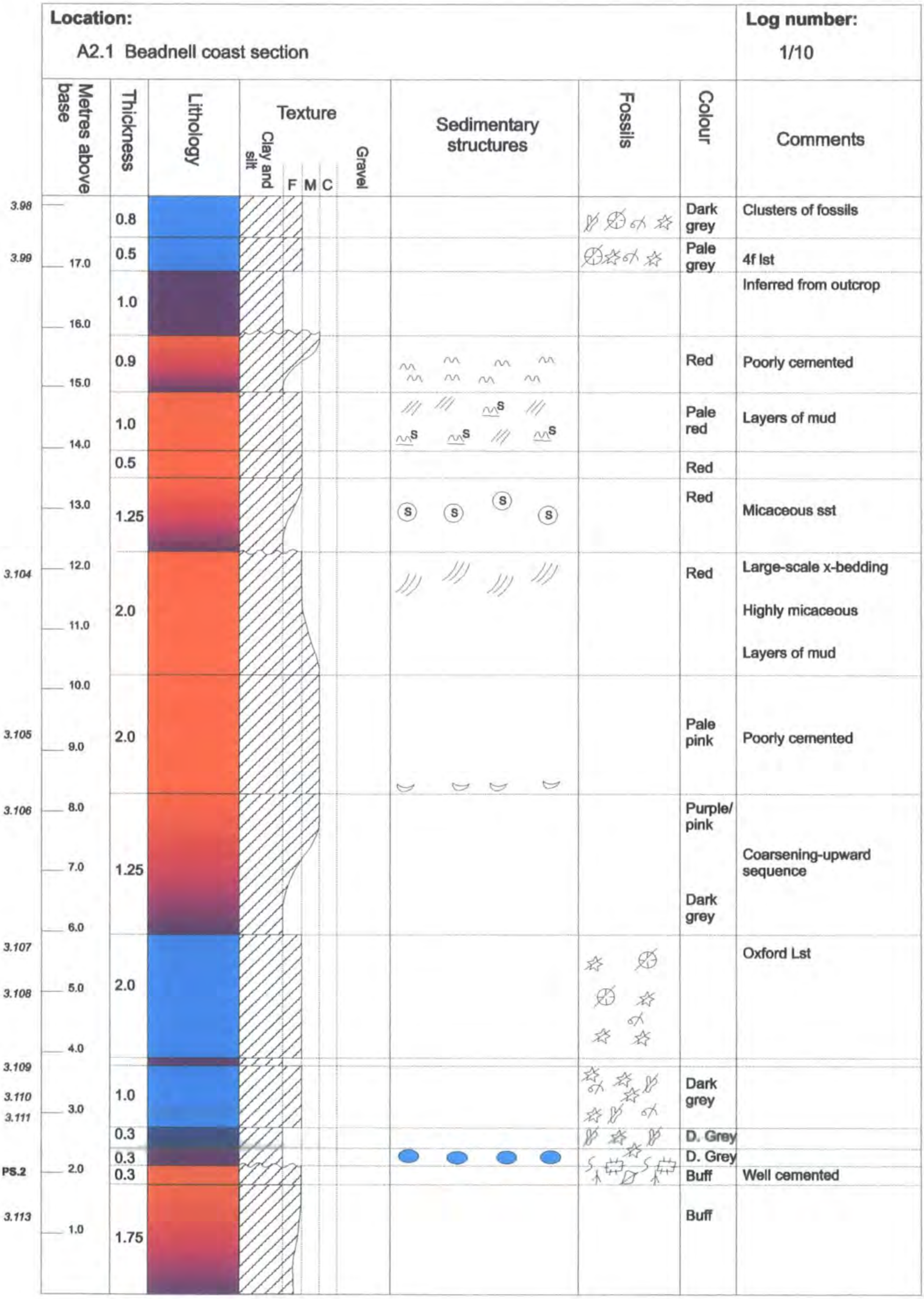
The following Appendix presents detailed sedimentary logs for the studied successions. Logs have been drawn up at a scale of 1:50. All information gathered in the field has been presented and recorded on the logs including lithology, grain/size, sedimentary structures and fossils. Sample numbers (where collected) and examples mentioned in the text have been added on the far left-hand side. Figure A2-1 presents a key for the logs.

igure A2-1 Key for sedimentary logs

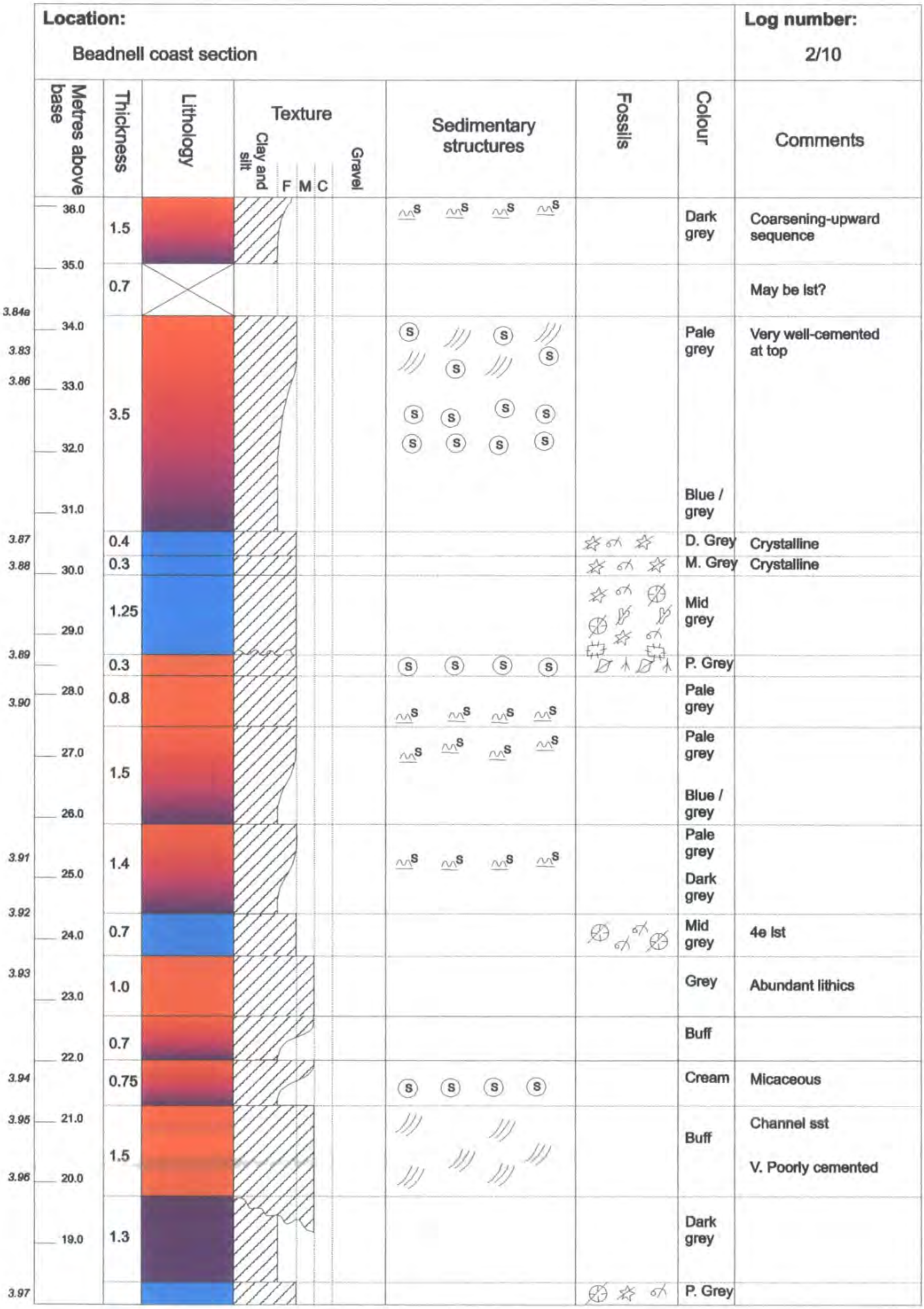


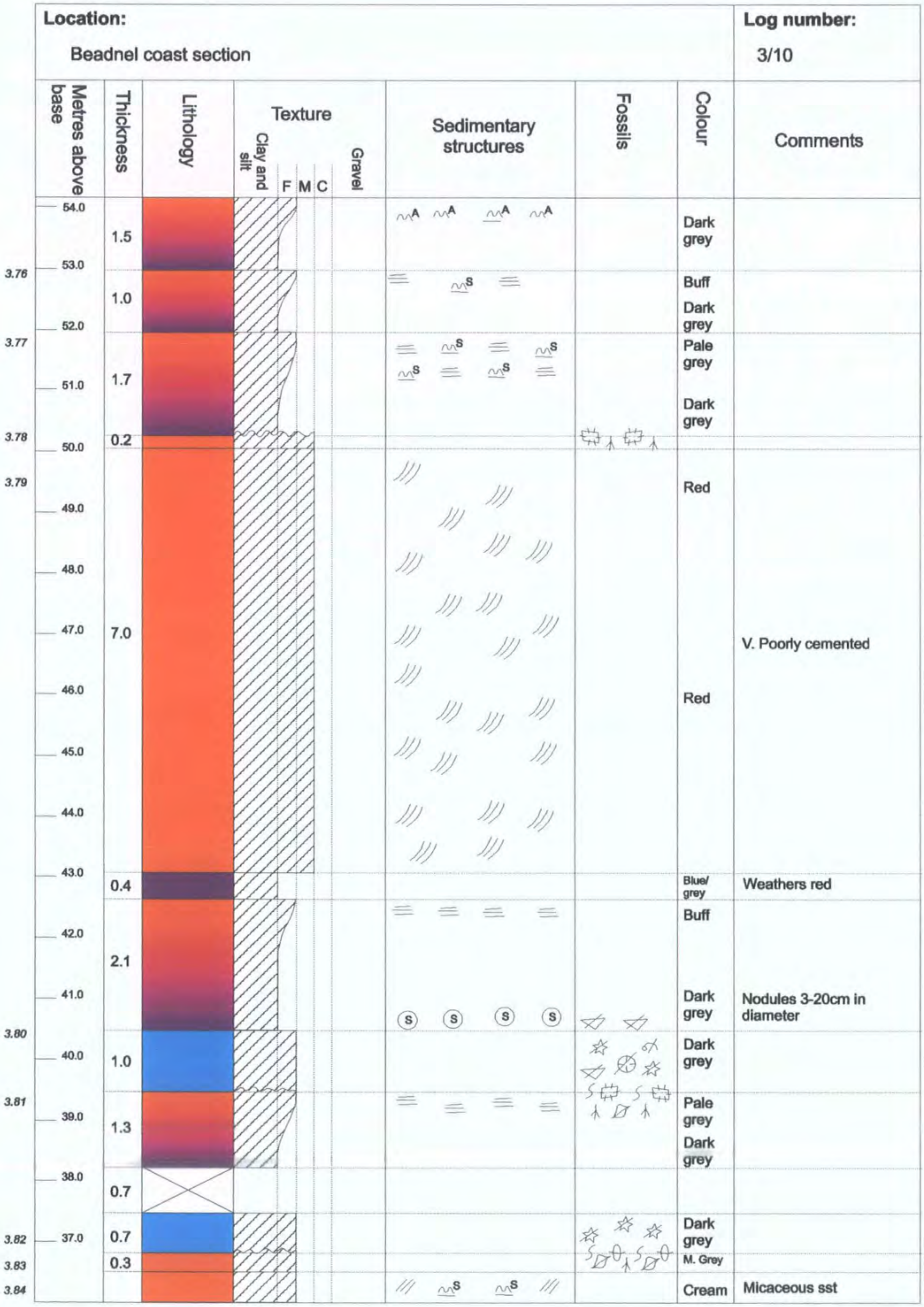
Location: A2.1 Beadnell coast section

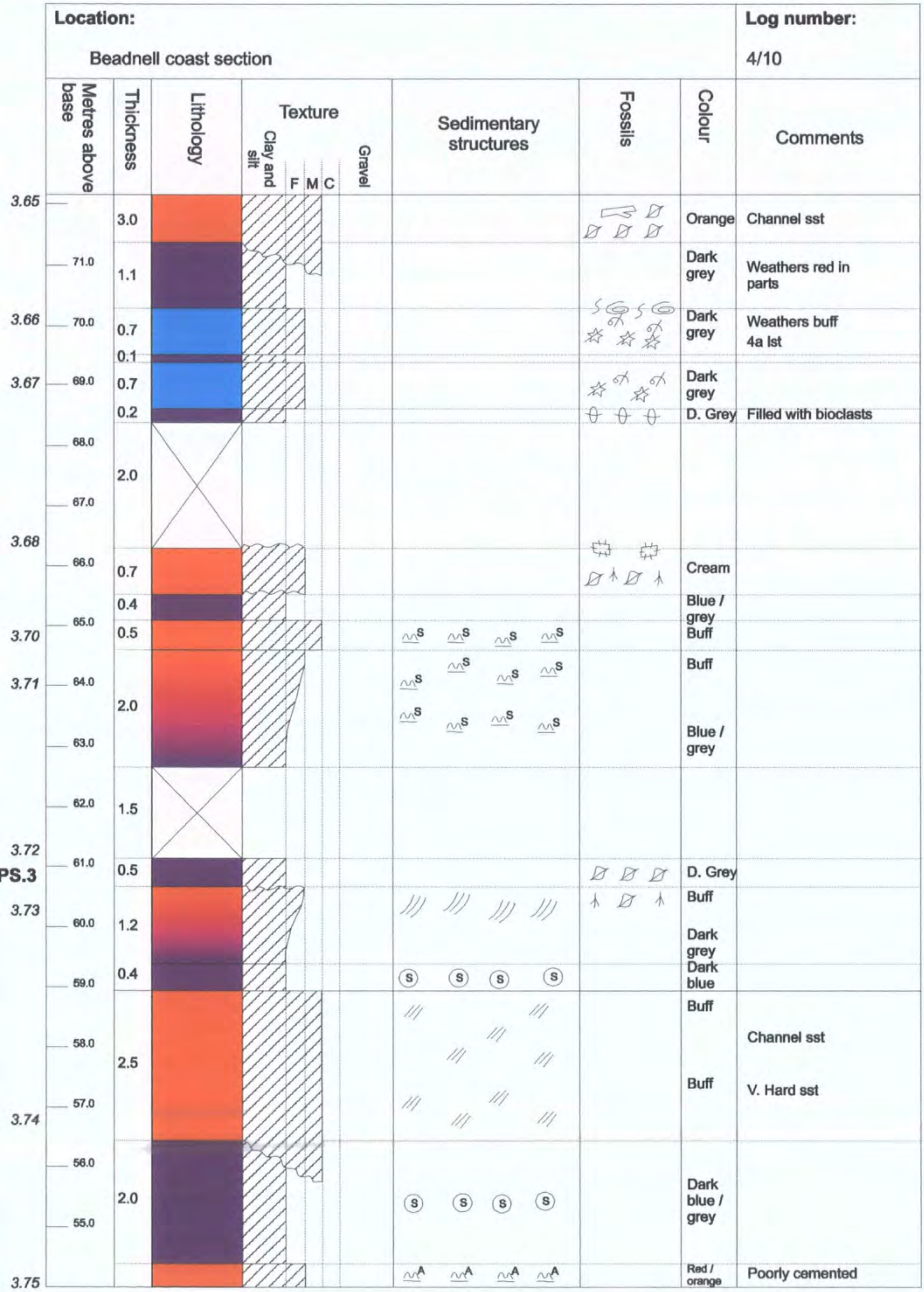
Log number: 1/10



Metres above base	Thickness	Lithology	Texture	Sedimentary structures	Fossils	Colour	Comments
	0.8					Dark grey	Clusters of fossils
	0.5					Pale grey	4f lst
	1.0						Inferred from outcrop
	0.9					Red	Poorly cemented
	1.0					Pale red	Layers of mud
	0.5					Red	
	1.25					Red	Micaceous sst
	2.0					Red	Large-scale x-bedding Highly micaceous Layers of mud
	2.0					Pale pink	Poorly cemented
	1.25					Purple/ pink Dark grey	Coarsening-upward sequence
	2.0						Oxford Lst
	1.0					Dark grey	
	0.3					D. Grey	
	0.3					D. Grey	
	0.3					Buff	Well cemented
	1.75					Buff	

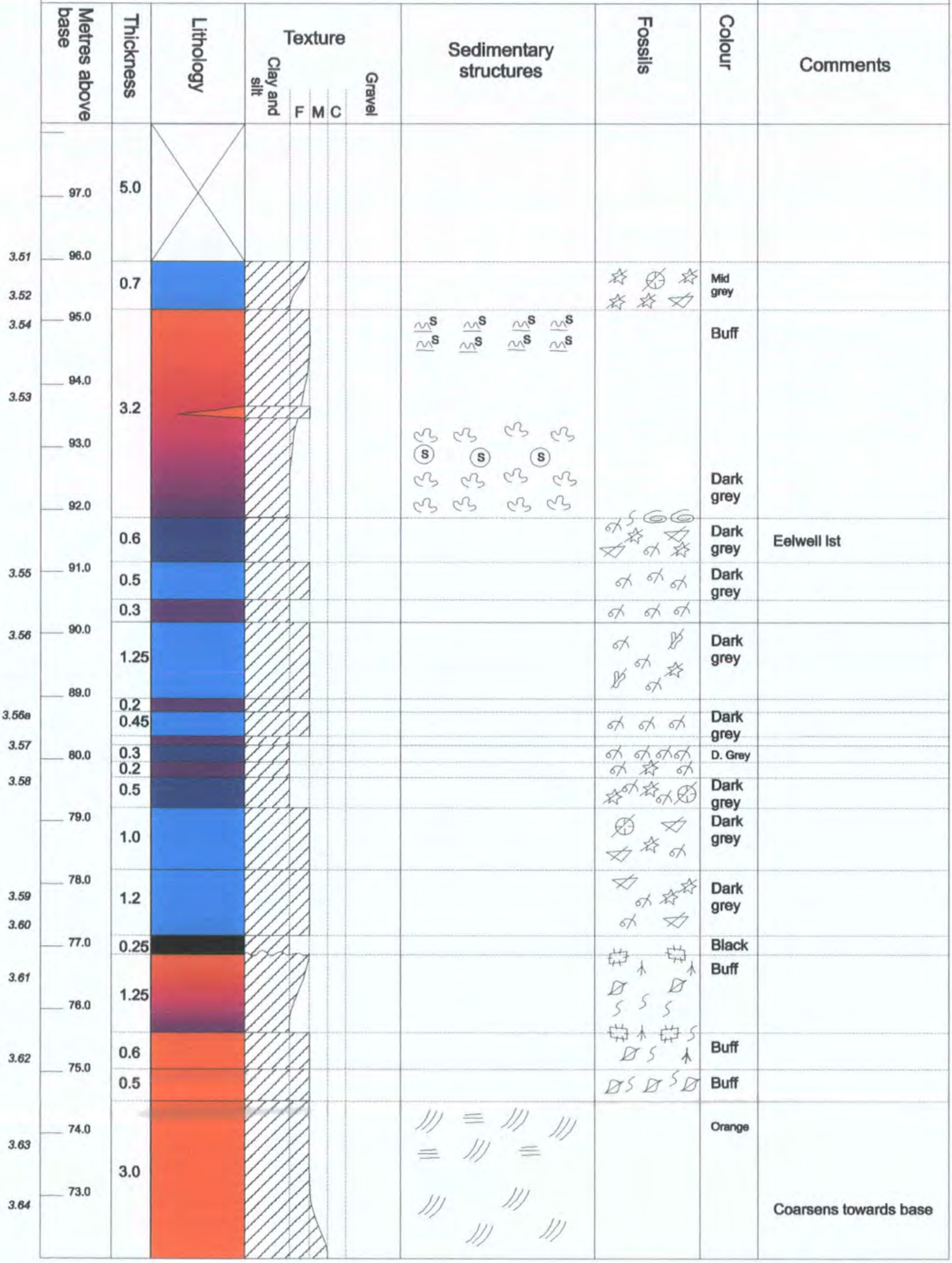

Location:
Beadnell coast section
Log number:
2/10
Metres above base
Thickness
Lithology
Texture
Clay and silt
F
M
C
Gravel
Sedimentary structures
Fossils
Colour
Comments
36.0
1.5
Dark grey
Coarsening-upward sequence
35.0
0.7
May be lst?
3.84a
34.0
3.5
Pale grey
Very well-cemented at top
3.83
3.86
33.0
32.0
31.0
Blue / grey
3.87
0.4
D. Grey
Crystalline
3.88
30.0
0.3
M. Grey
Crystalline
1.25
29.0
Mid grey
3.89
0.3
P. Grey
28.0
3.90
0.8
Pale grey
27.0
1.5
Pale grey
26.0
Blue / grey
3.91
25.0
1.4
Pale grey
Dark grey
3.92
24.0
0.7
Mid grey
4e lst
3.93
23.0
1.0
Grey
Abundant lithics
0.7
Buff
22.0
3.94
0.75
Cream
Micaceous
3.95
21.0
1.5
Buff
Channel sst
V. Poorly cemented
3.96
20.0
19.0
1.3
Dark grey
3.97
P. Grey


Location:
Beadnel coast section
Log number:
3/10
Metres above base
Thickness
Lithology
Texture
Clay and silt
F
M
C
Gravel
Sedimentary structures
Fossils
Colour
Comments
54.0
1.5
A
Dark grey
3.76
53.0
1.0
S
Buff
Dark grey
52.0
3.77
1.7
S
Pale grey
51.0
Dark grey
3.78
0.2
50.0
3.79
Red
49.0
48.0
47.0
7.0
V. Poorly cemented
46.0
Red
45.0
44.0
43.0
0.4
Blue/ grey
Weathers red
2.1
Buff
42.0
41.0
Dark grey
Nodules 3-20cm in diameter
S
3.80
40.0
1.0
Dark grey
3.81
39.0
1.3
Pale grey
Dark grey
38.0
0.7
3.82
37.0
0.7
Dark grey
3.83
0.3
M. Grey
3.84
S
Cream
Micaceous sst


Location:
Beadnell coast section
Log number:
4/10
Metres above base
Thickness
Lithology
Texture
Clay and silt
F
M
C
Gravel
Sedimentary structures
Fossils
Colour
Comments
3.65
3.0
Orange
Channel sst
71.0
1.1
Dark grey
Weathers red in parts
3.66
70.0
0.7
Dark grey
Weathers buff
4a lst
0.1
3.67
69.0
0.7
Dark grey
0.2
D. Grey
Filled with bioclasts
68.0
2.0
67.0
3.68
66.0
0.7
Cream
0.4
Blue / grey
65.0
3.70
0.5
Buff
S
3.71
64.0
2.0
Buff
Blue / grey
63.0
62.0
1.5
3.72
61.0
PS.3
0.5
D. Grey
3.73
60.0
1.2
Buff
Dark grey
0.4
Dark blue
59.0
S
Buff
58.0
Channel sst
2.5
Buff
V. Hard sst
57.0
3.74
56.0
2.0
Dark blue / grey
55.0
3.75
Red / orange
Poorly cemented
A

Location: Beadnell coast section

Log number: 5/10



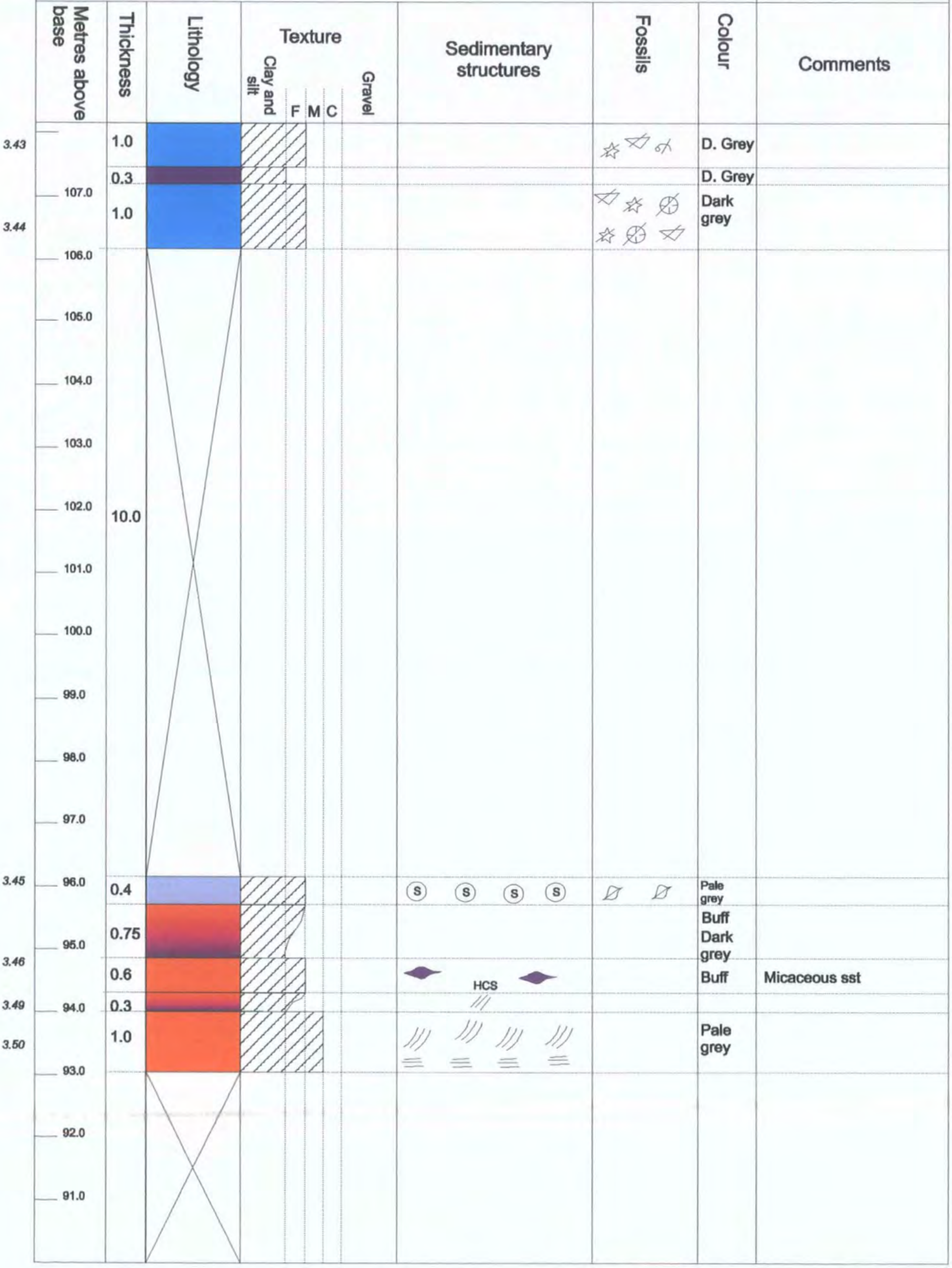
Thickness	Colour	Comments
5.0		
0.7	Mid grey	
3.2	Buff Dark grey	
0.6	Dark grey	Eelwell lst
0.5	Dark grey	
0.3		
1.25	Dark grey	
0.2		
0.45	Dark grey	
0.3	D. Grey	
0.2		
0.5	Dark grey	
1.0	Dark grey	
1.2	Dark grey	
0.25	Black	
1.25	Buff	
0.6	Buff	
0.5	Buff	
3.0	Orange	Coarsens towards base

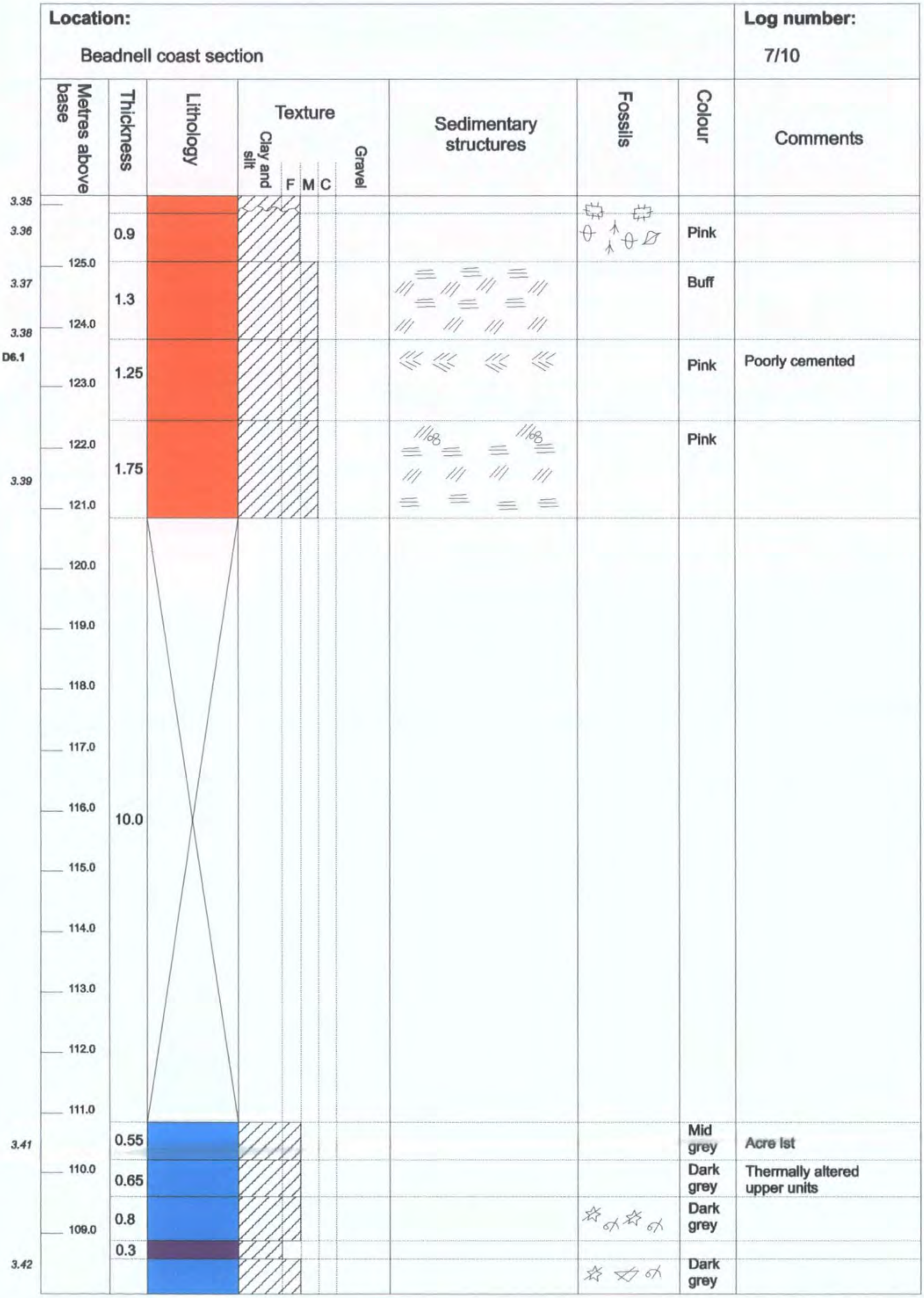
Location:

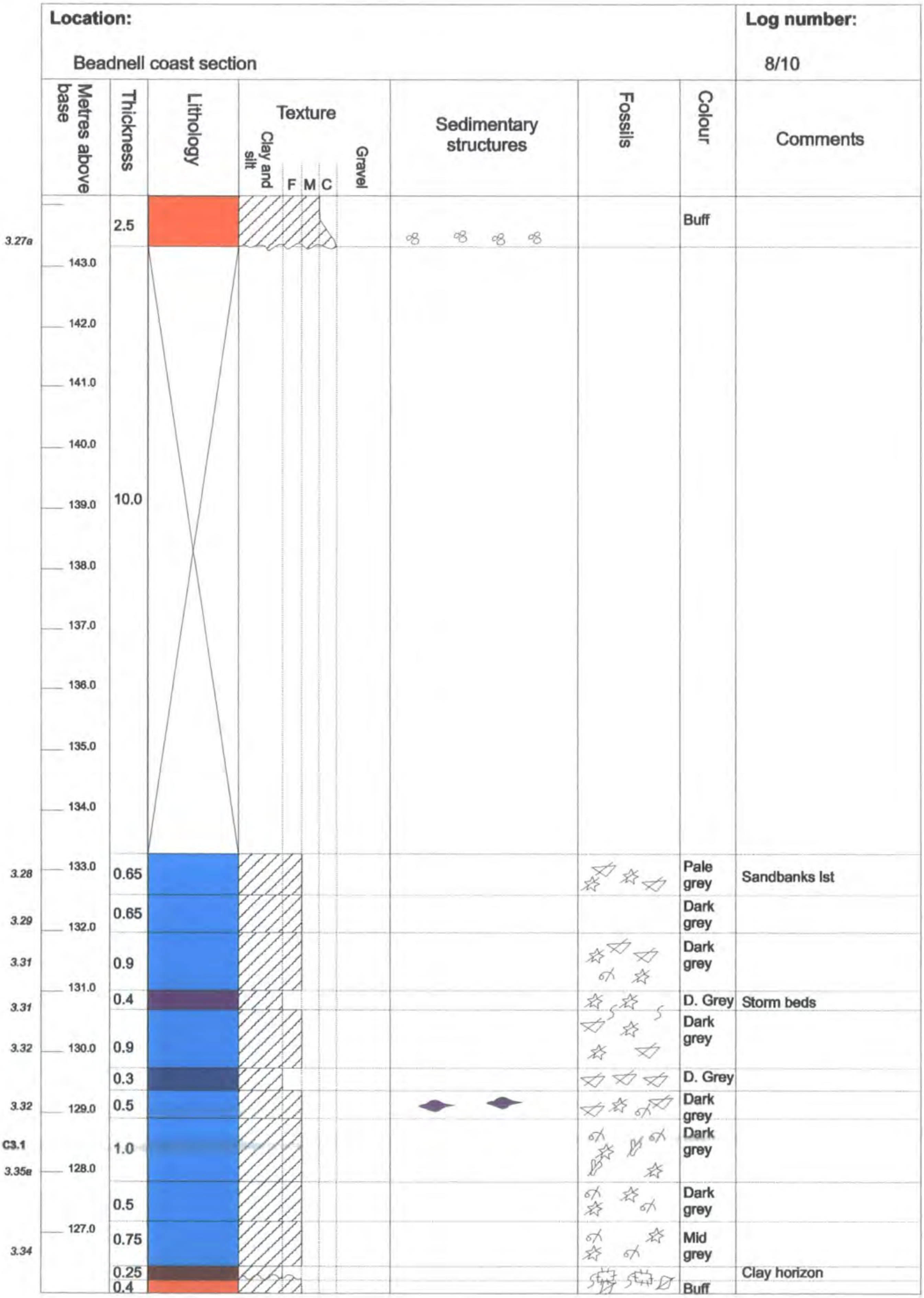
Beadnell coast section

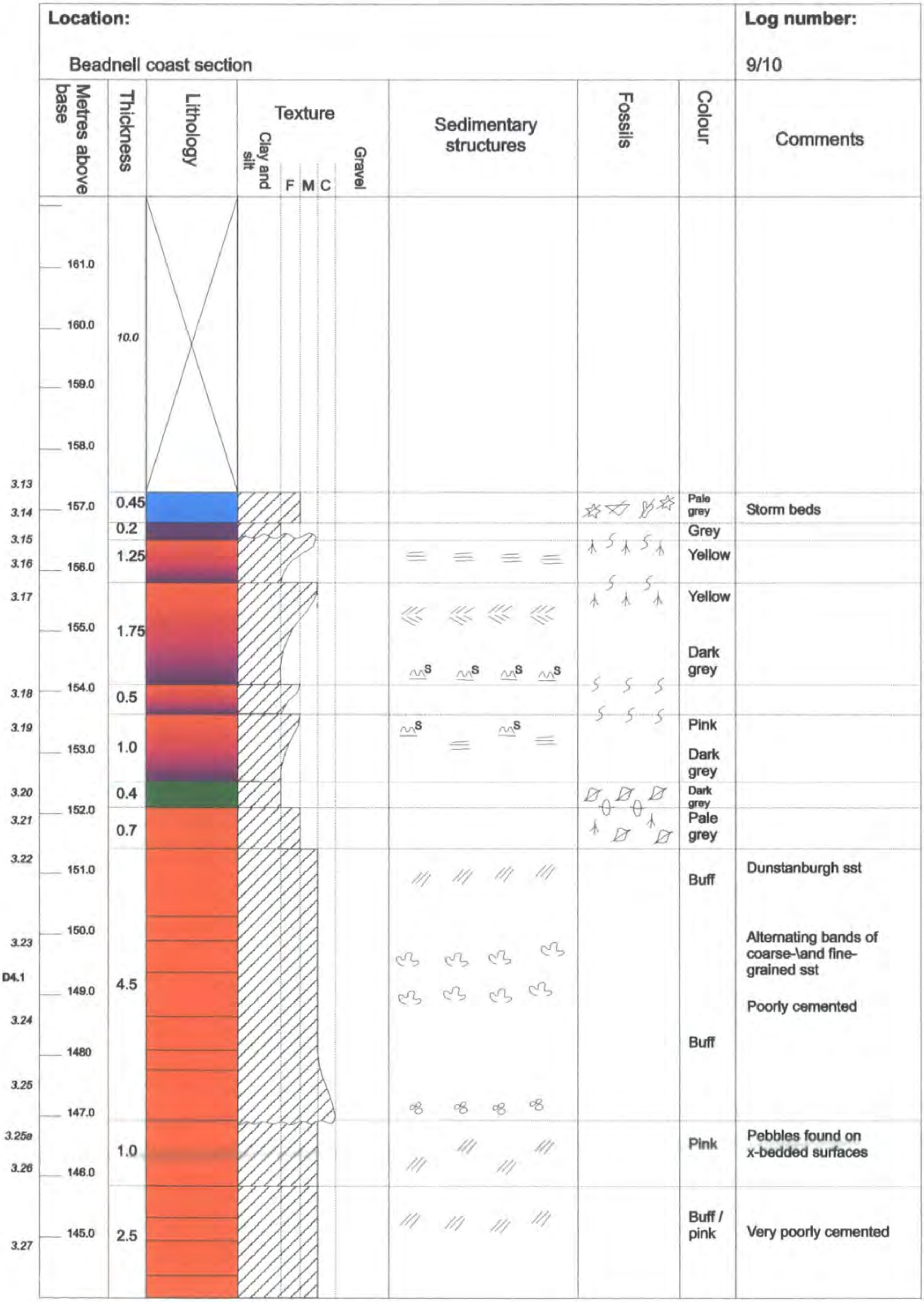
Log number:

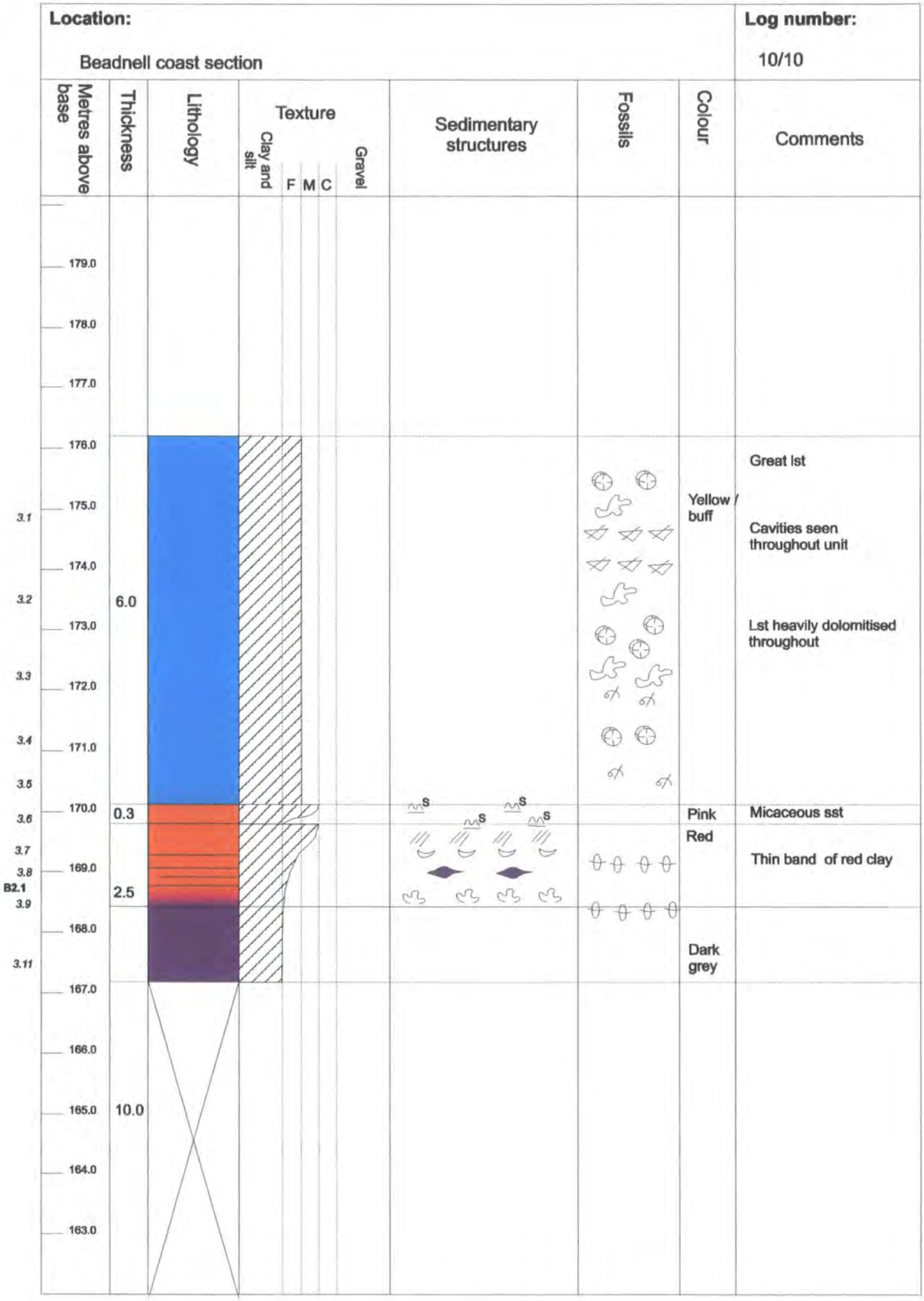
6/10

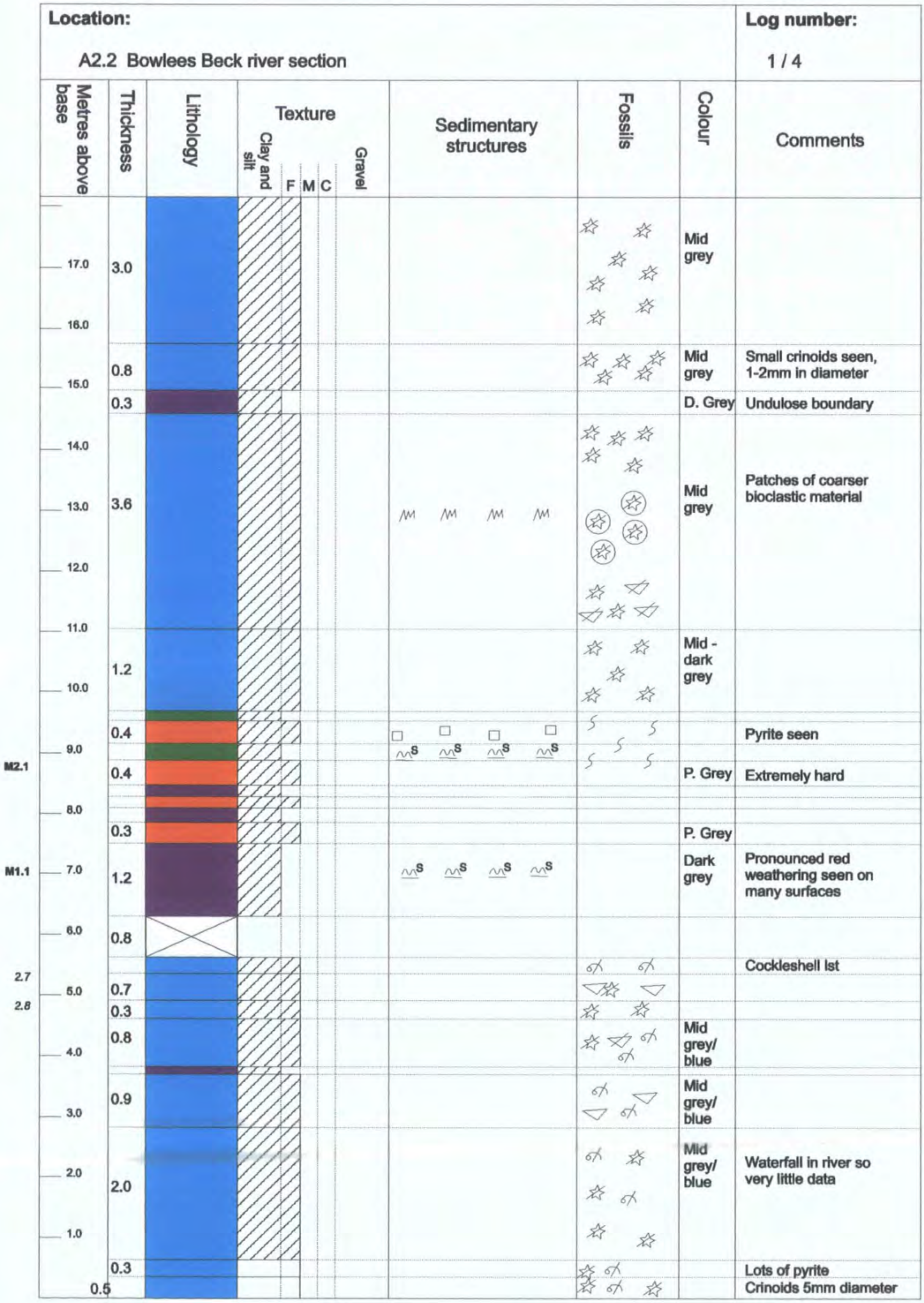


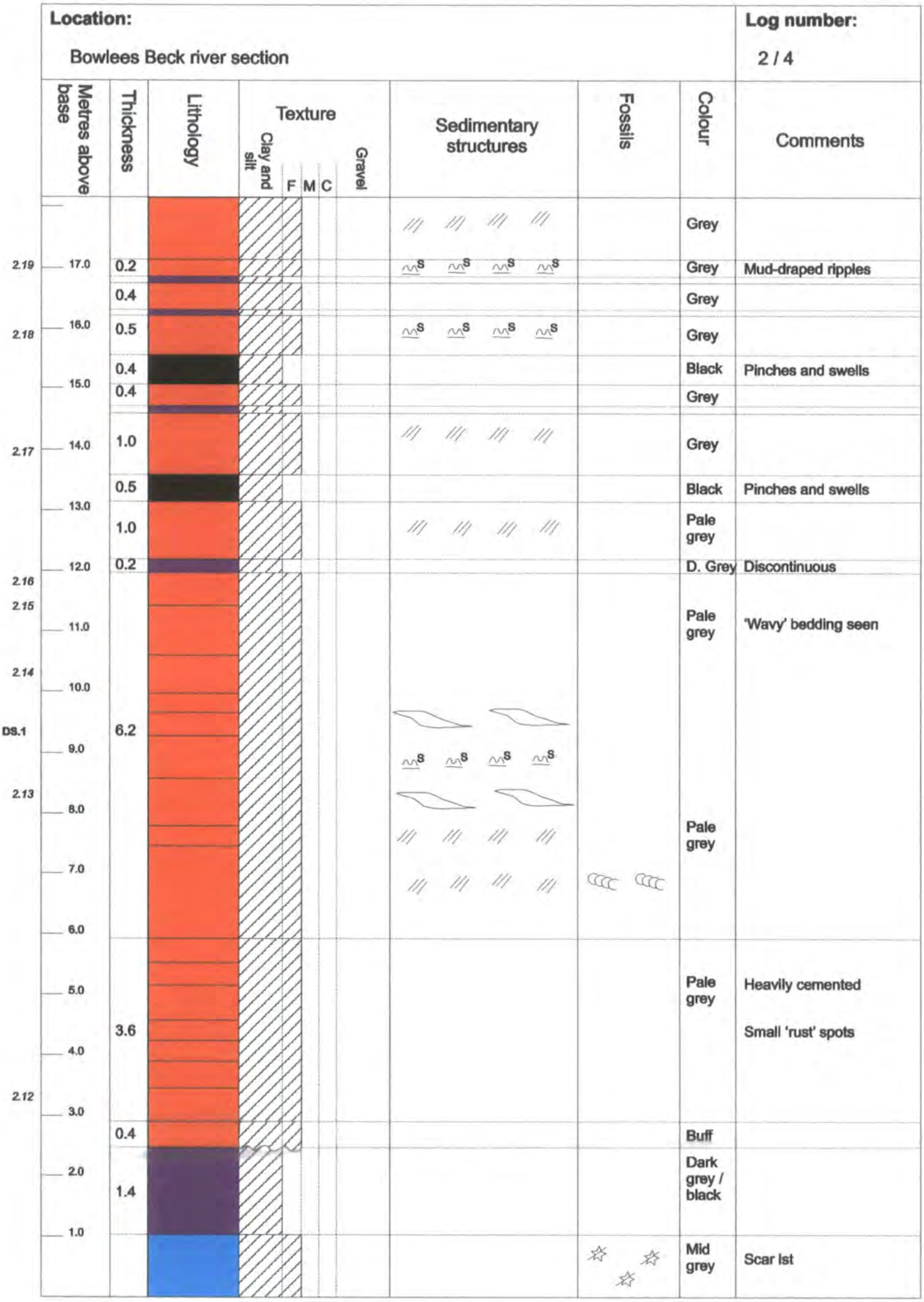

Location:
Beadnell coast section
Log number:
7/10
Metres above base
Thickness
Lithology
Texture
Clay and silt
F
M
C
Gravel
Sedimentary structures
Fossils
Colour
Comments
3.35
3.36
0.9
Pink
125.0
3.37
1.3
Buff
124.0
3.38
D6.1
1.25
Pink
Poorly cemented
123.0
122.0
Pink
1.75
3.39
121.0
120.0
119.0
118.0
117.0
116.0
10.0
115.0
114.0
113.0
112.0
111.0
Mid grey
3.41
0.55
Acre lst
110.0
0.65
Dark grey
Thermally altered upper units
0.8
Dark grey
109.0
0.3
3.42
Dark grey


Location:
Beadnell coast section
Log number:
8/10
Metres above base
Thickness
Lithology
Texture
Clay and silt
F
M
C
Gravel
Sedimentary structures
Fossils
Colour
Comments
3.27a
2.5
Buff
143.0
142.0
141.0
140.0
139.0
10.0
138.0
137.0
136.0
135.0
134.0
3.28
133.0
0.65
Pale grey
Sandbanks lst
3.29
132.0
0.65
Dark grey
3.31
0.9
Dark grey
131.0
3.31
0.4
D. Grey
Storm beds
0.9
Dark grey
3.32
130.0
0.3
D. Grey
3.32
129.0
0.5
Dark grey
C3.1
1.0
Dark grey
3.35a
128.0
0.5
Dark grey
127.0
3.34
0.75
Mid grey
0.25
Clay horizon
0.4
Buff


Location:
Beadnell coast section
Log number:
9/10
Metres above base
Thickness
Lithology
Texture
Clay and silt
F
M
C
Gravel
Sedimentary structures
Fossils
Colour
Comments
161.0
160.0
10.0
159.0
158.0
3.13
3.14
157.0
0.45
Pale grey
Storm beds
3.15
0.2
Grey
3.16
156.0
1.25
Yellow
3.17
Yellow
155.0
1.75
Dark grey
S
3.18
154.0
0.5
3.19
Pink
153.0
1.0
Dark grey
3.20
0.4
Dark grey
3.21
152.0
0.7
Pale grey
3.22
151.0
Buff
Dunstanburgh sst
150.0
3.23
Alternating bands of coarse-\and fine-grained sst
D4.1
149.0
4.5
Poorly cemented
3.24
Buff
1480
3.25
147.0
3.25a
1.0
Pink
Pebbles found on x-bedded surfaces
3.26
146.0
Buff / pink
145.0
2.5
Very poorly cemented
3.27


Location:
Beadnell coast section
Log number:
10/10
Metres above base
Thickness
Lithology
Texture
Clay and silt
F
M
C
Gravel
Sedimentary structures
Fossils
Colour
Comments
179.0
178.0
177.0
176.0
175.0
174.0
173.0
172.0
171.0
170.0
169.0
168.0
167.0
166.0
165.0
164.0
163.0
3.1
3.2
3.3
3.4
3.5
3.6
3.7
3.8
B2.1
3.9
3.11
6.0
0.3
2.5
10.0
S
S
S
S
Yellow / buff
Pink
Red
Dark grey
Great lst
Cavities seen throughout unit
Lst heavily dolomitised throughout
Micaceous sst
Thin band of red clay


Location:
A2.2 Bowlees Beck river section
Log number:
1 / 4
Metres above base
Thickness
Lithology
Texture
Clay and silt
F
M
C
Gravel
Sedimentary structures
Fossils
Colour
Comments
17.0
16.0
15.0
14.0
13.0
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.5
M2.1
M1.1
2.7
2.8
3.0
0.8
0.3
3.6
1.2
0.4
0.4
0.3
1.2
0.8
0.7
0.3
0.8
0.9
2.0
0.3
Mid grey
Mid grey
Small crinoids seen, 1-2mm in diameter
D. Grey
Undulose boundary
Mid grey
Patches of coarser bioclastic material
Mid - dark grey
Pyrite seen
S
P. Grey
Extremely hard
P. Grey
Dark grey
Pronounced red weathering seen on many surfaces
Cockleshell lst
Mid grey/ blue
Mid grey/ blue
Mid grey/ blue
Waterfall in river so very little data
Lots of pyrite
Crinoids 5mm diameter



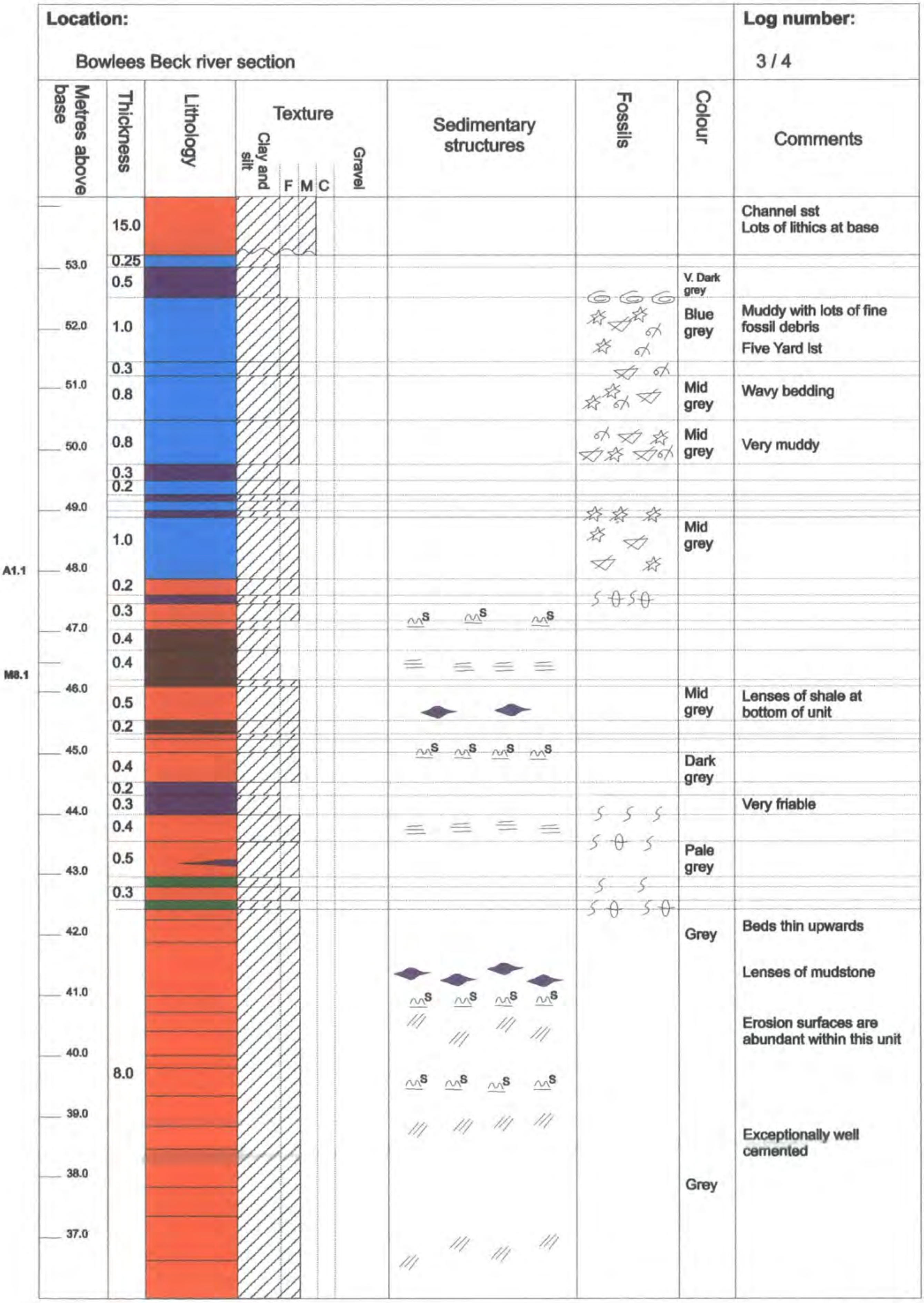
Location:

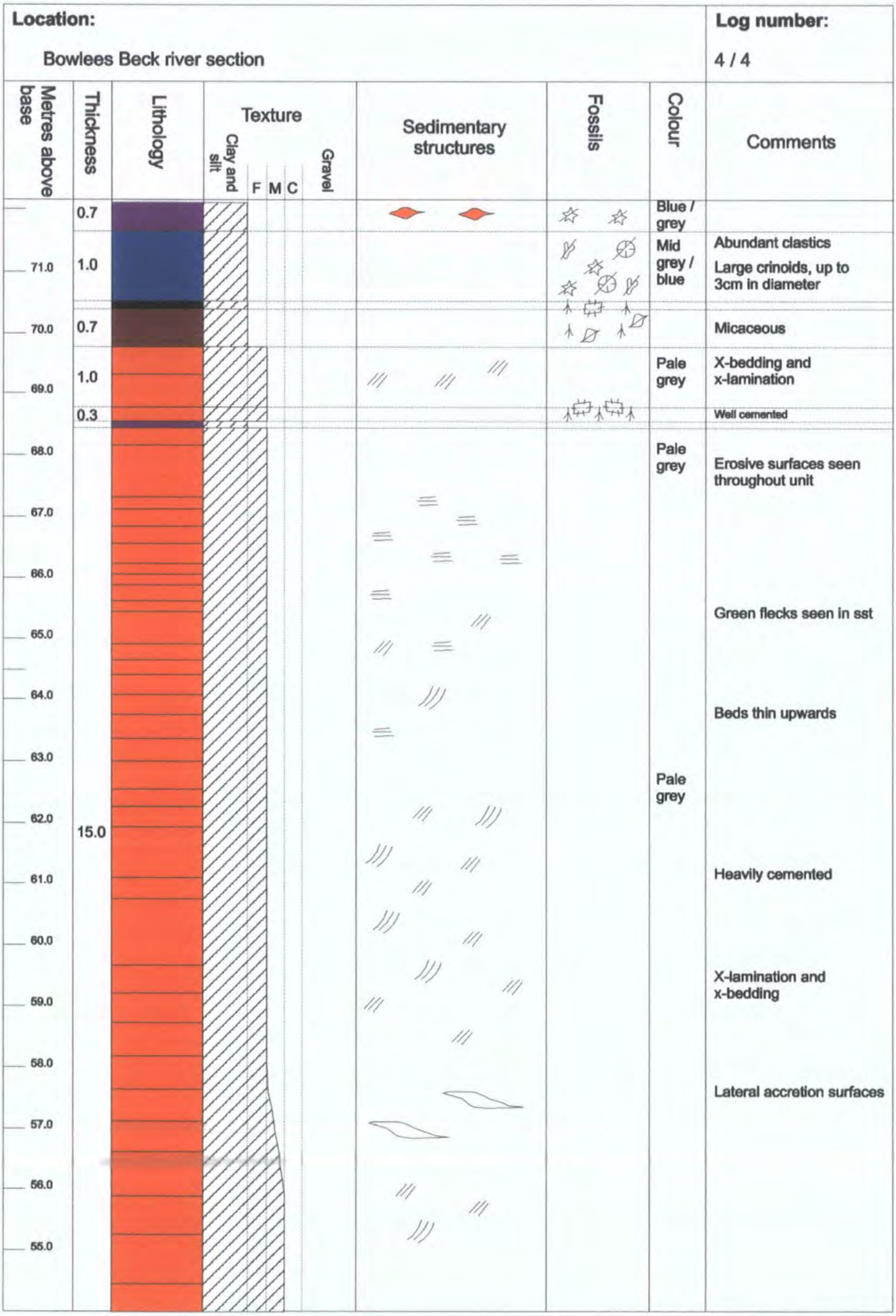
Bowlees Beck river section

Log number:

2 / 4

Thickness	Colour	Comments
	Grey	
0.2	Grey	Mud-draped ripples
0.4	Grey	
0.5	Grey	
0.4	Black	Pinches and swells
0.4	Grey	
1.0	Grey	
0.5	Black	Pinches and swells
1.0	Pale grey	
0.2	D. Grey	Discontinuous
6.2	Pale grey Pale grey	'Wavy' bedding seen
3.6	Pale grey	Heavily cemented Small 'rust' spots
0.4	Buff	
1.4	Dark grey / black	
	Mid grey	Scar lst


Location:
Bowlees Beck river section
Log number:
3 / 4
Metres above base
Thickness
Lithology
Texture
Clay and silt
F
M
C
Gravel
Sedimentary structures
Fossils
Colour
Comments
15.0
Channel sst
Lots of lithics at base
53.0
0.25
0.5
V. Dark grey
52.0
1.0
Blue grey
Muddy with lots of fine fossil debris
Five Yard lst
0.3
51.0
0.8
Mid grey
Wavy bedding
50.0
0.8
Mid grey
Very muddy
0.3
0.2
49.0
1.0
Mid grey
A1.1
48.0
0.2
0.3
47.0
0.4
0.4
M8.1
46.0
0.5
Mid grey
Lenses of shale at bottom of unit
0.2
45.0
0.4
Dark grey
0.2
0.3
Very friable
44.0
0.4
0.5
Pale grey
43.0
0.3
42.0
Grey
Beds thin upwards
Lenses of mudstone
41.0
Erosion surfaces are abundant within this unit
40.0
8.0
39.0
Exceptionally well cemented
38.0
Grey
37.0

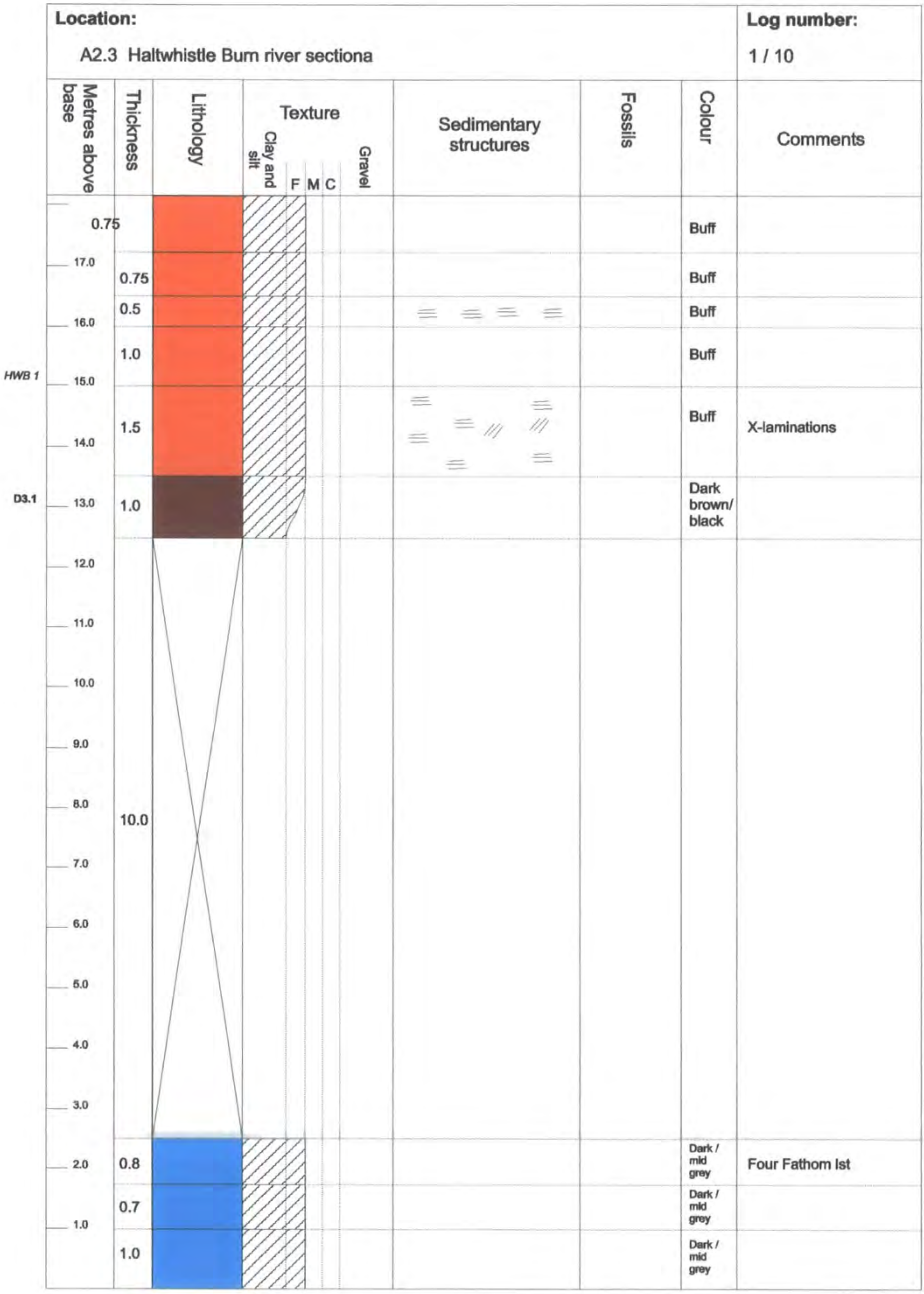

Location:
Bowlees Beck river section
Log number:
4 / 4
Metres above base
Thickness
Lithology
Texture
Clay and silt
F
M
C
Gravel
Sedimentary structures
Fossils
Colour
Comments
0.7
Blue / grey
1.0
Mid grey / blue
Abundant clastics
Large crinoids, up to 3cm in diameter
0.7
Micaceous
1.0
Pale grey
X-bedding and x-lamination
0.3
Well cemented
Pale grey
Erosive surfaces seen throughout unit
Green flecks seen in sst
Beds thin upwards
Pale grey
15.0
Heavily cemented
X-lamination and x-bedding
Lateral accretion surfaces
71.0
70.0
69.0
68.0
67.0
66.0
65.0
64.0
63.0
62.0
61.0
60.0
59.0
58.0
57.0
56.0
55.0

Location:

A2.3 Haltwhistle Burn river sectiona

Log number:

1 / 10



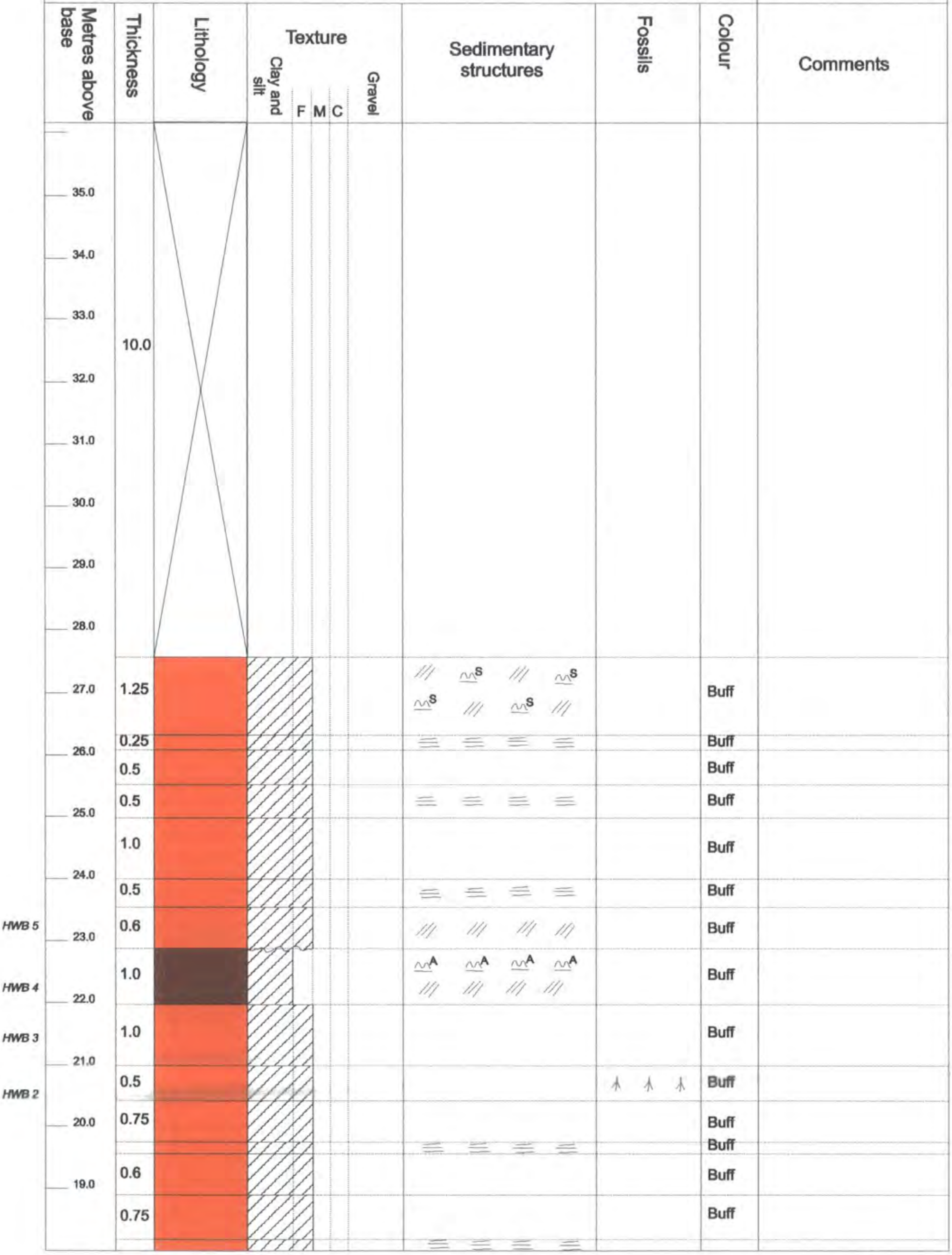
Metres above base	Thickness	Lithology	Texture	Sedimentary structures	Fossils	Colour	Comments
0.75						Buff	
	0.75					Buff	
	0.5					Buff	
	1.0					Buff	
	1.5					Buff	X-laminations
	1.0					Dark brown/ black	
	10.0						
	0.8					Dark / mid grey	Four Fathom lst
	0.7					Dark / mid grey	
	1.0					Dark / mid grey	

Location:

Haltwhistle Burn river section

Log number:

2 / 10

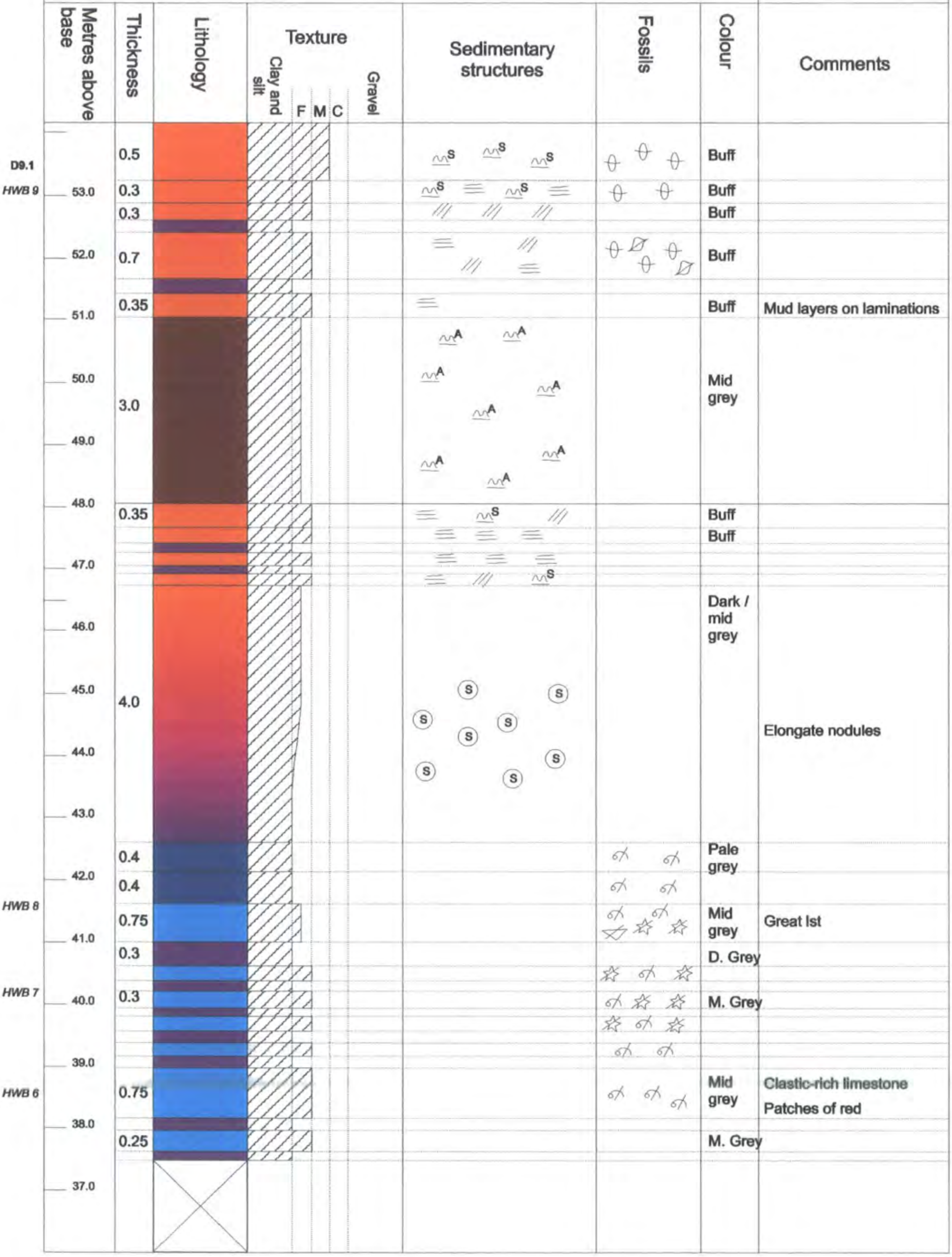


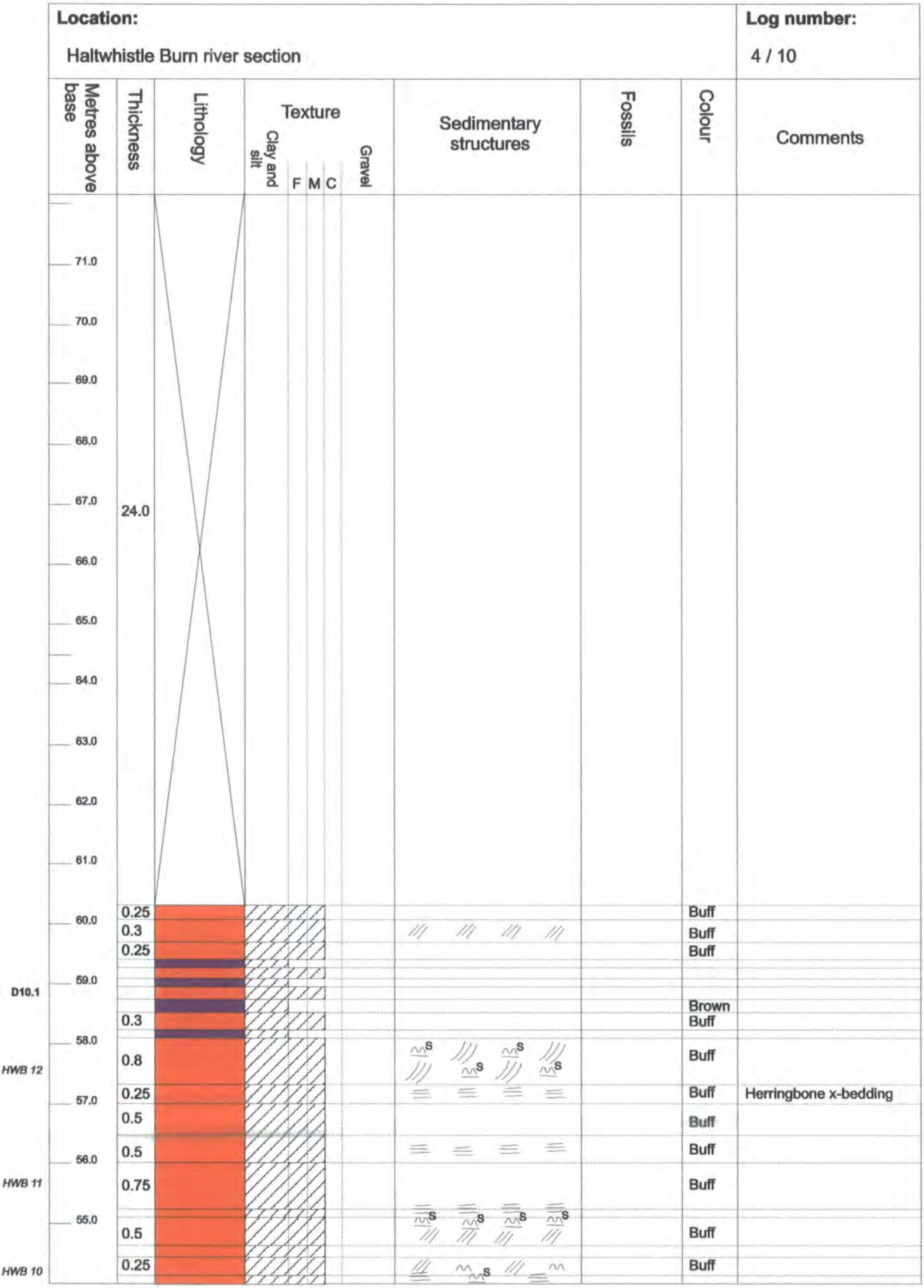
Location:

Haltwhistle Burn river section

Log number:

3 / 10



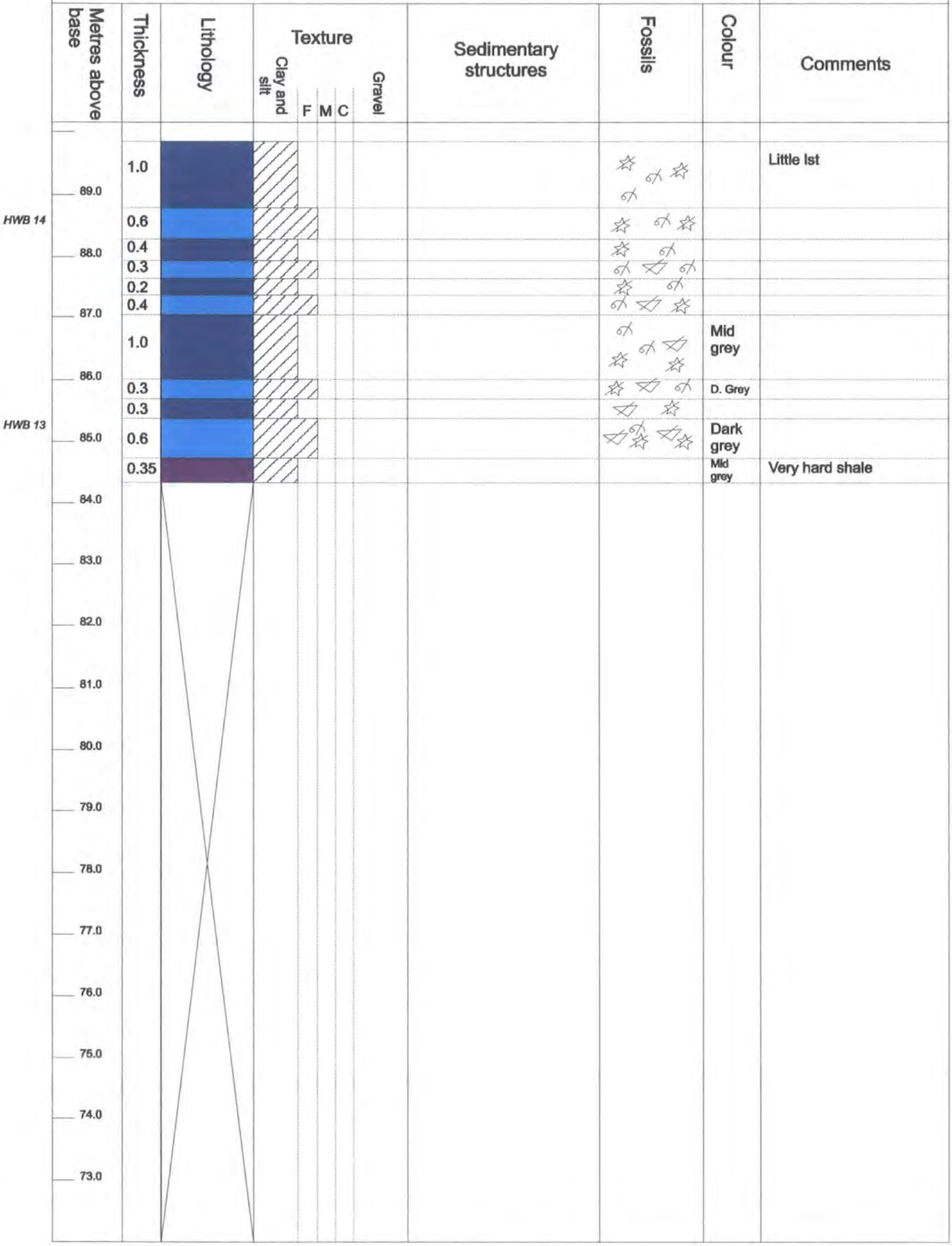

Location:
Haltwhistle Burn river section
Log number:
4 / 10
Metres above base
Thickness
Lithology
Texture
Clay and silt
F
M
C
Gravel
Sedimentary structures
Fossils
Colour
Comments
71.0
70.0
69.0
68.0
67.0
66.0
65.0
64.0
63.0
62.0
61.0
60.0
59.0
58.0
57.0
56.0
55.0
24.0
0.25
0.3
0.25
0.3
0.8
0.25
0.5
0.5
0.75
0.5
0.25
D10.1
HWB 12
HWB 11
HWB 10
S
Buff
Buff
Buff
Brown
Buff
Buff
Buff
Buff
Buff
Buff
Buff
Buff
Herringbone x-bedding

Location:

Haltwhistle Burn river section

Log number:

5 / 10



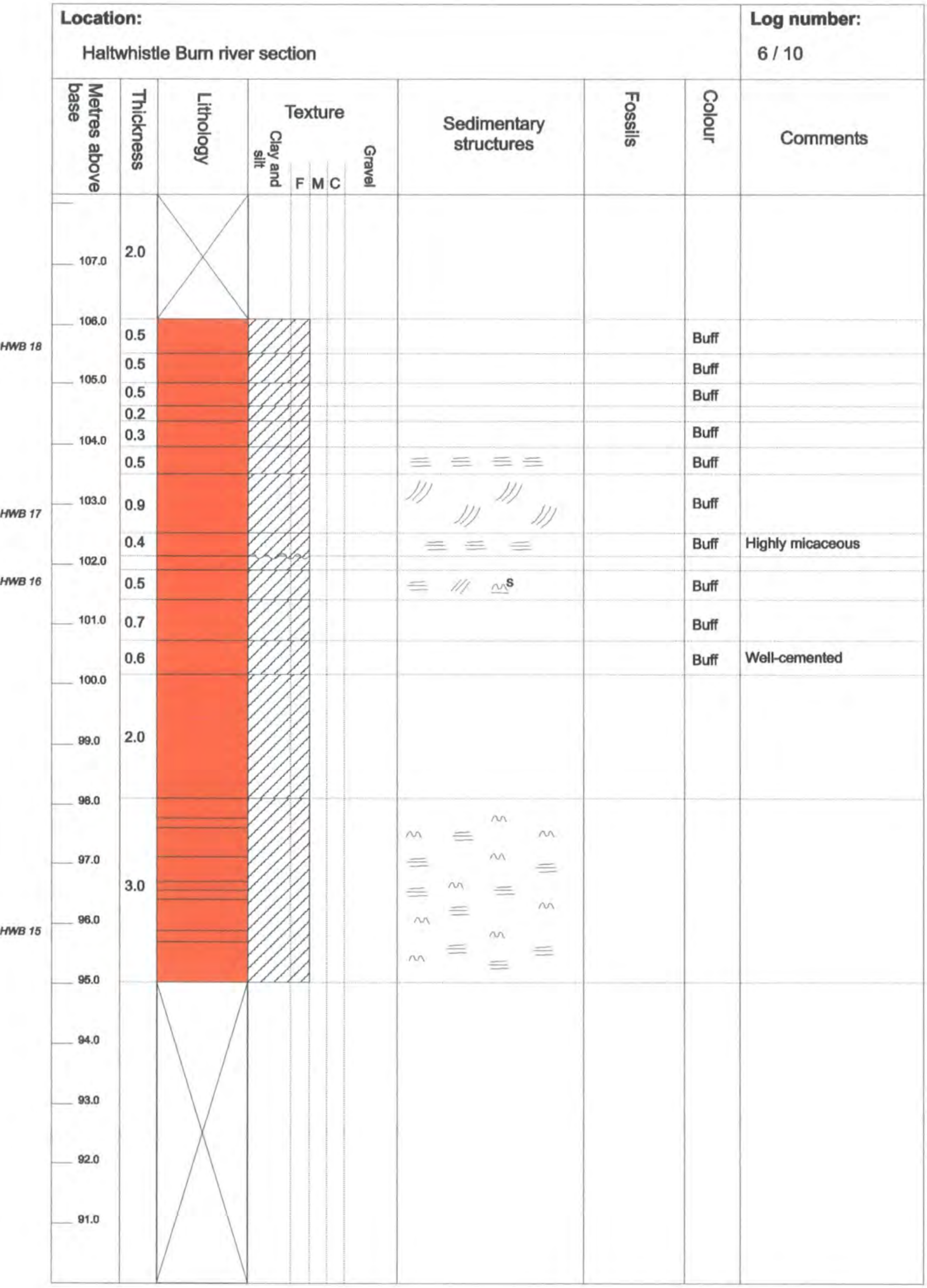
Thickness	Colour	Comments
1.0		Little lst
0.6		
0.4		
0.3		
0.2		
0.4		
1.0	Mid grey	
0.3	D. Grey	
0.3		
0.6	Dark grey	
0.35	Mid grey	Very hard shale

Location:

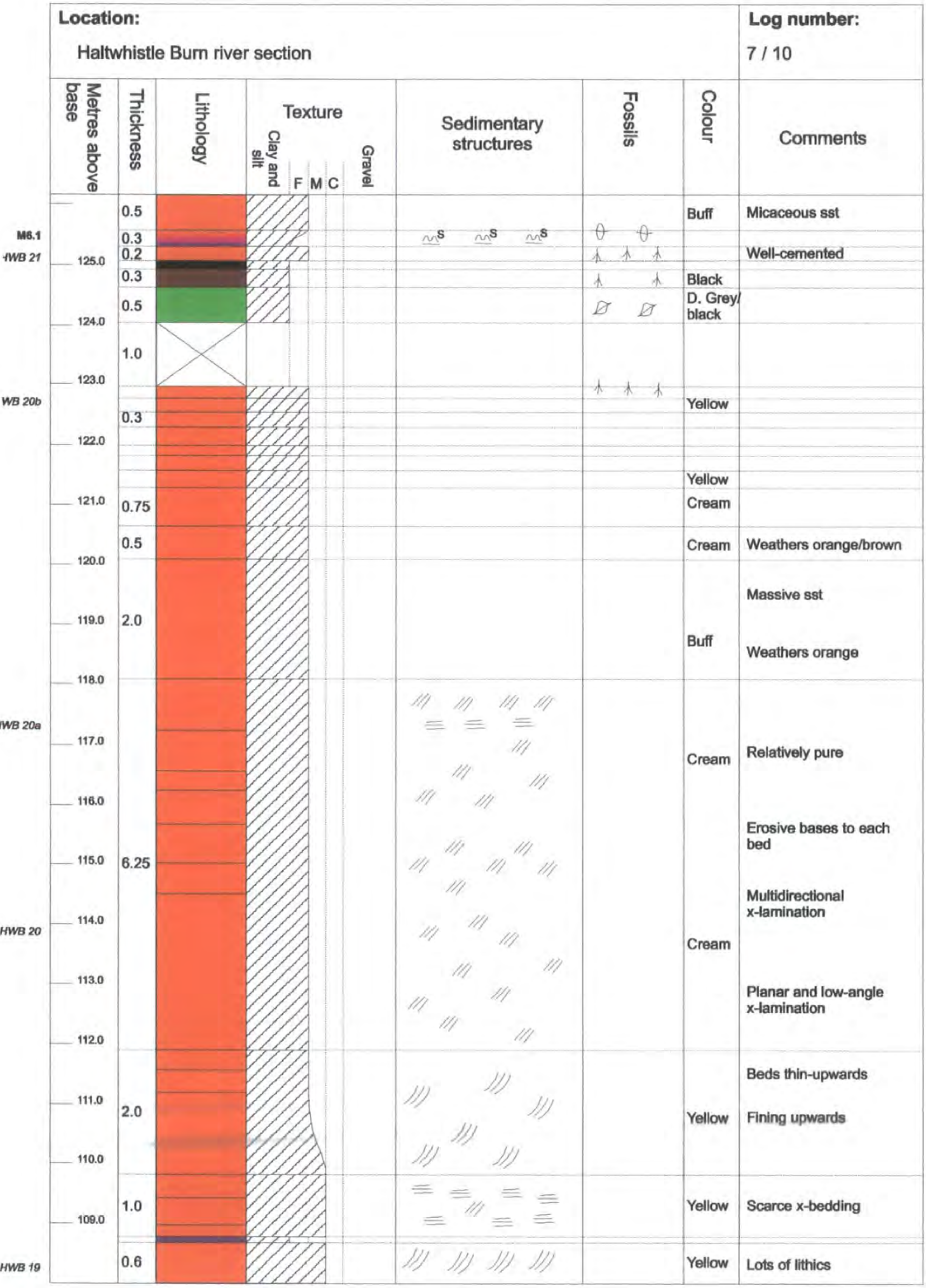
Haltwhistle Burn river section

Log number:

6 / 10



Thickness	Colour	Comments
2.0		
0.5	Buff	
0.5	Buff	
0.5	Buff	
0.2		
0.3	Buff	
0.5	Buff	
0.9	Buff	
0.4	Buff	Highly micaceous
0.5	Buff	
0.7	Buff	
0.6	Buff	Well-cemented
2.0		
3.0		

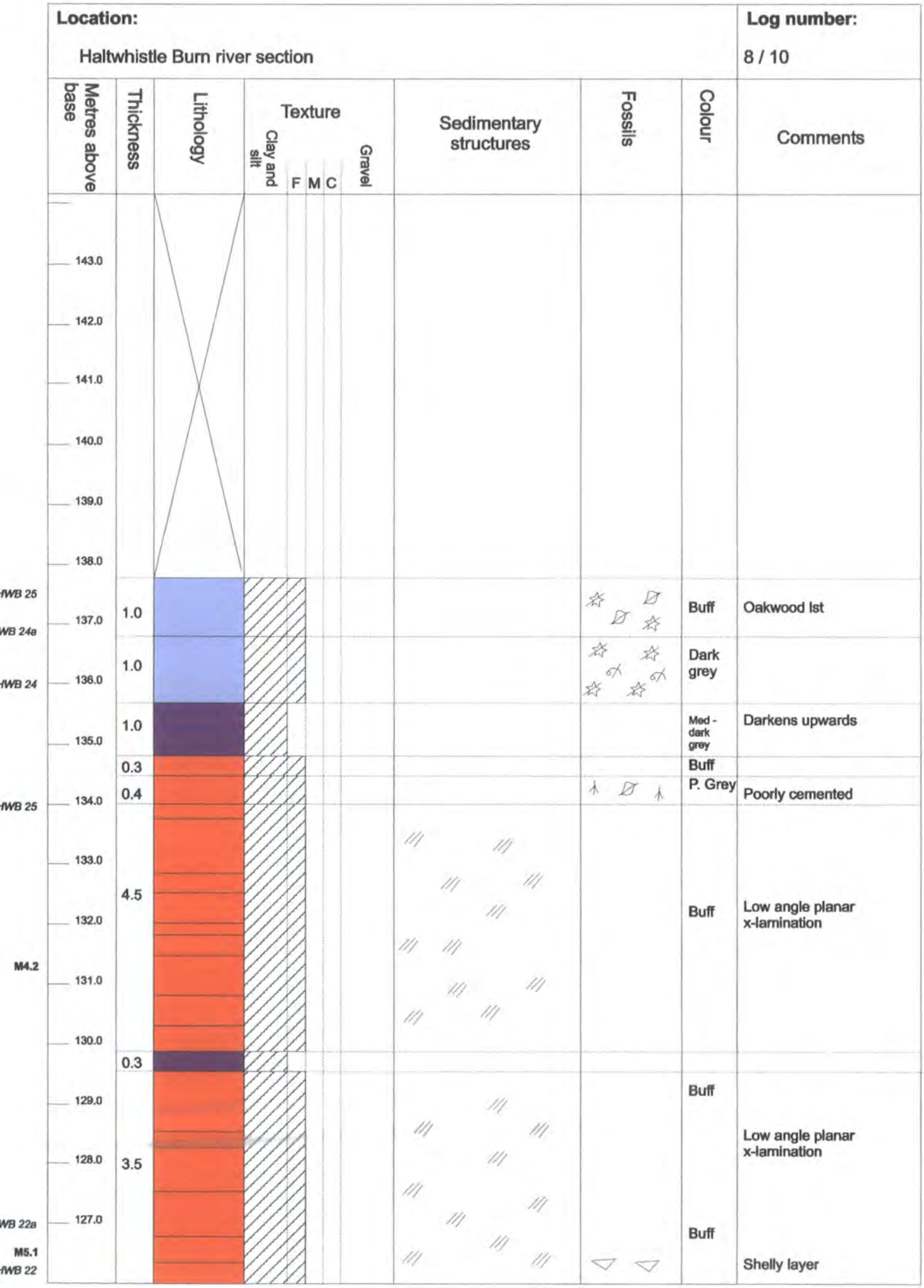

Location:
Haltwhistle Burn river section
Log number:
7 / 10
Metres above base
Thickness
Lithology
Texture
Clay and silt
F
M
C
Gravel
Sedimentary structures
Fossils
Colour
Comments
0.5
Buff
Micaceous sst
M6.1
0.3
S
S
S
HWB 21
125.0
0.2
Well-cemented
0.3
Black
0.5
D. Grey/ black
124.0
1.0
123.0
WB 20b
Yellow
0.3
122.0
Yellow
121.0
0.75
Cream
0.5
Cream
Weathers orange/brown
120.0
Massive sst
119.0
2.0
Buff
Weathers orange
118.0
WB 20a
117.0
Cream
Relatively pure
116.0
Erosive bases to each bed
115.0
6.25
Multidirectional x-lamination
114.0
HWB 20
Cream
113.0
Planar and low-angle x-lamination
112.0
Beds thin-upwards
111.0
2.0
Yellow
Fining upwards
110.0
1.0
Yellow
Scarce x-bedding
109.0
HWB 19
0.6
Yellow
Lots of lithics

Location:

Haltwhistle Burn river section

Log number:

8 / 10



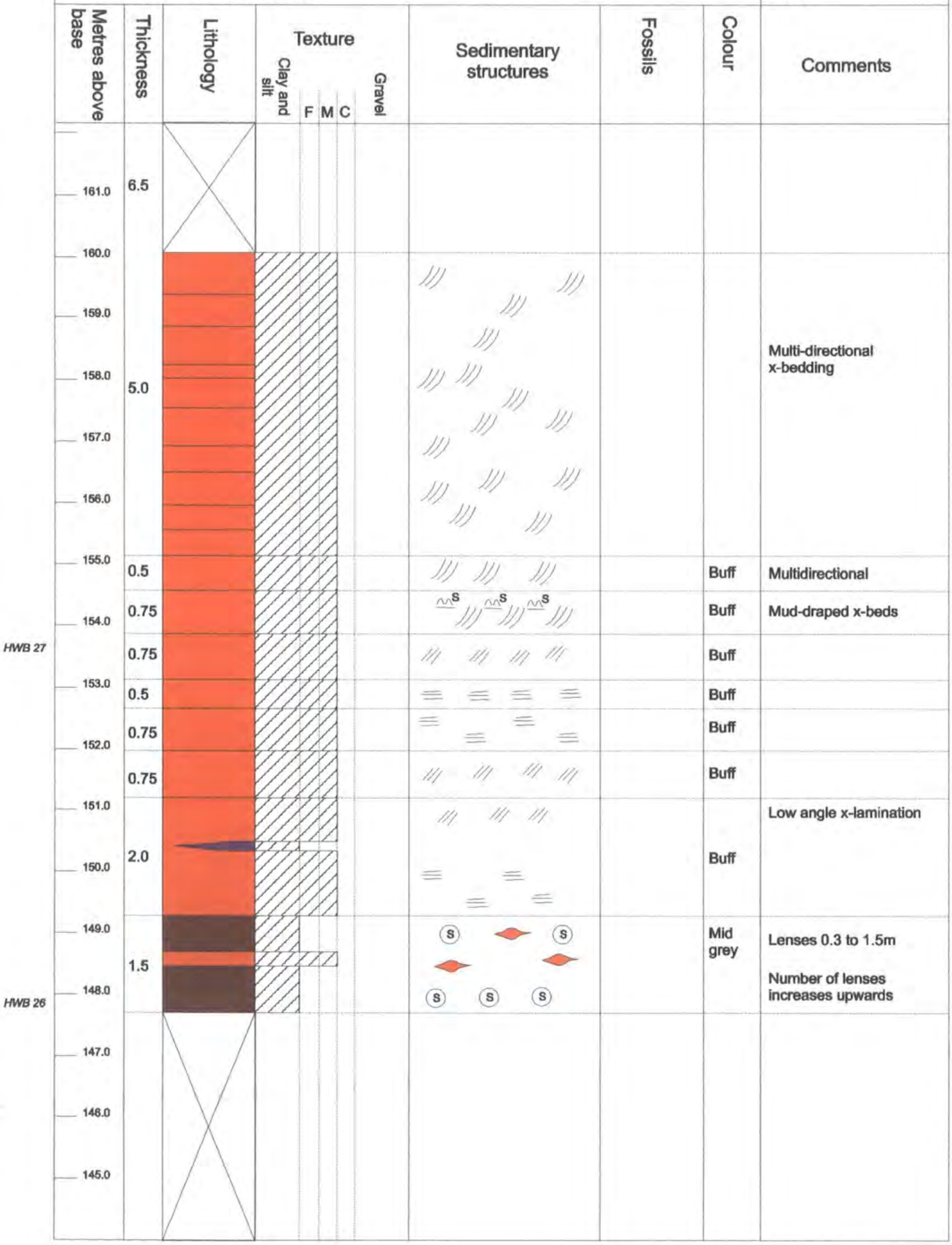
Thickness	Colour	Comments
1.0	Buff	Oakwood lst
1.0	Dark grey	
1.0	Med - dark grey	Darkens upwards
0.3	Buff	
0.4	P. Grey	Poorly cemented
4.5	Buff	Low angle planar x-lamination
0.3		
3.5	Buff Buff	Low angle planar x-lamination Shelly layer

Location:

Haltwhistle Burn river section

Log number:

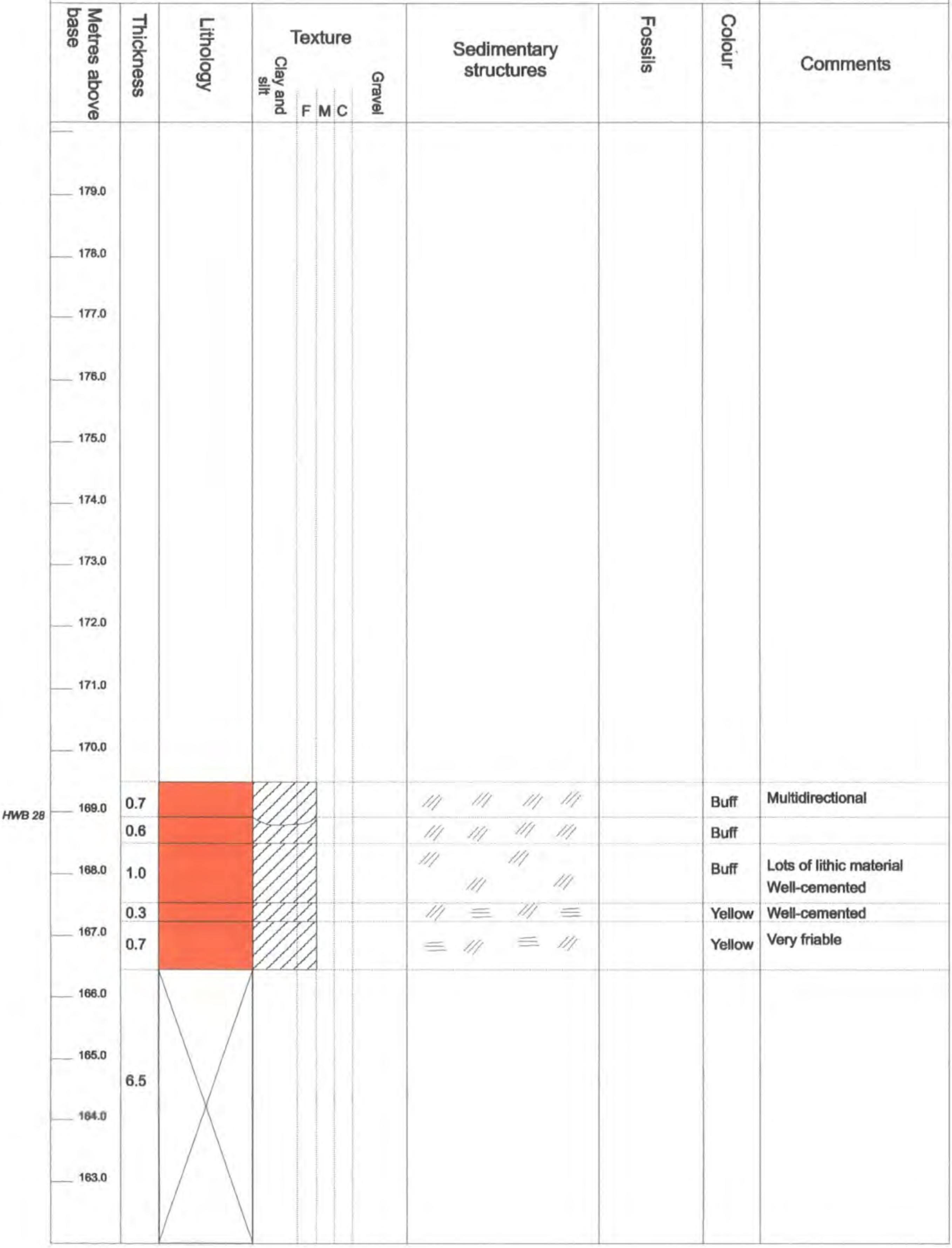
9 / 10



Metres above base	Thickness	Lithology	Texture	Sedimentary structures	Fossils	Colour	Comments
	6.5						
	5.0						Multi-directional x-bedding
	0.5					Buff	Multidirectional
	0.75					Buff	Mud-draped x-beds
HWB 27	0.75					Buff	
	0.5					Buff	
	0.75					Buff	
	0.75					Buff	
	2.0					Buff	Low angle x-lamination
HWB 26	1.5					Mid grey	Lenses 0.3 to 1.5m Number of lenses increases upwards

Location: Haltwhistle Burn river section

Log number: 10 / 10



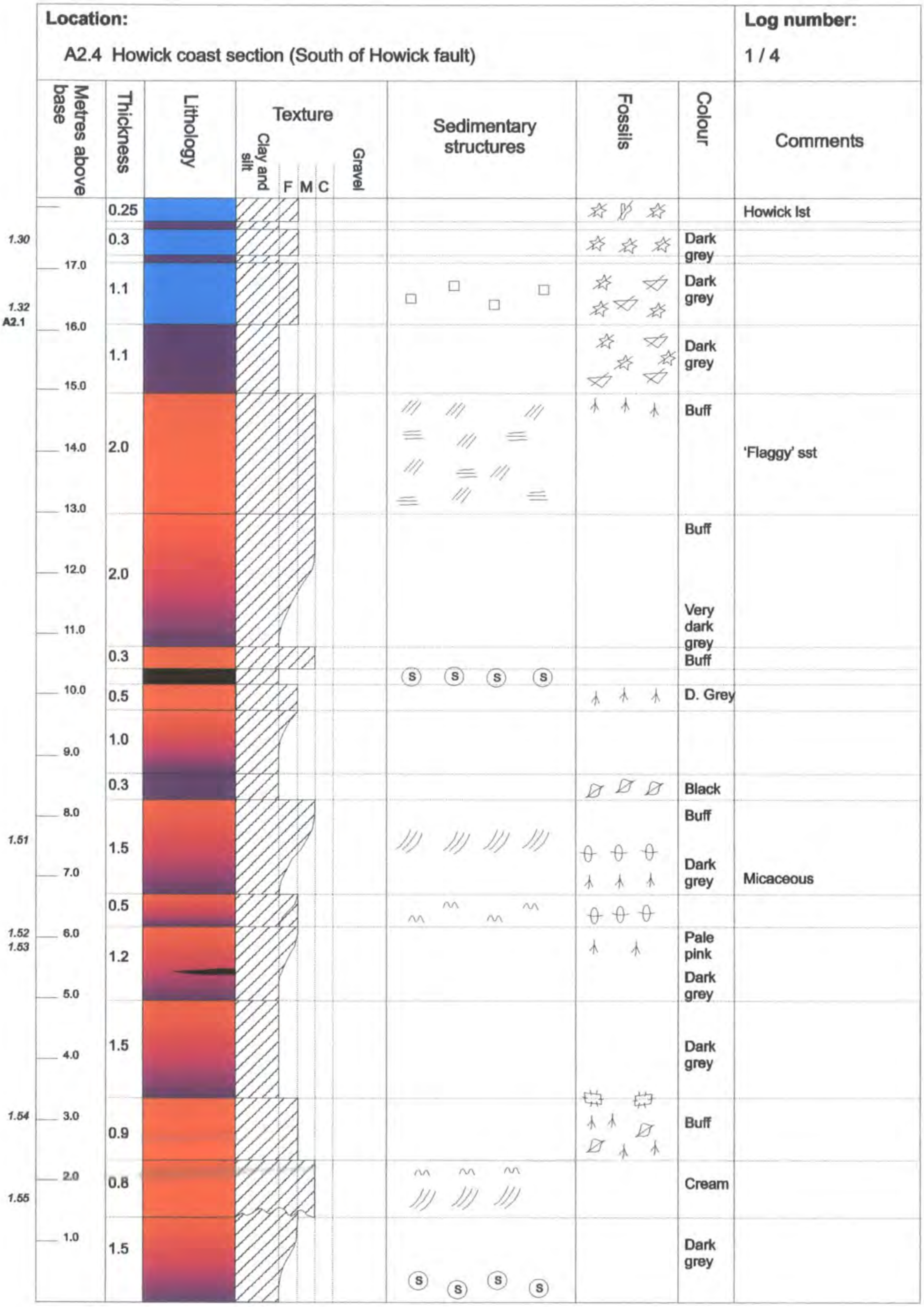
Thickness	Colour	Comments
0.7	Buff	Multidirectional
0.6	Buff	
1.0	Buff	Lots of lithic material Well-cemented
0.3	Yellow	Well-cemented
0.7	Yellow	Very friable
6.5		

Location:

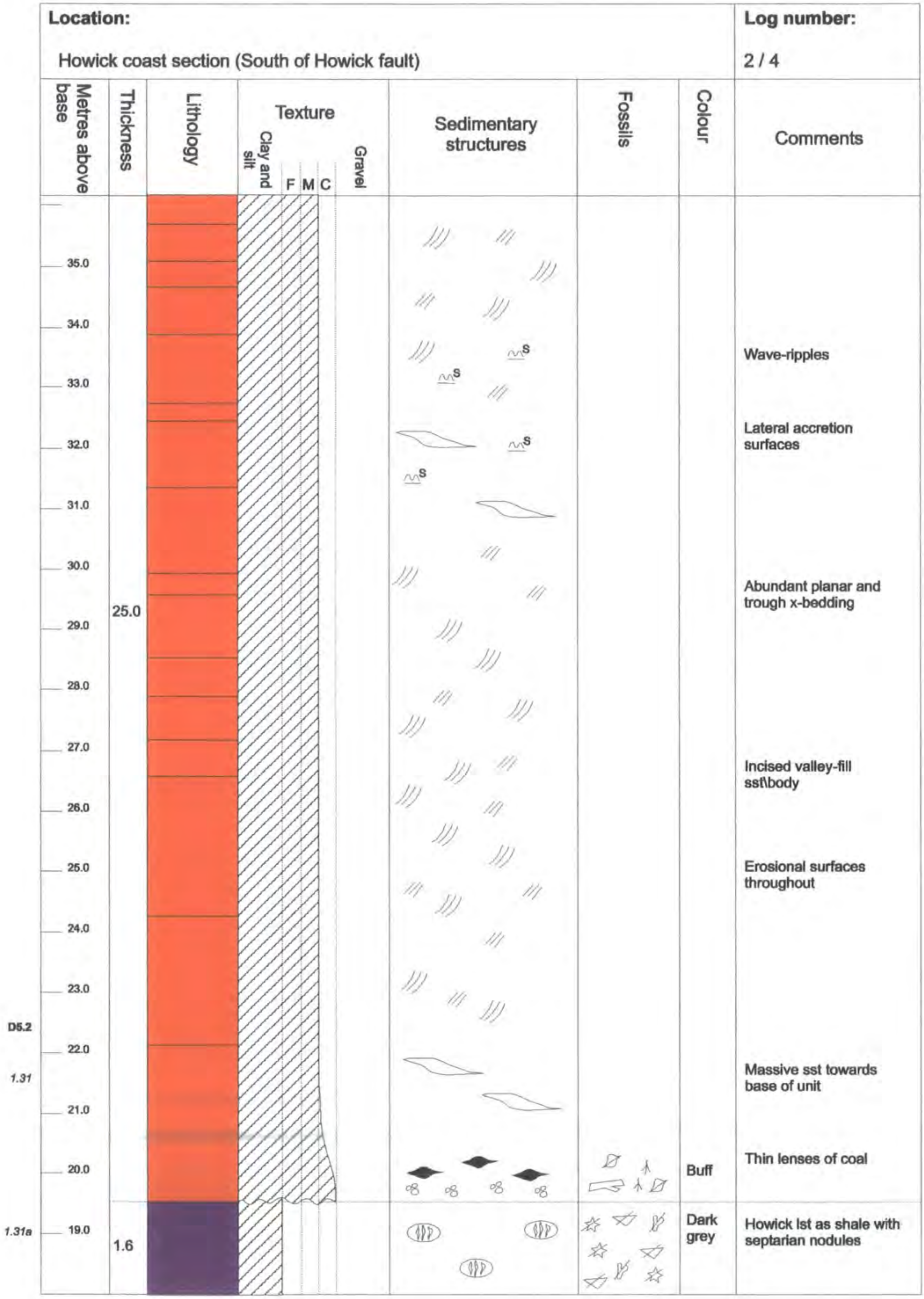
A2.4 Howick coast section (South of Howick fault)

Log number:

1 / 4



Metres above base	Thickness	Lithology	Texture	Sedimentary structures	Fossils	Colour	Comments
	0.25						Howick lst
	0.3					Dark grey	
17.0	1.1					Dark grey	
16.0	1.1					Dark grey	
15.0 14.0	2.0					Buff	'Flaggy' sst
13.0 12.0 11.0	2.0					Buff Very dark grey	
	0.3					Buff	
10.0	0.5					D. Grey	
9.0	1.0						
	0.3					Black	
8.0 7.0	1.5					Buff Dark grey	Micaceous
	0.5						
6.0 5.0	1.2					Pale pink Dark grey	
4.0	1.5					Dark grey	
3.0	0.9					Buff	
2.0	0.8					Cream	
1.0	1.5					Dark grey	

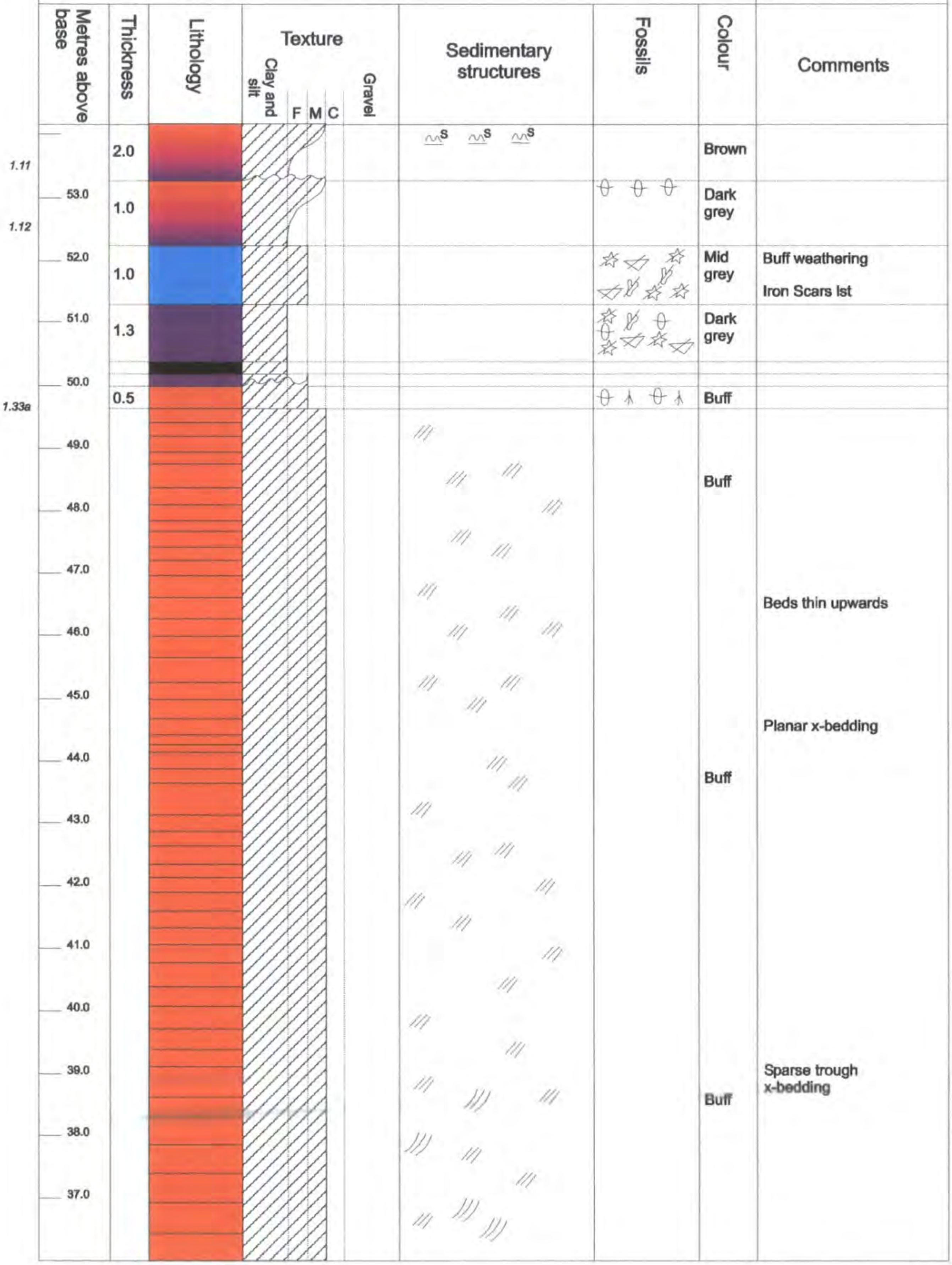

Location:
Howick coast section (South of Howick fault)
Log number:
2 / 4
Metres above base
Thickness
Lithology
Texture
Clay and silt
F
M
C
Gravel
Sedimentary structures
Fossils
Colour
Comments
35.0
34.0
33.0
32.0
31.0
30.0
29.0
28.0
27.0
26.0
25.0
24.0
23.0
22.0
21.0
20.0
19.0
D5.2
1.31
1.31a
25.0
1.6
S
Buff
Dark grey
Wave-ripples
Lateral accretion surfaces
Abundant planar and trough x-bedding
Incised valley-fill sst\body
Erosional surfaces throughout
Massive sst towards base of unit
Thin lenses of coal
Howick lst as shale with septarian nodules

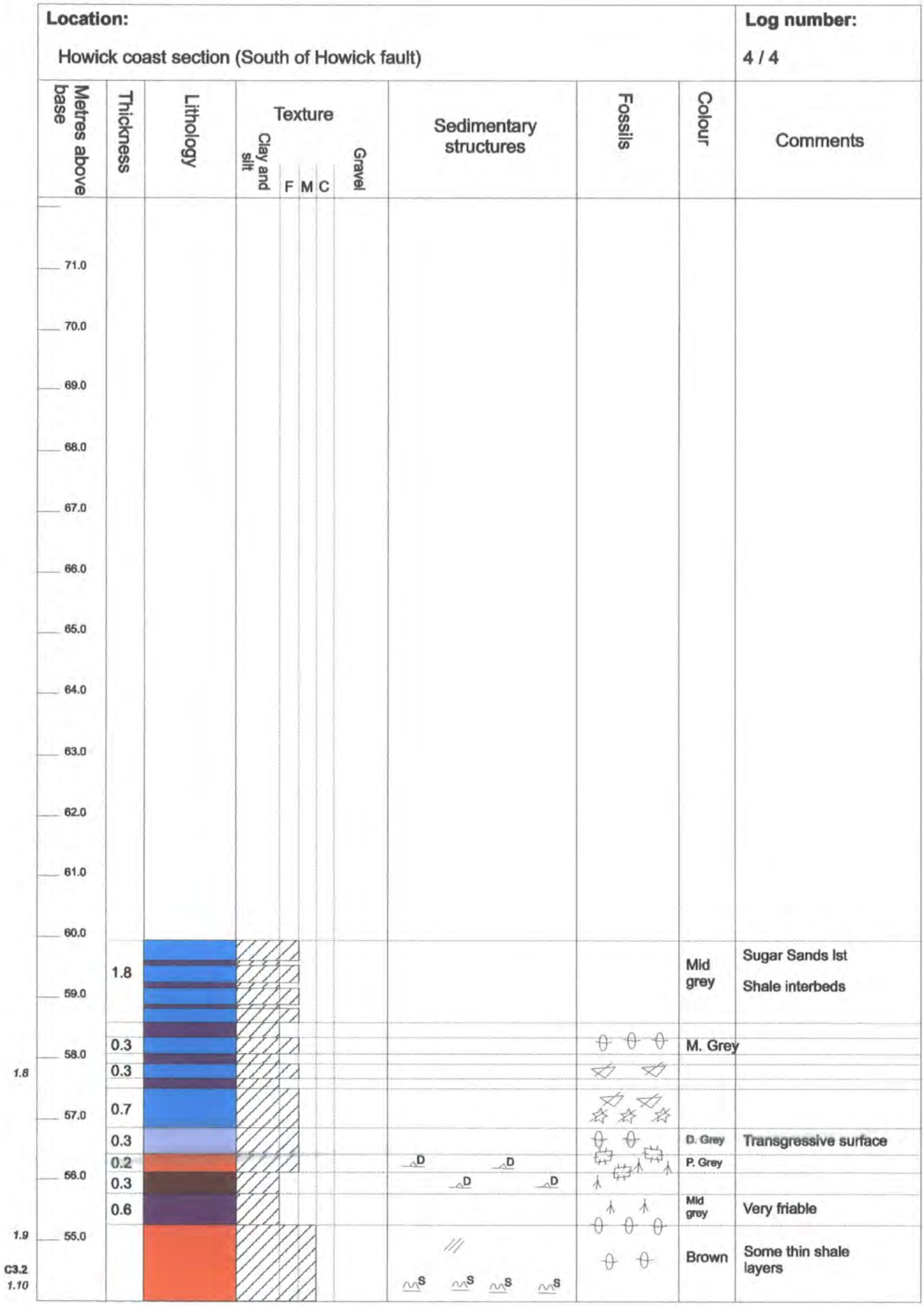
Location:

Howick coast section (South of Howick fault)

Log number:

3 / 4





Location:

Howick coast section (South of Howick fault)

Log number:

4 / 4

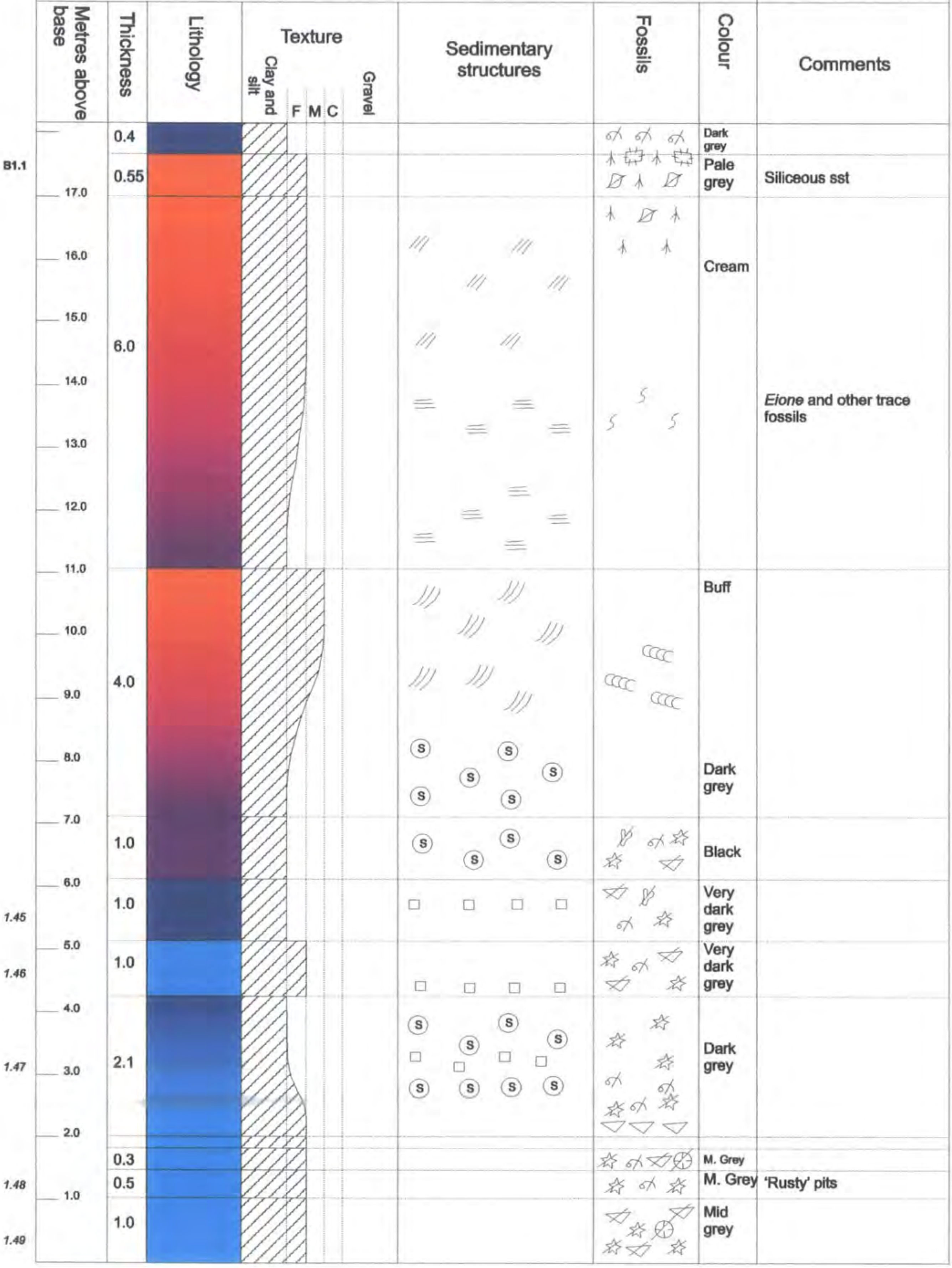
Metres above base	Thickness	Lithology	Texture	Sedimentary structures	Fossils	Colour	Comments
	1.8					Mid grey	Sugar Sands lst Shale interbeds
	0.3					M. Grey	
	0.3						
	0.7						
	0.3					D. Grey	Transgressive surface
	0.2			D D		P. Grey	
	0.3			D D			
	0.6					Mid grey	Very friable
				S S S S		Brown	Some thin shale layers

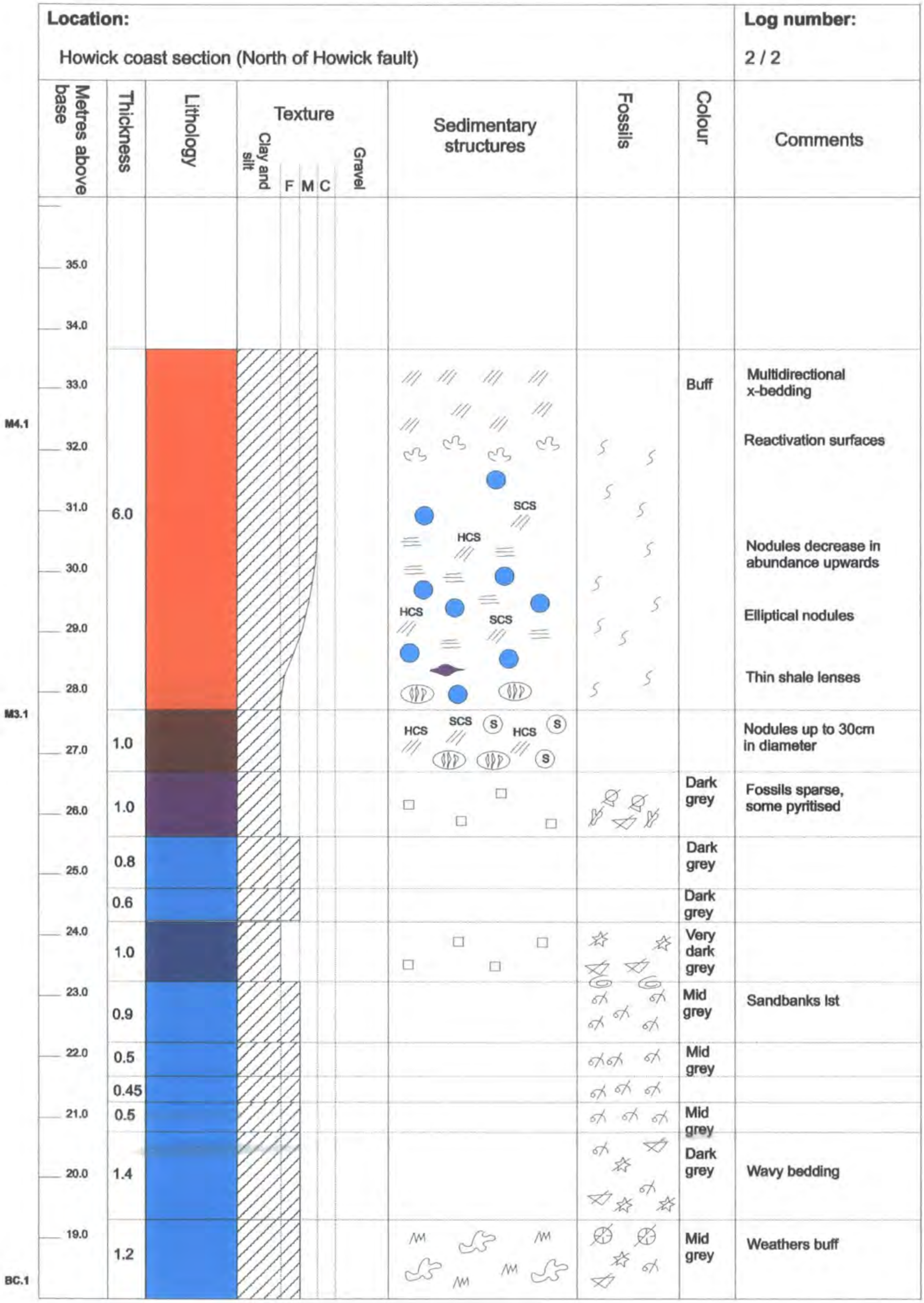
Location:

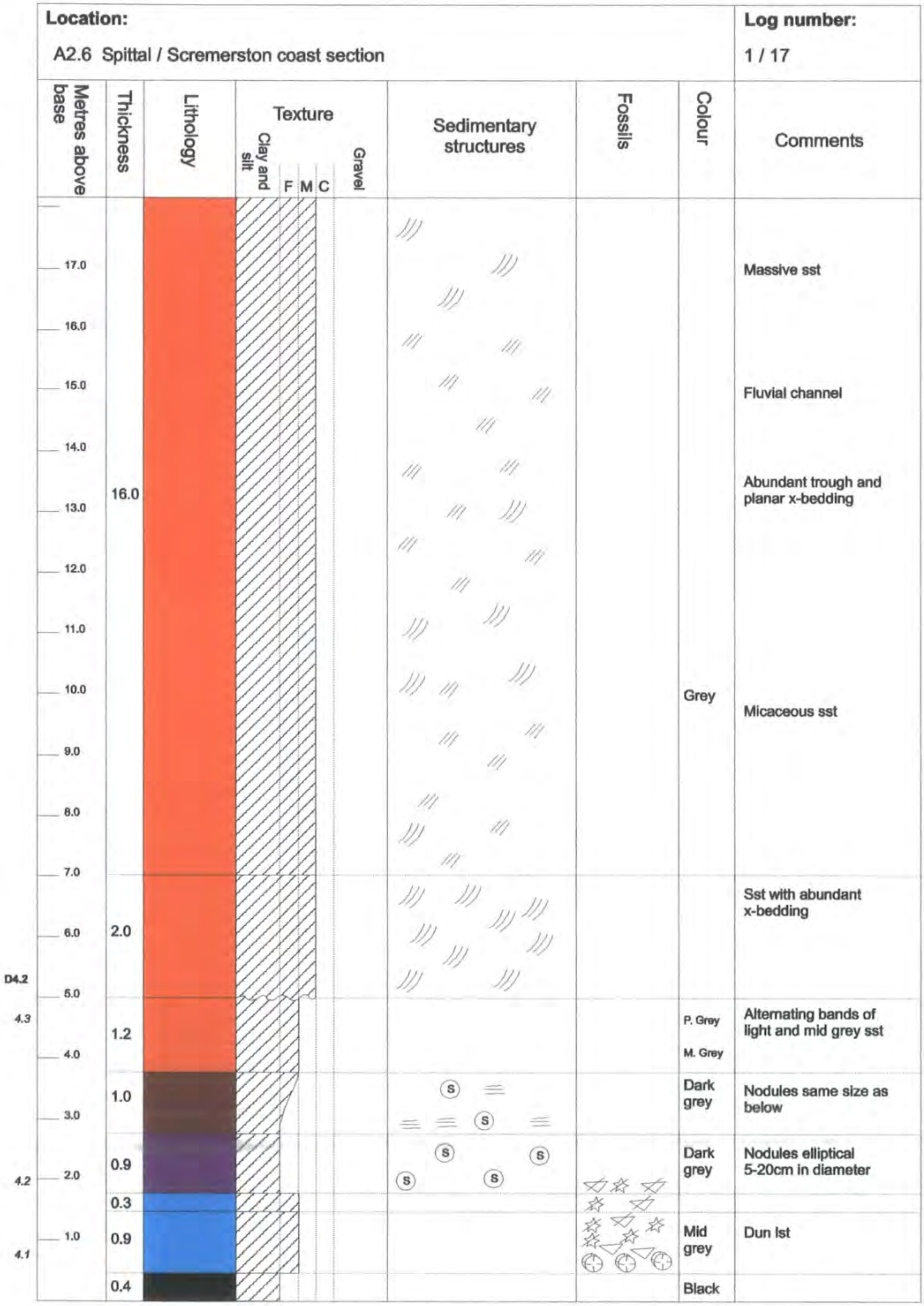
A2.5 Howick coast section (North of Howick fault)

Log number:

1 / 2




Location:
Howick coast section (North of Howick fault)
Log number:
2 / 2
Metres above base
Thickness
Lithology
Texture
Clay and silt
F
M
C
Gravel
Sedimentary structures
Fossils
Colour
Comments
35.0
34.0
33.0
M4.1
32.0
31.0
30.0
29.0
28.0
M3.1
27.0
26.0
25.0
24.0
23.0
22.0
21.0
20.0
19.0
BC.1
6.0
1.0
1.0
0.8
0.6
1.0
0.9
0.5
0.45
0.5
1.4
1.2
SCS
HCS
HCS
SCS
SCS
HCS
HCS
S
S
S
Buff
Dark grey
Dark grey
Dark grey
Very dark grey
Mid grey
Mid grey
Mid grey
Dark grey
Mid grey
Multidirectional x-bedding
Reactivation surfaces
Nodules decrease in abundance upwards
Elliptical nodules
Thin shale lenses
Nodules up to 30cm in diameter
Fossils sparse, some pyritised
Sandbanks lst
Wavy bedding
Weathers buff



Location:

A2.6 Spittal / Scremerston coast section

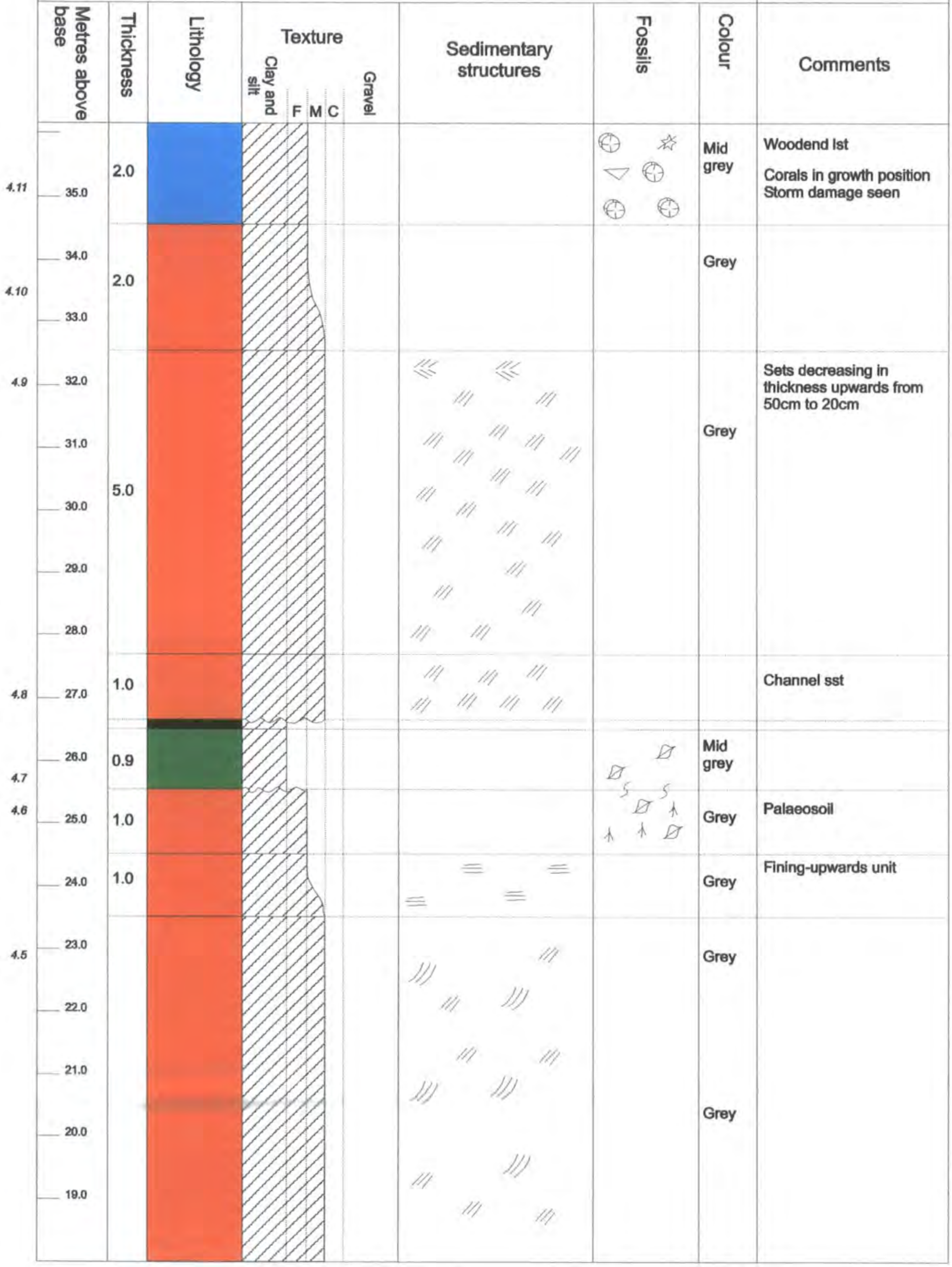
Log number:

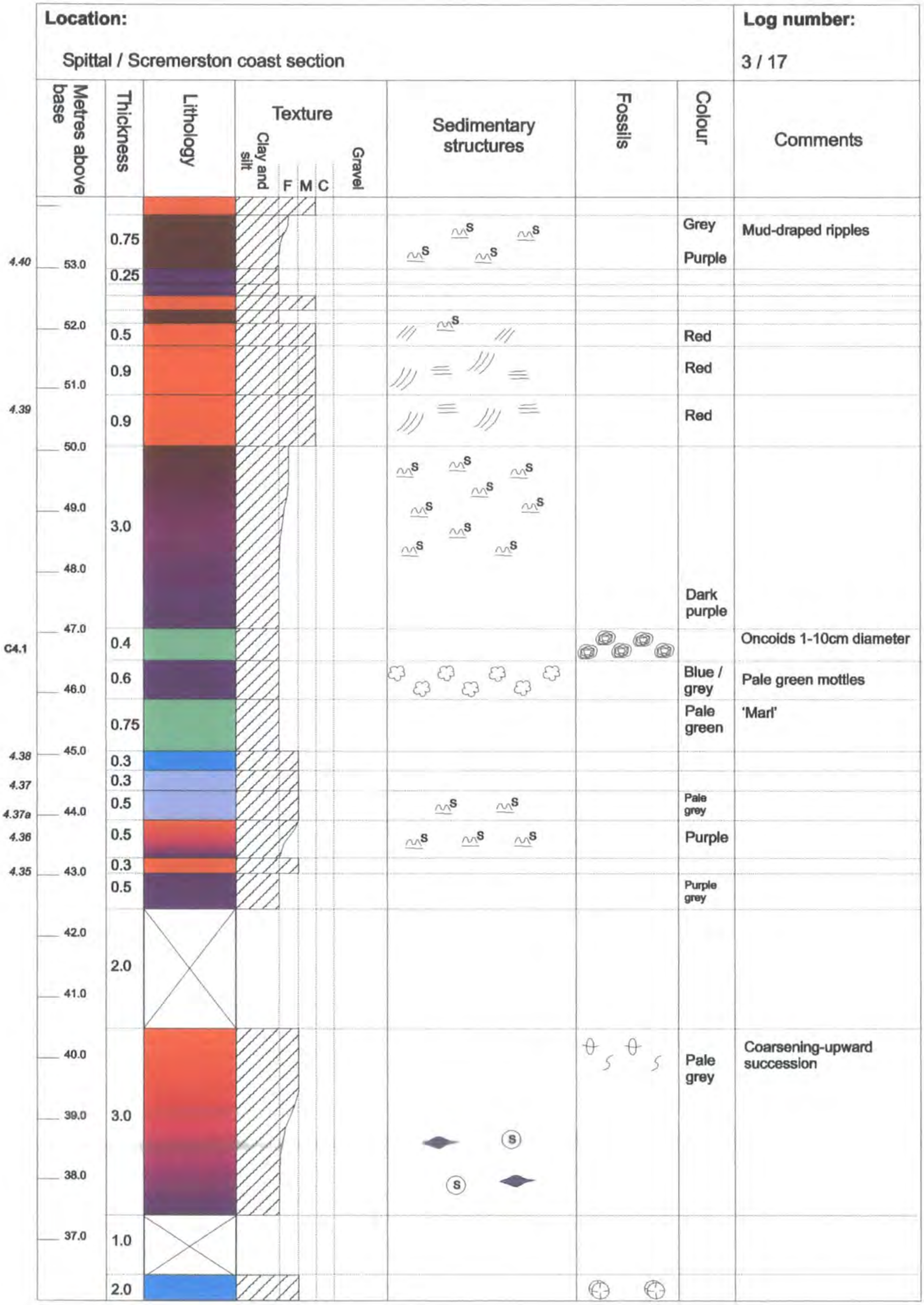
1 / 17

Metres above base	Thickness	Lithology	Texture (Clay and silt, F, M, C, Gravel)	Sedimentary structures	Fossils	Colour	Comments
17.0 16.0 15.0 14.0 13.0 12.0 11.0 10.0 9.0 8.0 7.0	16.0					Grey	Massive sst Fluvial channel Abundant trough and planar x-bedding Micaceous sst
6.0 5.0	2.0						Sst with abundant x-bedding
4.0	1.2					P. Grey M. Grey	Alternating bands of light and mid grey sst
3.0	1.0					Dark grey	Nodules same size as below
2.0	0.9					Dark grey	Nodules elliptical 5-20cm in diameter
	0.3						
1.0	0.9					Mid grey	Dun lst
	0.4					Black	

Location:
Spittal / Scremerston coast section

Log number:
2 / 17



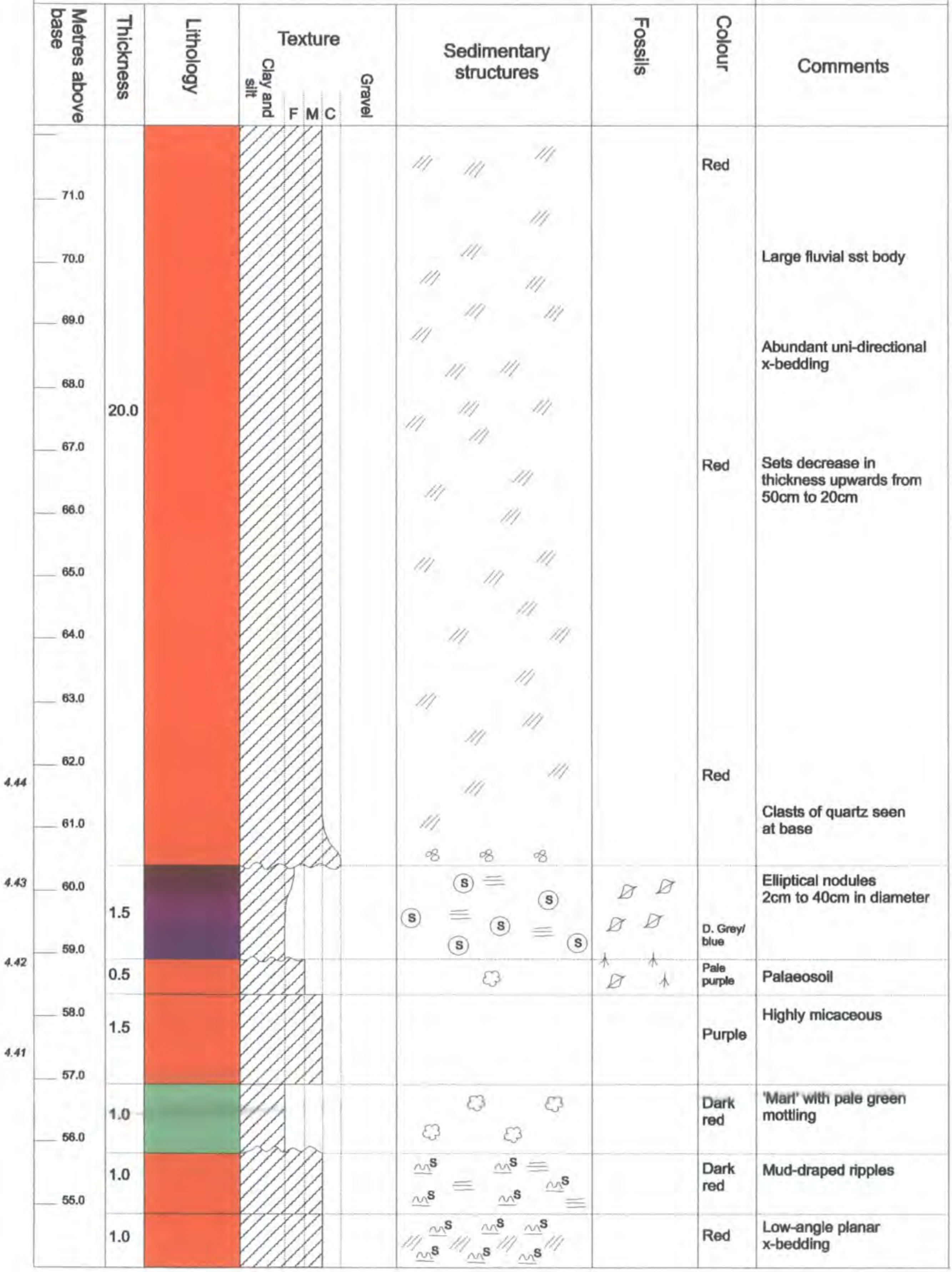

Location:
Spittal / Scremerston coast section
Log number:
3 / 17
Metres above base
Thickness
Lithology
Texture
Clay and silt
F
M
C
Gravel
Sedimentary structures
Fossils
Colour
Comments
0.75
Grey
Mud-draped ripples
4.40
53.0
0.25
Purple
52.0
0.5
Red
0.9
Red
51.0
4.39
0.9
Red
50.0
49.0
3.0
48.0
Dark purple
47.0
C4.1
0.4
Oncoids 1-10cm diameter
0.6
Blue / grey
Pale green mottles
46.0
0.75
Pale green
'Marl'
4.38
45.0
0.3
4.37
0.3
0.5
Pale grey
4.37a
44.0
4.36
0.5
Purple
4.35
43.0
0.3
0.5
Purple grey
42.0
2.0
41.0
40.0
Pale grey
Coarsening-upward succession
39.0
3.0
38.0
37.0
1.0
2.0

Location:

Spittal / Scremerston coast section

Log number:

4 / 17



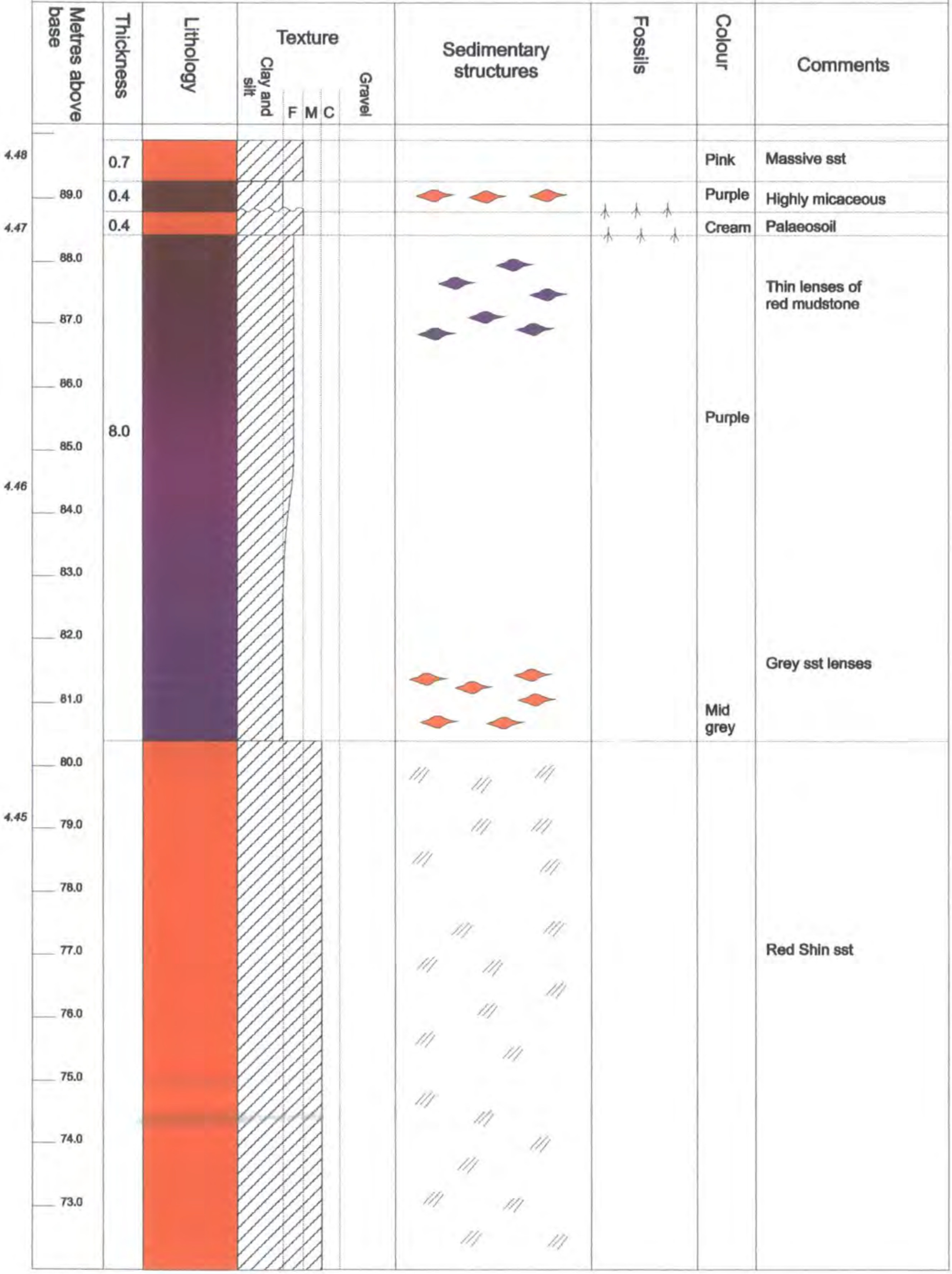
Thickness	Colour	Comments
20.0	Red Red Red	Large fluvial sst body Abundant uni-directional x-bedding Sets decrease in thickness upwards from 50cm to 20cm Clasts of quartz seen at base
1.5	D. Grey/ blue	Elliptical nodules 2cm to 40cm in diameter
0.5	Pale purple	Palaeosoil
1.5	Purple	Highly micaceous
1.0	Dark red	'Marl' with pale green mottling
1.0	Dark red	Mud-draped ripples
1.0	Red	Low-angle planar x-bedding

Location:

Spittal / Scremerston coast section

Log number:

5 / 17

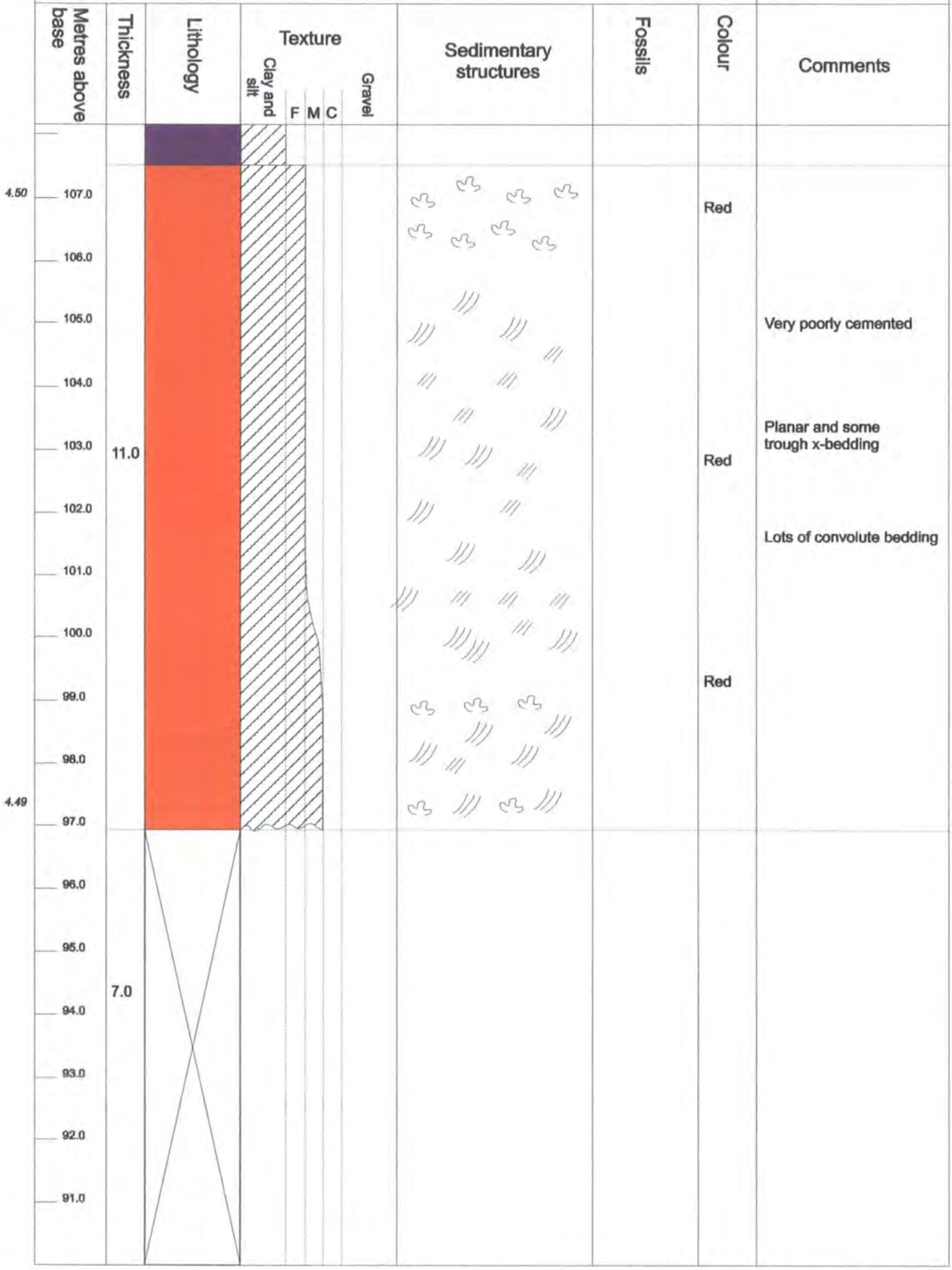


Location:

Spittal / Scremerston coast section

Log number:

6 / 17

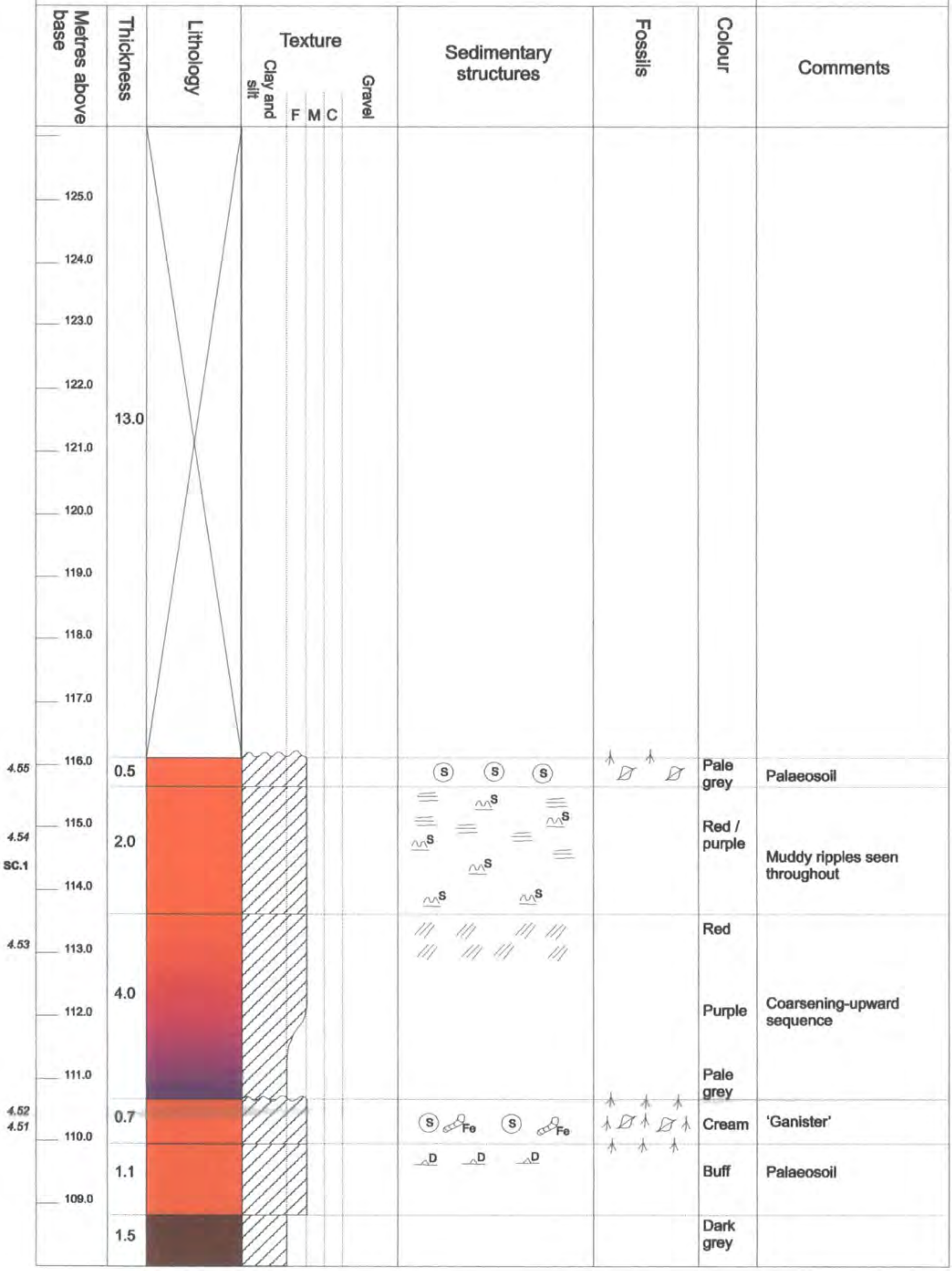


Location:

Spittal / Scremerston coast section

Log number:

7 / 17



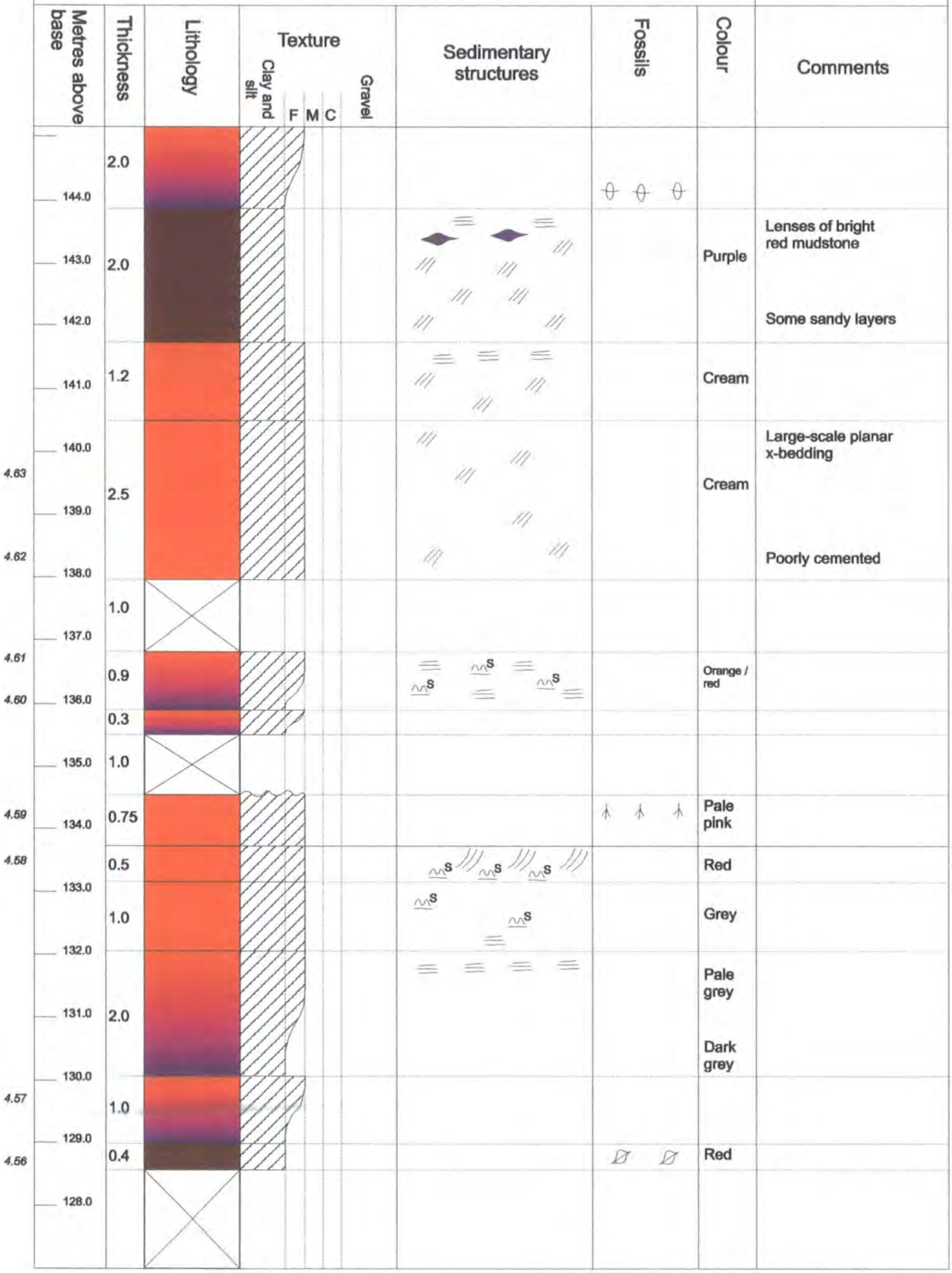
Thickness	Colour	Comments
13.0		
0.5	Pale grey	Palaeosoil
2.0	Red / purple	Muddy ripples seen throughout
4.0	Red Purple Pale grey	Coarsening-upward sequence
0.7	Cream	'Ganister'
1.1	Buff	Palaeosoil
1.5	Dark grey	

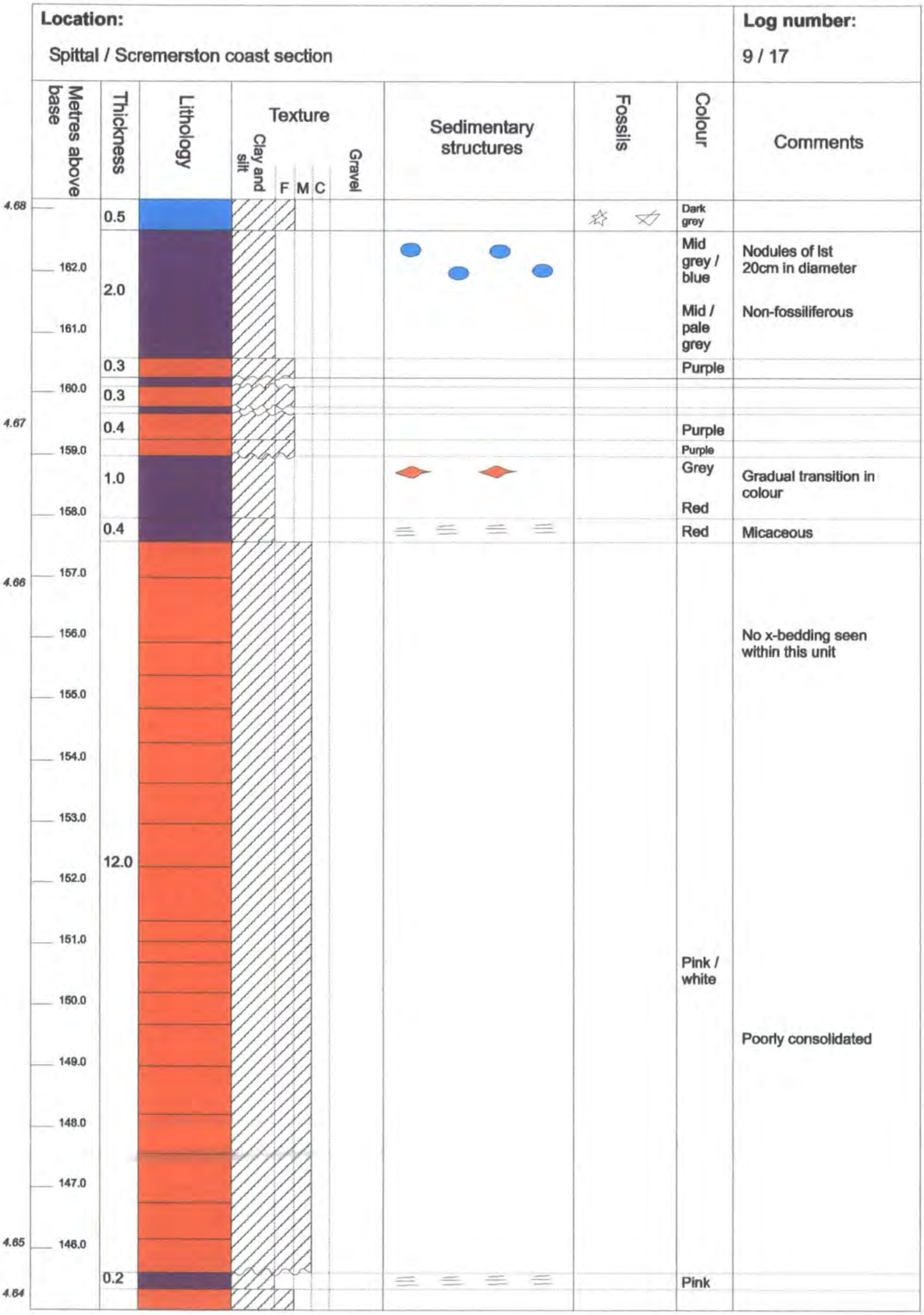
Location:

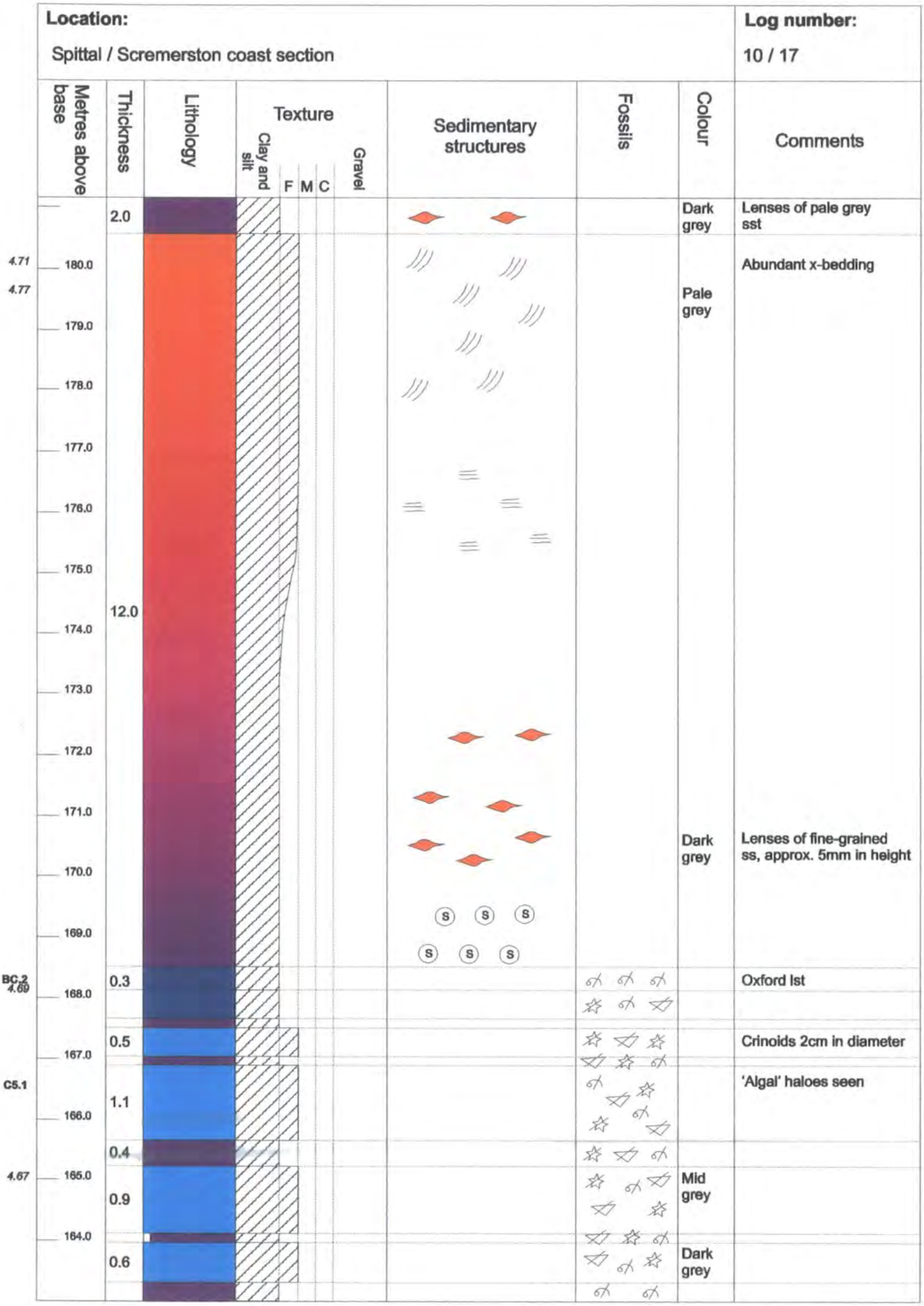
Spittal / Scremerston coast section

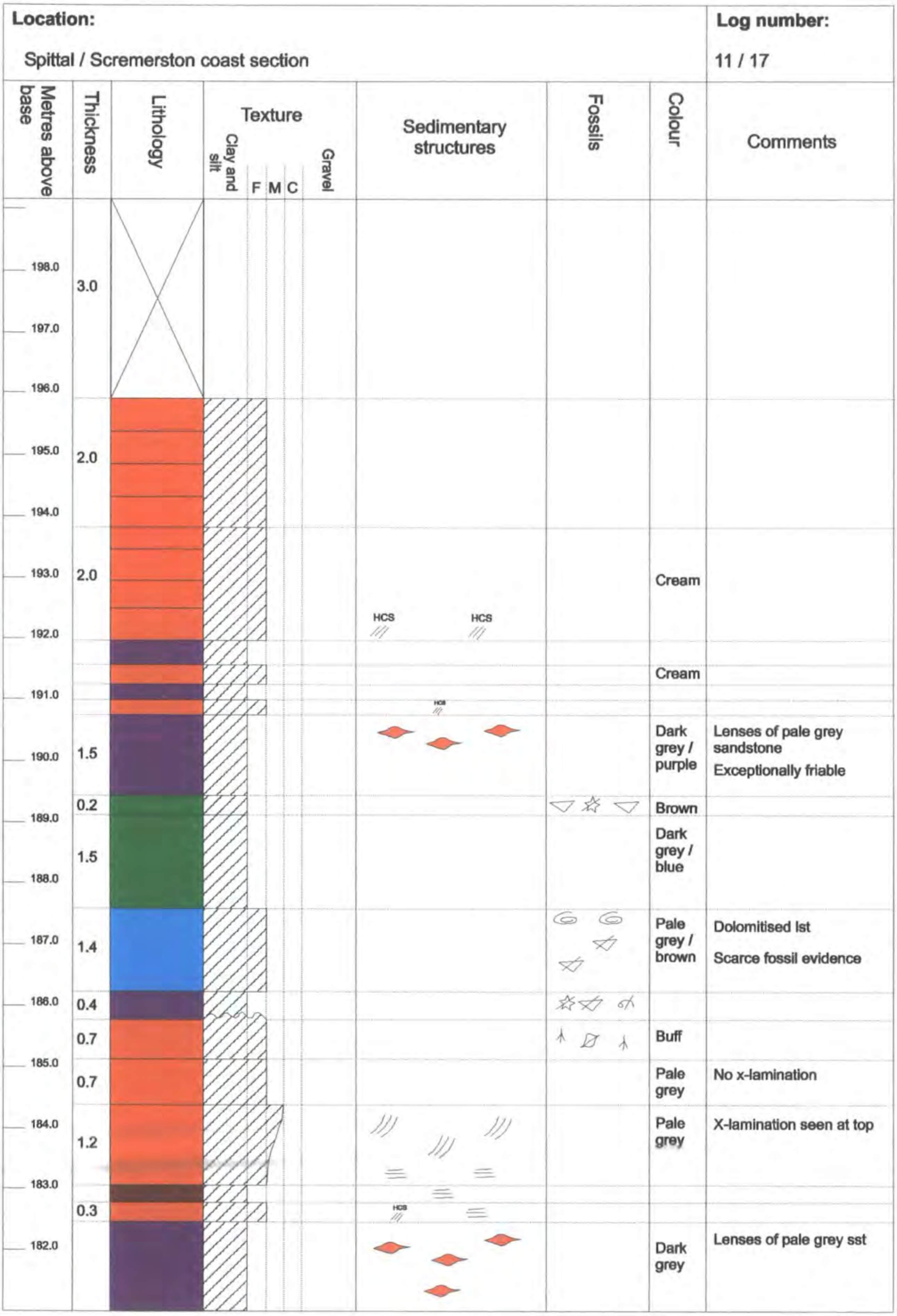
Log number:

8 / 17




Location:
Spittal / Scremerston coast section
Log number:
9 / 17
Metres above base
Thickness
Lithology
Texture
Clay and silt
F
M
C
Gravel
Sedimentary structures
Fossils
Colour
Comments
4.68
0.5
Dark grey
162.0
2.0
161.0
Mid grey / blue
Nodules of lst 20cm in diameter
Mid / pale grey
Non-fossiliferous
0.3
Purple
160.0
0.3
4.67
0.4
Purple
159.0
Purple
1.0
Grey
Gradual transition in colour
158.0
Red
0.4
Red
Micaceous
157.0
4.66
156.0
No x-bedding seen within this unit
155.0
154.0
153.0
12.0
152.0
151.0
Pink / white
150.0
Poorly consolidated
149.0
148.0
147.0
4.65
146.0
0.2
Pink
4.64


Location:
Spittal / Scremerston coast section
Log number:
10 / 17
Metres above base
Thickness
Lithology
Texture
Clay and silt
F
M
C
Gravel
Sedimentary structures
Fossils
Colour
Comments
2.0
Dark grey
Lenses of pale grey sst
4.71
4.77
180.0
179.0
178.0
177.0
176.0
175.0
174.0
173.0
172.0
171.0
170.0
169.0
12.0
Abundant x-bedding
Pale grey
Dark grey
Lenses of fine-grained ss, approx. 5mm in height
S
BC.2
4.69
168.0
0.3
Oxford lst
167.0
0.5
Crinoids 2cm in diameter
C5.1
166.0
1.1
'Algal' haloes seen
0.4
4.67
165.0
0.9
Mid grey
164.0
0.6
Dark grey



Location:

Spittal / Scremerston coast section

Log number:

11 / 17

Lenses of pale grey sandstone

Exceptionally friable

Dolomitised lst

Scarce fossil evidence

No x-lamination

X-lamination seen at top

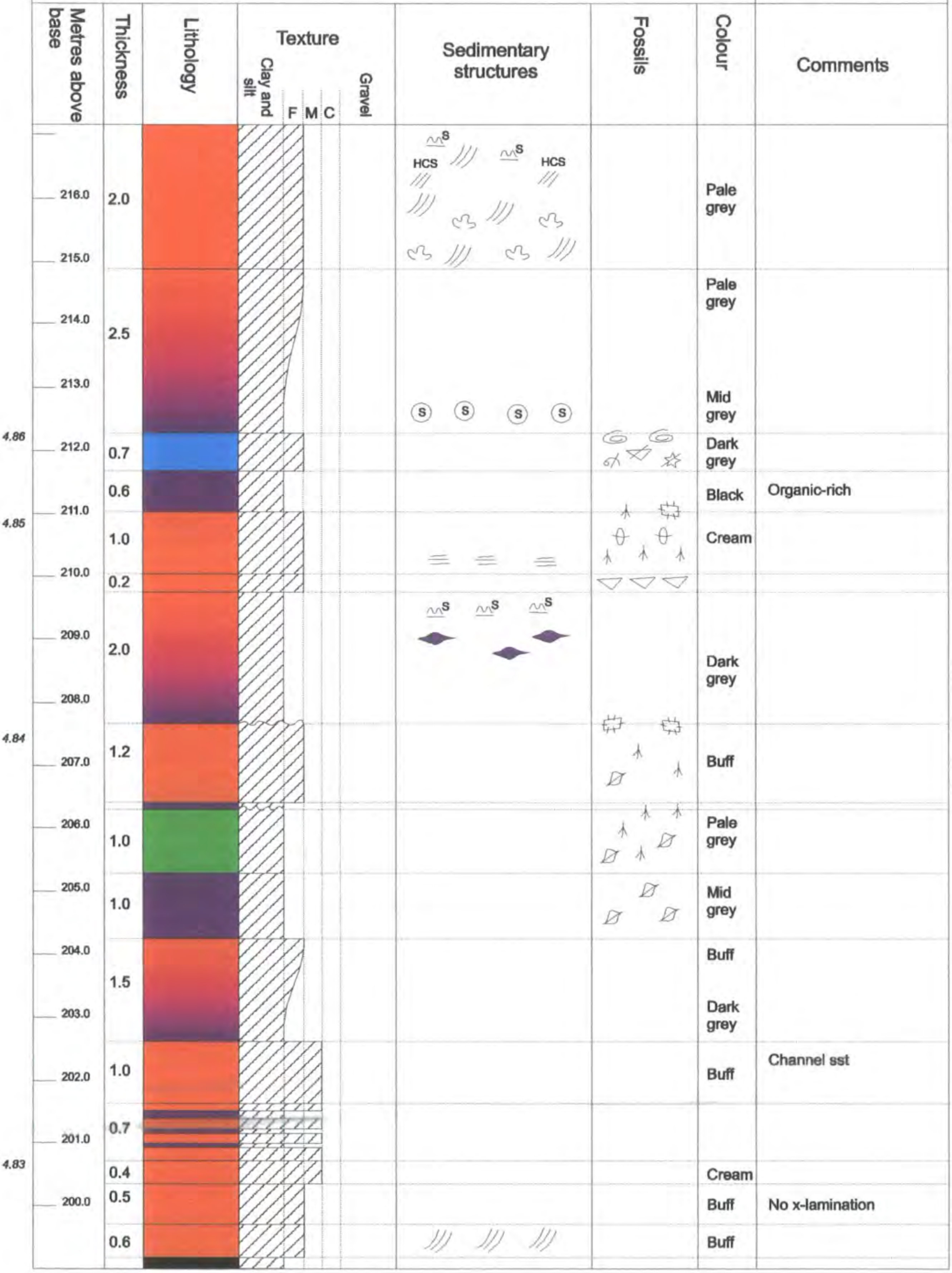
Lenses of pale grey sst

Location:

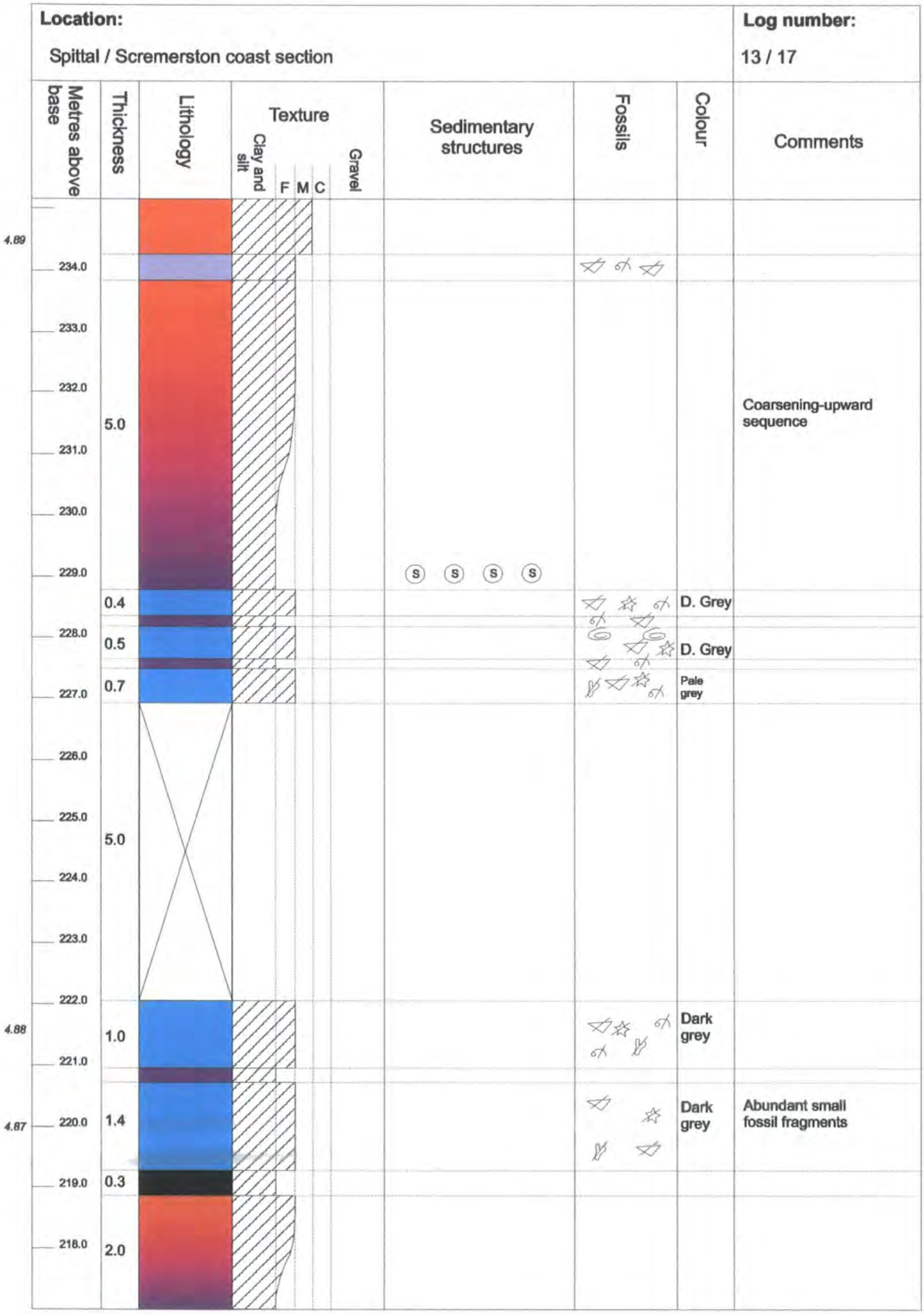
Spittal / Scremerston coast section

Log number:

12 / 17



Thickness	Colour	Comments
2.0	Pale grey	
2.5	Pale grey Mid grey	
0.7	Dark grey	
0.6	Black	Organic-rich
1.0	Cream	
0.2		
2.0	Dark grey	
1.2	Buff	
1.0	Pale grey	
1.0	Mid grey	
1.5	Buff Dark grey	
1.0	Buff	Channel sst
0.7		
0.4	Cream	
0.5	Buff	No x-lamination
0.6	Buff	



Location:

Spittal / Scremerston coast section

Log number:

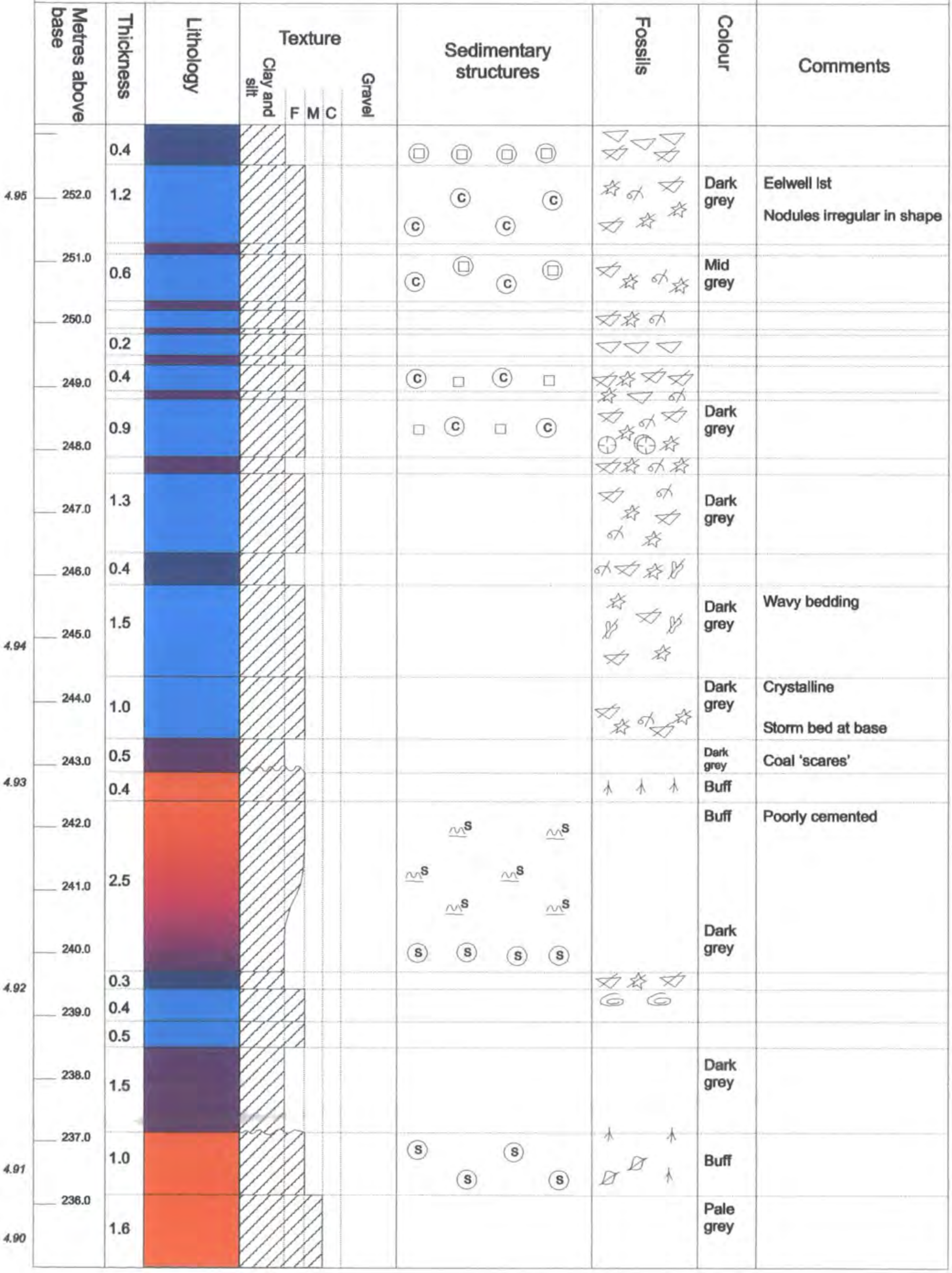
13 / 17

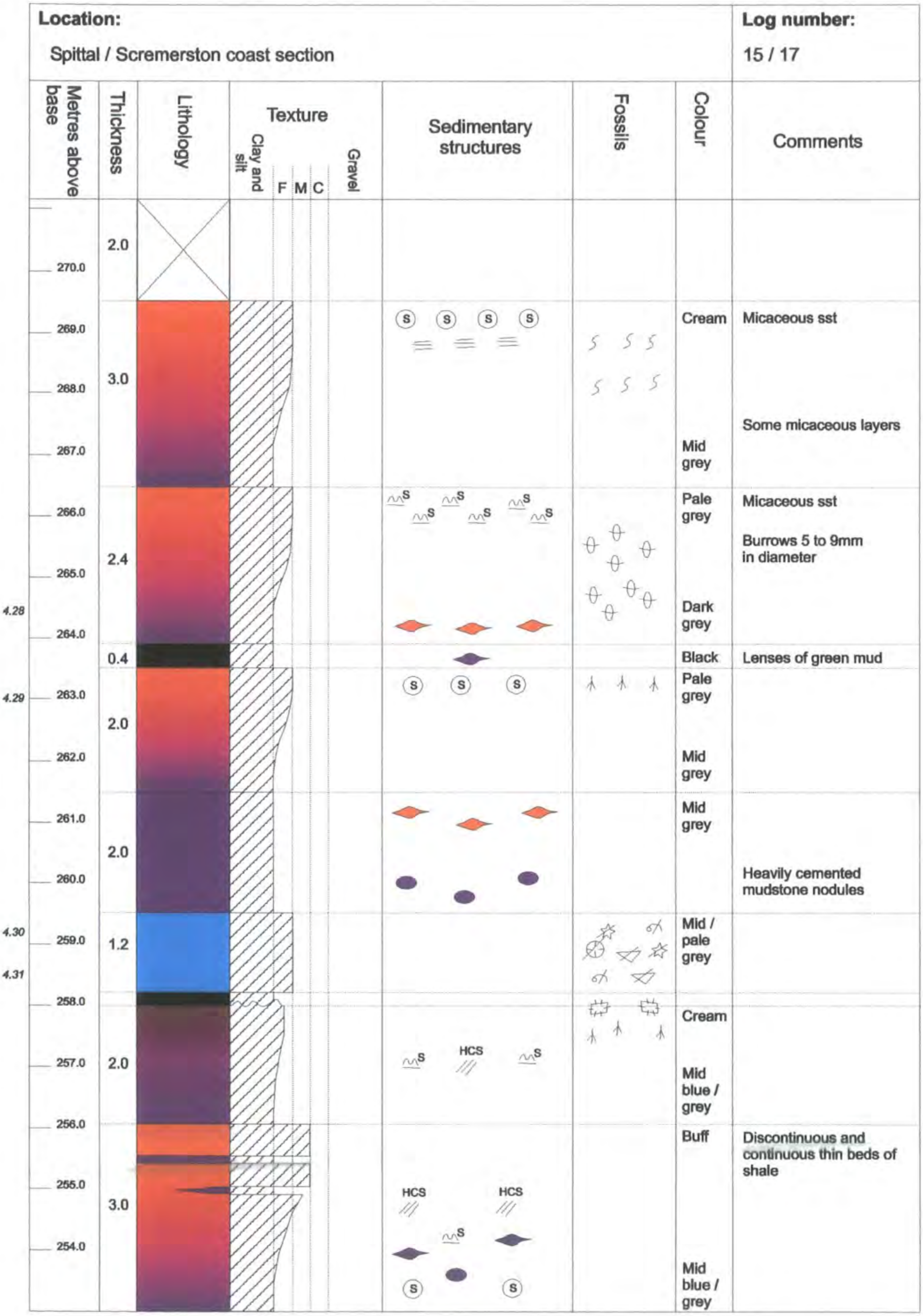
Location:

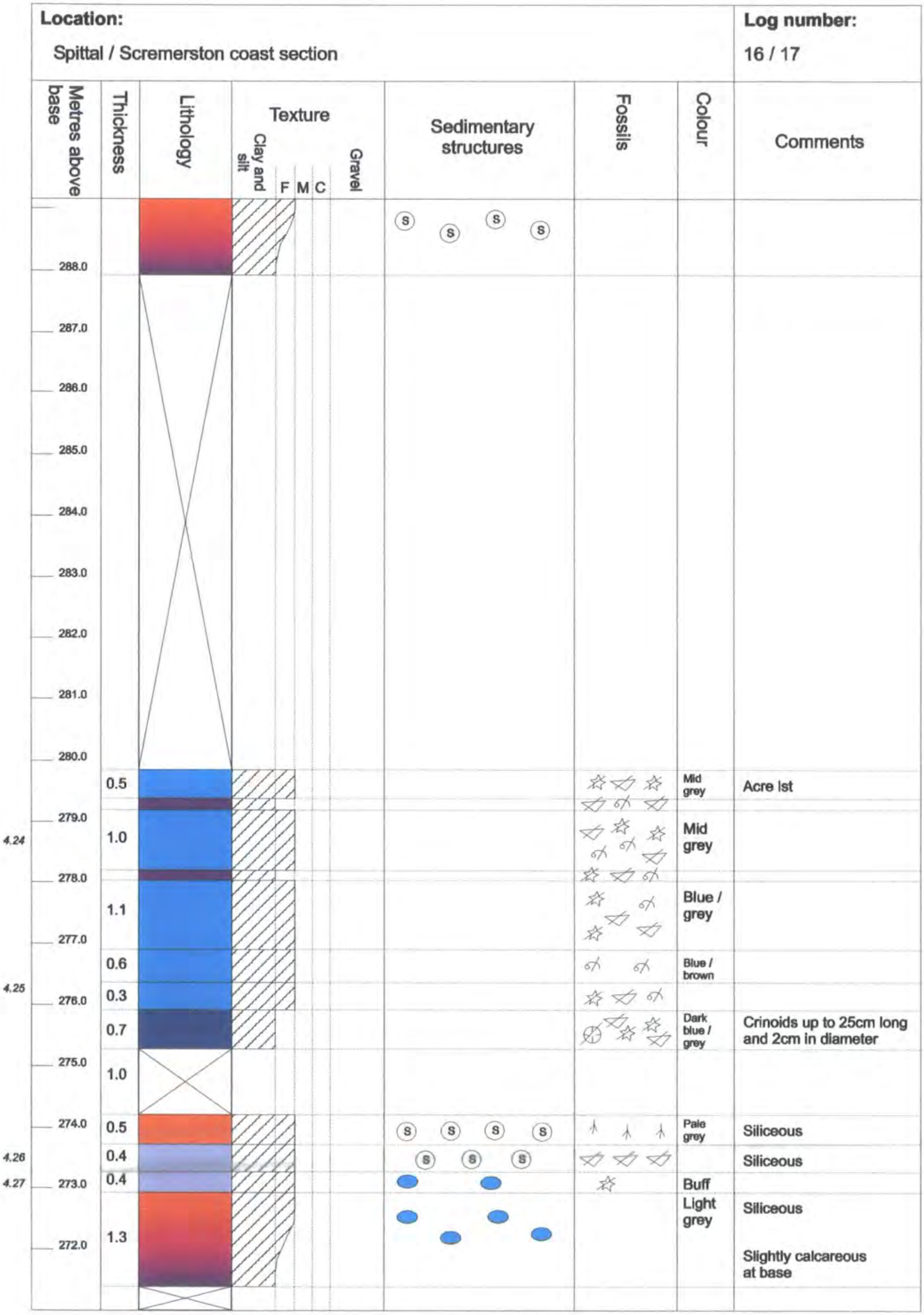
Spittal / Scremerston coast section

Log number:

14 / 17

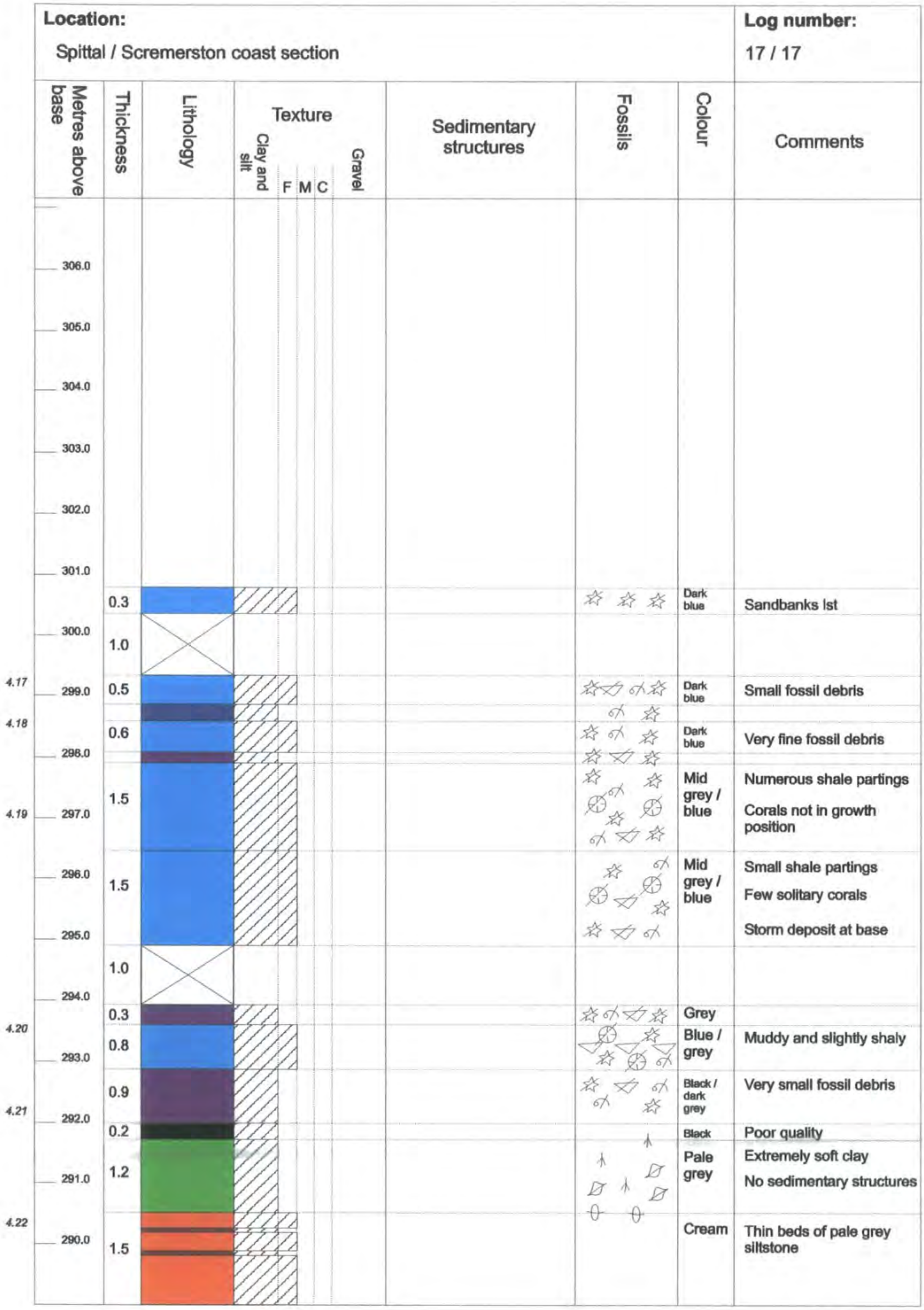



Location:
Spittal / Scremerston coast section
Log number:
15 / 17
Metres above base
Thickness
Lithology
Texture
Clay and silt
F
M
C
Gravel
Sedimentary structures
Fossils
Colour
Comments
270.0
269.0
268.0
267.0
266.0
265.0
264.0
263.0
262.0
261.0
260.0
259.0
258.0
257.0
256.0
255.0
254.0
4.28
4.29
4.30
4.31
2.0
3.0
2.4
0.4
2.0
2.0
1.2
2.0
3.0
S
HCS
Cream
Mid grey
Pale grey
Dark grey
Black
Pale grey
Mid grey
Mid grey
Mid / pale grey
Cream
Mid blue / grey
Buff
Mid blue / grey
Micaceous sst
Some micaceous layers
Micaceous sst
Burrows 5 to 9mm in diameter
Lenses of green mud
Heavily cemented mudstone nodules
Discontinuous and continuous thin beds of shale


Location:
Spittal / Scremerston coast section
Log number:
16 / 17
Metres above base
Thickness
Lithology
Texture
Clay and silt
F
M
C
Gravel
Sedimentary structures
Fossils
Colour
Comments
288.0
287.0
286.0
285.0
284.0
283.0
282.0
281.0
280.0
0.5
Mid grey
Acre lst
279.0
4.24
1.0
Mid grey
278.0
1.1
Blue / grey
277.0
0.6
Blue / brown
4.25
276.0
0.3
0.7
Dark blue / grey
Crinoids up to 25cm long and 2cm in diameter
275.0
1.0
274.0
0.5
Pale grey
Siliceous
4.26
0.4
Siliceous
4.27
273.0
0.4
Buff
Light grey
Siliceous
272.0
1.3
Slightly calcareous at base

Location: Spittal / Scremerston coast section

Log number: 17 / 17



Thickness	Colour	Comments
0.3	Dark blue	Sandbanks lst
1.0		
0.5	Dark blue	Small fossil debris
0.6	Dark blue	Very fine fossil debris
1.5	Mid grey / blue	Numerous shale partings Corals not in growth position
1.5	Mid grey / blue	Small shale partings Few solitary corals Storm deposit at base
1.0		
0.3	Grey	
0.8	Blue / grey	Muddy and slightly shaly
0.9	Black / dark grey	Very small fossil debris
0.2	Black	Poor quality
1.2	Pale grey	Extremely soft clay No sedimentary structures
1.5	Cream	Thin beds of pale grey siltstone

Appendix Three

A3. COMPOSITIONAL ANALYSIS OF THIN-SECTIONS 326

A3.1 Bowlees Beck river section 326

A3.2 Beadnell coast section 327

A3.3 Howick coast section 329

A3.4 Spittal coast section 330

A3. Compositional analysis of thin-sections

The following Appendix indicates the composition of each sandstone thin-section analysed. This data has been used for the classification of each sandstone sample but was primarily collected for provenance analysis.

The thin sections studied were of 'standard' size, 3cm x 2cm. Thin-sections were not stained.

A3.1 Bowlees Beck river section

Sample Number	Quartz (%)	Feldspar (%)	Lithics (%)
2.1	96.2	0.4	3.4
2.1a	94.1	0.4	5.5
2.2a	93.6	0	6.4
2.3	97.3	0.6	2.1
2.4	95.5	0.9	3.6
2.4a	96.8	1.6	1.6
2.10	93.7	0.3	6
2.10a	97	0.7	2.3
2.11	95.5	1	3.5
METB.2	97	0.7	2.3
2.12	93.5	0.3	6.2
2.13	95.3	0	4.7
2.14	97	0	3
2.15	98.1	0	1.9
2.16	96	0.3	3.7
2.16a	97.7	0	2.3
2.17	98.5	0	1.5
2.20	95.6	1.5	2.9
2.21	94.5	1.4	4.1
METB.1	98.3	0	1.7

A3.2 Beadnell coast section

Sample Number	Quartz (%)	Feldspar (%)	Lithics (%)
3.6	-	-	-
3.22	97.2	1	1.8
3.8	97.8	0.3	1.9
3.11a	97.8	0.8	1.4
3.12	95.6	0.4	4
3.15	95.6	1.1	3.3
3.16	89.7	0.4	9.9
3.17	92.7	1.2	6.1
3.18	-	-	-
3.19	86.3	2.8	10.9
3.23	92.7	1	6.3
3.24	74.7	4.9	20.4
3.25	86.2	1.4	12.4
3.26	94.2	1.1	4.7
3.26a	79.8	5.1	15.1
3.27	84.6	0.4	15
3.35	91	0.3	8.7
3.36	88.4	0.4	11.2
3.37	90.5	2.1	7.4
3.38	83.7	4.1	12.2
3.39	82.7	0.5	16.8
3.45	85.8	2.4	11.8
3.46	85.7	2.6	11.7
3.49	86.2	1.9	11.9
3.50	87.2	2.7	10.1
3.53	86.9	2.5	10.6
3.61	90.3	1.7	8
3.62	93.4	1.6	5
3.63	89	3.4	7.6
3.64	81.6	1.7	16.7
3.68	87.1	1.1	11.8
3.70	91.7	1.2	7.1
3.73	89.4	2.5	8.1
3.74	91.9	0	8.1
3.75	90.1	3	6.9
3.76	83.5	3	13.5
3.77	82.6	1.9	15.5
3.78	83.7	2.7	13.6
3.79	79.1	4.6	16.3
3.81	90.8	1.6	7.6
3.83	-	-	-
3.84	91.4	2.6	6

3.84a	86.9	0.5	12.6
3.85	87.4	0.9	11.7
3.86	84.8	1	14.2
3.89	90.3	1.2	8.5
3.90	90.4	1.3	8.3
3.91	89.9	1	9.1
3.93	93.4	1.4	5.2
3.94	91.6	2.5	5.9
3.95	84.9	2.9	12.2
3.96	82.6	1.8	15.6
3.101	95.1	0.4	4.5
3.102	93	3	4
3.103	93.2	1.2	5.6
3.104	93.9	1.2	4.9
3.105	90.1	0.4	9.5
3.106	92.5	0.4	7.1

A3.3 Howick coast section

Sample Number	Quartz (%)	Feldspar (%)	Lithics (%)
1.9	95.1	0.7	4.2
1.12	97.1	0.3	2.6
1.15	97.7	0.4	1.9
1.16	94.8	0	5.2
1.19	93.4	3.7	2.9
1.20	95.2	0.4	4.4
1.21	95.2	0.4	4.4
1.22	97.6	0.3	2.1
1.23	94.9	0.7	4.4
1.24	83.1	1.1	15.8
1.25	-	-	-
1.26	95	0.4	4.6
1.27	95	0.7	4.3
1.28	94.8	1.1	4.1
1.29	96.8	0.3	2.9
1.31	93.6	1.7	4.7
1.33	91.6	1.5	6.9
1.38	90.5	0	9.5
1.38a	98.5	0	1.5
1.39	86.3	1.8	11.9
1.39a	92.1	1.3	6.6
1.42	97.9	0	2.1
1.43	90.8	0.4	8.8
1.51	97.5	0	2.5
1.52	95.3	0	4.7
1.54	97.4	0	2.6
1.55	93.8	0	6.2
1.57	96.4	0	3.6
H1	100	0	0
H2	98.4	0.5	1.1
H3	98.1	0	2.9
H5a	97.2	0	2.8
H16	93.5	2.6	3.9
H17	91.7	3.2	5.1

A3.4 Spittal coast section

Sample Number	Quartz (%)	Feldspar (%)	Lithics (%)
4.3	93.2	0.8	7
4.4	91.5	0.6	7.9
4.5	77.4	3.1	19.5
4.6	90.9	1.7	7.4
4.8	88	1.7	10.3
4.9	94.9	1.6	3.5
4.10	90.3	1.3	8.4
4.12	89.2	2	8.8
4.13	93.4	2.1	5.5
4.14	83.4	7.1	9.5
4.15	92.8	2.3	4.9
4.16	89	4	7
4.22	96.3	0.6	3.1
4.26	96.4	1.5	2.1
4.17	95.8	0.7	3.5
4.29	91.5	0.8	7.7
4.35	91.1	0.7	8.2
4.36	95.2	0.8	4
4.76	94.5	1.4	4.1
4.82	99	0.7	0.3
4.93	92.4	1.4	6.2
4.91	99.7	0	0.3
4.90	89.6	2.6	7.8
4.78	91.2	6	2.8
4.75	95.7	2	2.3
4.79	98.3	0.7	1
4.81	94.4	4.5	1.1
4.82	97.6	2.4	0
4.85	97.9	1.3	0.8
4.83	93.5	2	4.5
4.57	97.4	0.8	1.8
4.59	95.4	0.4	4.2
4.62	95.9	2.8	1.3
4.64	96.1	0.8	3.1
4.63	99.3	0	0.7
4.66	90.6	2.9	6.5
4.70	96.6	0.3	3.1
4.58	96.3	0.4	3.3
4.71	93.8	2.2	4
4.74	97.2	1.4	1.4
4.49	89.5	3.3	7.2
4.36	97.6	1.5	0.9

4.39	95.5	0.3	4.2
4.45	87.7	2.5	9.8
4.35	95.7	0.4	3.9
4.41	95.3	0	4.7
4.52	95.3	2	2.7
4.50	93	1.1	5.9
4.53	95.4	1	3.6
4.29	91	1.7	7.3
4.48	93.6	2.8	3.6
4.47	96	1.1	2.9
4.44	88.2	2.2	9.6
4.51	97.4	0.7	1.9

Appendix Four

A4. CYCLE THICKNESS DATA.. 332

A4. Cycle Thickness data

The following tables provide all measured cycle thickness data which has been studied for this thesis. The carbonate, fine-grained siliciclastic, coarse-grained siliciclastic and coal content of each cycle have also been recorded. Tables are organised in alphabetical order.

Allenheads No. 1 borehole

Cycle	Thickness (m)	Carbonate (m)	Fine Clastics (m)	Coarse Clastics (m)	Coal (m)
Robinson	6.83	3.99	0.55	2.29	-
Birkdale	6.96	0.58	2.99	3.35	0.04
Lower Peghorn	6.96	3.79	1.37	1.80	-
Upper Peghorn	5.81	1.19	0.92	3.70	-
Smiddy	35.78	8.74	10.95	16.03	0.06
Lower Little	48.26	6.15	19.79	22.12	0.20
Tynebottom	30.58	8.76	13.64	8.18	-
Single Post	8.18	2.51	5.67	-	-
Cockleshell	13.23	0.43	4.95	7.85	-
Scar	27.97	12.20	7.48	8.29	-
Five Yard	18.69	4.78	8.55	5.36	-
Three Yard	28.78	2.57	16.91	9.30	-
Four Fathom	28.73	5.64	12.87	10.22	-
Iron Post	7.33	1.68	3.55	2.10	-
Great	40.04	20.68	9.80	9.37	0.19
Little	-	-	-	-	-

Allenheads No. 2 borehole

Cycle	Thickness (m)	Carbonate (m)	Fine Clastics (m)	Coarse Clastics (m)	Coal (m)
Crag	9.27	0.15	9.12	-	-
Knucton Shell Beds	59.08	1.19	21.29	36.60	-
Coalcleugh Marine Band	-	-	-	-	-

No. 1 Ancroft borehole

Cycle	Thickness (m)	Carbonate (m)	Fine Clastics (m)	Coarse Clastics (m)	Coal (m)
Dun	38.71	1.83	20.04	16.54	0.30
Woodend	220.83	3.35	108.76	106.48	2.24
Oxford	-	-	-	-	-

Archerbeck borehole

Cycle	Thickness (m)	Carbonate (m)	Fine Clastics (m)	Coarse Clastics (m)	Coal (m)
Dinwoodie Beds	55.15	2.50	38.20	14.35	0.10
Kinmont	210.94	26.00	134.31	49.80	0.83
Cornet	4.47	2.80	1.70	-	-
Callant	56.44	10.10	21.34	24.50	0.50
Penton	26.27	12.50	9.67	3.80	0.30
Bridge	21.23	3.50	6.31	11.30	0.12
Linns	17.68	4.40	4.96	8.30	0.02
Tombstone	24.96	4.50	12.45	7.90	0.11
Gastropod	10.66	7.00	1.75	1.70	0.21
Harelaw Hill	51.17	11.50	18.66	20.70	0.31
Buccleuch	42.55	13.80	16.95	11.50	0.30
Under	10.89	7.90	1.89	0.90	0.20
Catsbit	43.44	23.00	9.43	10.50	0.51
Blae Pot	-	-	-	-	-

Barlington borehole

Cycle	Thickness (m)	Carbonate (m)	Fine Clastics (m)	Coarse Clastics (m)	Coal (m)
Fourlaws	19.28	1.17	8.99	8.92	0.20
Gunnerton Fell	56.54	2.82	30.20	23.52	-
Lower Demesne	13.31	4.55	1.83	6.93	-
Upper Demesne	-	-	-	-	-

Beadnell coast section

Cycle	Thickness	Carbonate	Fine Clastics	Coarse Clastics	Coal
Oxford	129.79	11.56	50.06	64.31	0.86
Eelwell	42.17	10.16	25.45	6.20	0.36
Acre	23.86	5.23	11.61	7.01	0.01
Sandbanks	57.24	10.07	18.92	27.95	0.30
Great	-	-	-	-	-

Belsay Hall borehole

Cycle	Thickness (m)	Carbonate (m)	Fine Clastics (m)	Coarse Clastics (m)	Coal (m)
Little	81.00	2.74	34.01	43.89	0.36
Oakwood	78.17	1.60	33.36	41.99	1.22
Belsay Dene	-	-	-	-	-

Black Heddon borehole

Cycle	Thickness (m)	Carbonate (m)	Fine Clastics (m)	Coarse Clastics (m)	Coal (m)
Little	88.30	2.94	27.25	57.40	0.71
Oakwood	71.20	1.50	28.04	40.67	0.99
Belsay Dene	-	-	-	-	-

Bowlees Beck river section

Cycle	Thickness (m)	Carbonate (m)	Fine Clastics (m)	Coarse Clastics (m)	Coal (m)
Cockleshell	9.85	6.25	2.90	0.70	-
Scar	34.40	5.00	6.90	22.10	0.40
Five Yard	29.75 +	4.75	-	-	-

Cairney Croft borehole

Cycle	Thickness (m)	Carbonate (m)	Fine Clastics (m)	Coarse Clastics (m)	Coal (m)
Naworth	142.97	14.71	47.57	80.33	0.36
Denton Hill	73.92	26.52	16.08	31.09	0.23
Low Tipalt	18.21	8.76	3.66	5.79	-
Middle Bankhouses	29.49	6.10	4.83	18.56	-
Greengate Well	-	-	-	-	-

Cawburn Rigg borehole

Cycle	Thickness (m)	Carbonate (m)	Fine Clastics (m)	Coarse Clastics (m)	Coal (m)
Middle Bankhouses	20.13	4.07	9.33	6.53	0.20
Upper Bankhouses	16.47	1.95	1.99	12.40	0.13
Greengate Well	-	-	-	-	-

Chopwell borehole

Cycle	Thickness (m)	Carbonate (m)	Fine Clastics (m)	Coarse Clastics (m)	Coal (m)
Four Fathom	47.34	6.15	12.57	28.57	0.05
Great	45.60	22.12	12.17	11.21	0.10
Little	46.89	3.71	15.16	28.02	-
Crag	63.93	2.59	13.26	48.05	0.03
Lower Felltop	23.49	4.78	1.55	17.11	0.05
Coalcleugh Shell Bed	20.14	0.81	9.12	10.21	-
Upper Felltop	22.86	5.74	7.09	10.03	-
Grindstone	30.94	1.85	8.69	20.40	-
Whitehouse	-	-	-	-	-

Ferneyrigg borehole

Cycle	Thickness (m)	Carbonate (m)	Fine Clastics (m)	Coarse Clastics (m)	Coal (m)
Fourlaws	68.48	6.14	25.46	35.82	1.06
Limestone of Stiddlehill	25.22	0.58	15.72	8.59	0.33
Lower Gunnerton Fell	6.25	1.42	0.70	4.13	-
Upper Gunnerton Fell	24.74	1.47	13.61	9.41	0.25
Ladies Wood	59.18	3.76	17.32	37.53	0.57
Lower Demesne	7.34	2.44	4.19	-	-
Upper Demesne	31.62	2.31	16.12	12.96	0.23
Lower Camphill	24.46	1.37	3.43	19.66	-
Lower Bankhouses	9.55	4.43	1.16	3.94	0.02
Middle Bankhouses	47.04	8.56	7.49	30.43	0.56
Greengate Well	-	-	-	-	-

Haltwhistle Burn river section

Cycle	Thickness (m)	Carbonate (m)	Fine Clastics (m)	Coarse Clastics (m)	Coal (m)
Four Fathom	38.10	2.50	22.00	13.60	-
Great	53.50	4.55	36.50	11.45	1.00
Little	50.50	4.50	12.20	33.40	0.40
Oakwood	-	-	-	-	-

Howick coast section

Cycle	Thickness (m)	Carbonate (m)	Fine Clastics (m)	Coarse Clastics (m)	Coal (m)
Acre	16.00	6.00	5.00	5.00	-
Sandbanks	55.17	6.63	24.08	23.49	0.97
Great	54.84	15.90	16.86	21.95	0.13
Little	74.65	0.97	27.17	45.16	1.35
Howick	32.90	0.50	2.10	29.95	0.35
Iron Scars	11.22	1.50	-	-	-
Sugar Sands	32.06	1.56	No Detailed Info		0.23
Lower Foxton	11.22	0.96	-	-	-
Upper Foxton	-	-	-	-	-

Kirkheaton borehole

Cycle	Thickness (m)	Carbonate (m)	Fine Clastics (m)	Coarse Clastics (m)	Coal (m)
Acre	32.49	0.94	20.60	10.80	0.15
Sandbanks	53.09	5.28	24.18	22.89	0.74
Great	-	-	-	-	-

RAF Ouston

Cycle	Thickness (m)	Carbonate (m)	Fine Clastics (m)	Coarse Clastics (m)	Coal (m)
Belsay Dene	19.43	1.57	11.83	6.03	-
Corbridge	30.32	7.02	4.55	18.45	0.30
Pike Hill	-	-	-	-	-

Roddymoor borehole 1

Cycle	Thickness (m)	Carbonate (m)	Fine Clastics (m)	Coarse Clastics (m)	Coal (m)
Jew	35.28	10.69	16.54	8.05	-
Tynebottom	35.10	12.27	8.41	14.42	-
Single Post	31.70	13.58	11.71	6.41	-
Five Yard	24.44	9.07	12.47	2.90	-
Three Yard	45.82	1.32	10.97	33.53	-
Four Fathom	28.19	5.64	18.54	3.96	0.05
Great	41.51	18.49	9.40	13.54	0.08
Little	29.64	1.42	17.63	10.08	0.51
Crag	40.18	3.78	32.49	3.91	-
Corbridge	44.43	3.89	26.44	13.64	0.46
Upper Felltop	-	-	-	-	-

Roddymoor borehole 2

Cycle	Thickness (m)	Carbonate (m)	Fine Clastics (m)	Coarse Clastics (m)	Coal (m)
Scar	27.78	9.01	10.34	1.43	-
Five Yard	21.85	8.53	12.85	0.47	-
Three Yard	42.31	3.91	10.97	27.43	-
Four Fathom	26.45	5.18	12.83	8.44	-
Iron Post	7.84	0.46	6.32	1.01	0.05
Great	41.51	18.49	9.40	13.49	0.13
Little	20.78	1.14	17.32	2.32	-
Faraday House	8.86	1.19	0.51	7.16	-
Bottom Crag	5.44	3.15	2.29	-	-
Top Crag	7.69	1.30	6.39	-	-
Knucton Shell Beds	27.05	2.08	23.42	1.55	-
Rookhope Shell Beds	11.28	3.68	7.59	0.01	-
Lower Felltop	4.70	0.53	3.45	0.72	-
Coalcleugh Shell Beds	29.29	2.49	13.44	13.36	-
Upper Felltop	-	-	-	-	-

Rookhope borehole

Cycle	Thickness (m)	Carbonate (m)	Fine Clastics (m)	Coarse Clastics (m)	Coal (m)
Melmerby Scar	20.09	18.72	1.37	-	-
Robinson	5.95	3.76	1.85	0.41	0.03
Birkdale	9.80	1.47	2.72	5.61	-
Lower Peghorn	8.56	3.61	0.71	4.24	-
Upper Peghorn	4.04	1.22	0.97	1.85	-
Smiddy	25.55	8.53	13.60	9.42	-
Grainbeck	6.22	1.83	1.98	2.41	-
Lower Little	14.13	4.65	1.49	7.99	-
Jew	29.53	10.73	10.62	8.12	0.06
Tynebottom	14.48	9.32	1.27	3.89	-
Single Post	10.26	1.86	4.38	4.02	-
Cockleshell	12.94	0.48	6.38	6.08	-
Scar	32.94	9.13	10.44	13.37	-
Five Yard	18.82	4.90	9.12	4.80	-
Three Yard	30.02	2.50	15.22	12.30	-
Four Fathom	27.35	5.71	8.33	13.31	-
Iron Post	11.28	0.61	1.99	8.68	-
Great	-	-	-	-	-

No. 2 Scremerston borehole

Cycle	Thickness (m)	Carbonate (m)	Fine Clastics (m)	Coarse Clastics (m)	Coal (m)
Dun	33.17	2.00	-	-	0.30
Woodend	-	-	-	-	-

Spittal / Scremerston coast section

Cycle	Thickness (m)	Carbonate (m)	Fine Clastics (m)	Coarse Clastics (m)	Coal (m)
Dun	45.30	1.20	3.00	41.00	0.10
Woodend	65.30	2.40	-	-	-
Oxford	120.91	12.09	82.18	26.49	0.15
Eelwell	37.64	9.75	20.89	7.00	-
Acre	28.96	5.33	17.83	5.80	-
Sandbanks	-	-	-	-	-

Weldon Bridge borehole

Cycle	Thickness (m)	Carbonate (m)	Fine Clastics (m)	Coarse Clastics (m)	Coal (m)
Great	63.50	14.63	16.54	31.65	0.68
Little	-	-	-	-	-

Appendix Five

A5. PALAEOSOIL IDENTIFICATION CRITERIA 340

A5.1 Stages of palaeosoil development 340

A5.2 Description of glaebules 341

A5.3 Field scale of acid reaction to approximate carbonate content 341

A5.4 Master horizons of soils 342

A5.5 Terms for pedotubules 343

A5.6 Soil horizon boundaries 343

A5.7 Palaeosoil identification chart 344

A5. Palaeosoil identification criteria

The following information has been used throughout this thesis to identify and classify palaeosoils. All information taken from Retallack, 1990.

A5.7 shows the palaeosoil recording sheet that was used to record information in the field.

A5.1 Stages of palaeosoil development

Stage	Development
Very weakly developed	Little evidence of soil development apart from root traces: abundant sedimentary, metamorphic or igneous textures remaining from parent material
Weakly developed	With a surface-rooted zone (A horizon), as well as incipient subsurface clayey, calcareous, sesquioxide or humic or surface organic horizons, but none of these developed to the extent that they would qualify as argillic, spodic or calcic horizons or Histosols
Moderately developed	With a surface-rooted zone and obvious subsurface clayey, calcareous, sesquioxide or humic or surface organic horizons, qualifying as argillic, spodic or calcic horizons or Histosols, and developed at least to the extent of nodules for calcic horizons
Strongly developed	With especially thick (2-3 m), red clayey or humic subsurface (B) horizons or surface organic horizons (coal or lignites) or especially well developed soil structure or calcic horizons as a continuous layer
Very strongly developed	Unusually thick (3 m or more) subsurface (B) horizons or surface horizons (coal or lignites); such a degree of development is found mainly at major geological unconformities

A5.2 Description of glaebules

Aspect	Category	Description
Distinctness	Very sharp Sharp Diffuse Very diffuse	Transition to matrix in less than 1 mm Transition to matrix over about 1 mm Transition to matrix over 1 - 5 mm Transition to matrix over more than 5 mm
Contrast	Faint Distinct Prominent	Recognisable only on close inspection Readily seen, differing by at least to Munsell hues, chromas or values Obvious, with hue, chroma or value several Munsell units apart
Abundance	Few Common Many	Less than 2% of exposed surface 2 – 20% of exposed surface more than 20% of exposed surface
Size	Fine Medium Coarse	Less than 5 mm diameter on exposed surface 5 – 15 mm diameter more than 15 mm diameter

A5.3 Field scale of acid reaction to approximate carbonate content

Class	Carbonate content (weight %)	Sound of reaction (hold close to ear)	Reaction with dilute acid
Non calcareous	Less than 0.5	None	Acid unreactive, may form inert bead
Weakly calcareous	0.5 – 1	Faintly increasing to slightly audible	Little movement within the acid drop, which could be flotation of dust particles as much as bubbles
Calcareous	1 – 5	Faintly increasing to moderately audible	Numerous bubbles, but not coalescing to form a froth
Strongly calcareous	5 – 10	Easily audible, heard away from ear	Bubbles forming a white froth, with bubbles up to 3 mm diameter, but drop not doming upward
Very strongly calcareous	More than 10	Easily audible	Drop vigorously frothing and doming upward with some bubbles up to 7 mm diameter

A5.4 Master horizons of soils

Horizon	Definition and variation
O horizon	Surface accumulation of organic material overlying a mineral soil *Histic epipedon* has at least 18% organic matter if the mineral fraction contains more than 60% clay or 12% organic matter if the mineral fraction has no clay, for a depth of 20 cm.
A horizon	Accumulation of humified organic matter mixed with mineral fraction. Occurs at the surface or below an O horizon. Organic matter contents are less than those required for the O horizon. *Mollic epipedon* has a fine structure (usually granular peds), dark colour (chroma of 3 or less, value darker than 5, when dry), contains at least 1% organic matter (0.58% organic carbon), and has a base saturation of over 50%: generally associated with grassland vegetation. *Umbric epipedon* is similar to a mollic epipedon except for the platy to massive structure and base saturation less than 50%: generally associated with forest vegetation. *Ochric epipedon* is to light in colour and low in organic matter to be mollic or umbric.
E horizon	Underlies an O or A horizon and is characterised by less organic matter, less sesquioxides (Fe_2O_3 and Al_2O_3), or less clay than the underlying horizon. This horizon is light coloured due mainly to the colour of primary mineral grains because secondary coatings on grains are absent. It is also known as an *albic horizon*.
B horizon	Underlies O, A or E horizon and shows discernable alteration of parent material. *Argillic horizon* has more silicate clay than A or E horizon or the assumed parent material. In other words, silicate clays have been translocated into the B from overlying horizons, or they have formed in place within the B horizon, or both. Clay translocation is recognised in the field by oriented clay films that coat mineral grains, small channels or ped surfaces. Compared with eluvial horizons argillic horizons have 3% more clay if eluvial horizon clay is 10-15%, 12% more clay if eluvial horizon clay is 15-40%, 8% more if it is 40-60% or 8% more fine clay if it is more than 60%. *Kandic horizon* is similar to argillic horizon in clay enrichment, but the clays are kaolinitic and there are very few weatherable minerals remaining. *Calcic horizon* is enriched in calcite or dolomite in the form of coatings, wisps or nodules, and is at least 15 cm thick with at least 5% more carbonate than underlying horizons. *Natric horizon* has a columnar or prismatic ped structure, and more than 15% saturation with exchangeable sodium. *Spodic horizon* generally occurs beneath an E horizon and is characterised by a concentration of organic matter and sesquioxides that have been translocated downward from the E horizon. *Oxic horizon* is highly weathered with hydrated oxides of iron and aluminium, 1:1 lattice clays, and low cation-exchange capacity. Few primary silicate minerals remain, with the exception of quartz and gibbsite, which are resistant to weathering. *Cambic horizon* is characterised by at least enough pedogenic alteration to eradicate pre-existing structures, form some soils structure, and remove or redistribute primary carbonate. Their colour has higher chroma or redder hue than does the colour of the underlying horizons.
K horizon	Subsurface horizon so impregnated with carbonate that its morphology is determined by the carbonate. Authigenic carbonate coats or engulfs all primary grains in a continuous medium and makes up 50% or more by volume of the horizon. The uppermost part of the horizon commonly is laminated
C horizon	Subsurface horizon, excluding bedrock, with slightly more weathered material from which the soil formed or is presumed to have formed. Lacks properties of A and B horizons, but includes weathering as shown by mineral oxidation, accumulation or silica, carbonates or more soluble salts, and gleying.
R horizon	Consolidated or weathered bedrock underlying the soil.

A5.5 Terms for pedotubules

Term	Definition
Granotubule	Filled with clastic grains and little clay
Aggrotubule	Filled with pellet-like clasts of clay and clastic grains
Isotubule	Filled with mixed clay and clastic grains without any orientation
Striotubule	Filled with mixed clay and clastic grains with curved layering
Orthotubule	Very similar fabric and composition to soil matrix
Metatubule	Different material from soil matrix and derived from some other soil horizon
Paratubule	Different material from soil matrix and unlike anything else within the profile

A5.6 Soil horizon boundaries

Term	Description
Abrupt	Less than one inch (2 cm) wide
Clear	1 – 2½ inches (2 – 5 cm)
Gradual	2½ – 5 inches (5 – 15 cm)
Diffuse	More than 5 inches (15 cm)
Smooth	Nearly a plane
Wavy	Undulating with pockets wider than deep
Irregular	Undulating with pockets deeper than wide
Broken	Parts of the horizon disconnected

Palaeosoil Recognition Sheet

Date		Locality	
Grid Ref:		Strat. Position	

General Description: ____________________

Development: (see chart) ____________________

Horizons Present: YES / NO
(If yes, fill in sheet for each)

Parent Material: ____________________

Horizon No.: _____ Classification: ____________

Upper Boundary: ____________________
Lower Boundary: ____________________

Colour Fresh: ____________________
Weathered: ____________________

Carbonate Content: ____________________

Approximate Mineralogy: ____________________

Sample Taken: YES / NO No.: ____________
Photo Taken: YES / NO

Traces of Life

	Rare	Common	Abundant
Root traces:	☐	☐	☐

Composition: ____________________
Position within horizon: ____________________
Shape: ____________________
Size: ____________________
Nature: ____________________

Other comments: ____________________

Root Mottles: ☐ ☐ ☐

Colour: ____________________

Rhizocretions: ☐ ☐ ☐

Composition: ____________________
Shape: ____________________
Size: ____________________

Other fossils: YES / NO

If present, state nature: ____________________

Coal on top: YES / NO
If yes, state thickness: ____________________

Macrostructures

Glaebules (nodules/concretions/septaria)

Composition: ____________________
Distinctness: ____________________
Contrast: ____________________
Abundance: ____________________
Size: ____________________

Other comments: ____________________

Pedotubules (see chart)

Comments: ____________________

Crystallaria (see chart)

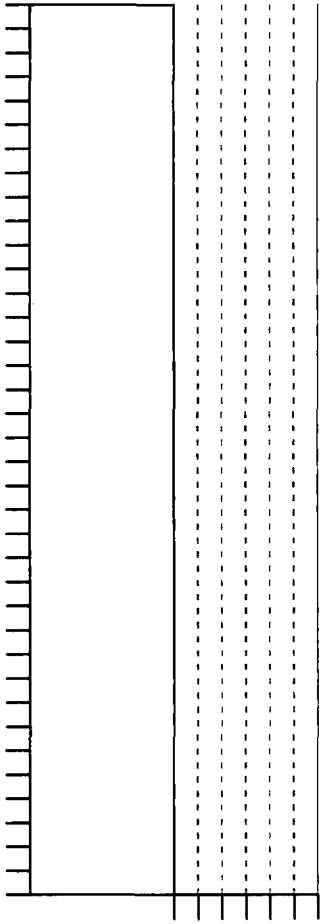
Comments: ____________________

Other features

Clastic dykes	YES / NO
Shrinkage cracks	YES / NO
Slicken sides	YES / NO
Stratification visible	YES / NO

Comments: ____________________

Log of profile / horizon (state)



Appendix Six

A6. GEOCHEMISTRY RESULTS 346

A6.1 Whole rock limestone results 346

A6.2 Brachiopod shell results 350

A6. Geochemistry results

The following tables provide all geochemistry results from both whole rock limestones (A6.1) and brachiopod shells (A6.2). A key for all sample names used in this section has been provided at the end of this Appendix.

A6.1 Whole rock limestone results

Beadnell coast section

Sample Name	$\delta^{13}C$	$\delta^{18}O$
BLAL1	-0.3	-5.1
BLAL2	0.0	-6.2
BLAL3	0.0	-11.4
BLEL1	0.5	-12.6
BLEL2	4.8	-7.1
BLEL3	1.0	-9.7
BLSBL1	0.5	-8.7
BLSBL2	2.2	-8.8
BLSBL3	0.3	-13.5
BLSBL4	2.3	-8.9
BLSBL5	2.0	-7.8

Bowlees Beck river section

Sample Name	$\delta^{13}C$	$\delta^{18}O$
BSCL1	-5.3	-14.6
BSCL2	-2.8	-15.1
BSFYL1	0.7	-12.8
BSFYL2	-0.4	-13.1
CC49396/BSFYL3	0.9	-12.8
BSFYL4	0.8	-12.3
BSFYL5	-1.2	-10.3
BSSL1	0.0	-12.1
BSSL2	0.7	-11.7
BSSL6	-0.7	-13.5

Howick coast section

Sample Name	$\delta^{13}C$	$\delta^{18}O$
HKAL1	0.1	-10.6
HKAL2	-1.4	-11.3
HKAL3	-4.0	-14.4
HKAL4	-2.6	-12.1
HKISL1	-4.1	-12.7
HKISL2	-4.0	-12.5
HKSLB1	-0.6	-6.2
HKSBL2	-0.7	-8.9
HKSBL3	-0.3	-8.4
HKSBL4	1.4	-10.8
HKSB4A	-0.2	-10.8
HKSSL1	-2.2	-14.1
HKSSL2	-0.1	-9.9
HKSSL3	0.8	-8.3

Heights Quarry

Sample Name	$\delta^{13}C$	$\delta^{18}O$
HQGL1	1.7	-12.0
HQGL2	1.7	-10.5
HQGL3	1.6	-12.4
HQGL4	1.5	-13.8
HQGL5	1.8	-11.8

Haltwhistle Burn river section

Sample Name	$\delta^{13}C$	$\delta^{18}O$
HWGL1	1.2	-6.5
HWGL2	0.8	-8.5
HWGL3	1.4	-6.8
HWGL4	1.0	-7.5
HWGL5	1.2	-7.5
HWGL6	-0.5	-10.4
HWGL7	-0.5	-9.2
HWLL1	3.2	-8.2
HWLL2	-1.1	-10.6
HWLL3	-0.3	-8.6
HWLL4	-0.3	-9.4
HWOL2	-2.8	-11.8
HWOL3	-2.8	-12.8
HWOL4	-3.9	-9.2

Spittal / Scremerston coast section

Sample Name	$\delta^{13}C$	$\delta^{18}O$
SLAL1	2.0	-9.1
SLDL1	-0.3	-4.3
SLDL1	0.6	-4.3
SLOL1	1.0	-10.3
SLOL2	1.5	-13.1
SLSBL1	2.5	-8.2
SLSBL2	2.8	-7.1
SLWL1	-1.4	-5.8
SLWL2	-1.1	-6.0

Rookhope borehole

Sample Name	$\delta^{13}C$	$\delta^{18}O$
RHSL1	-5.2	-14.5
RHSL2	-5.2	-15.2
RHMSL1	-3.5	-16.3
RHMSL2	-3.6	-17.4
RHMSL4	-4.3	-13.4
RHGL1	0.2	-15.7
RHGL2	0.4	-13.5
RHGL3	1.1	-11.2
RHGL4	1.3	-12.2
RHFFL1	-1.2	-15.2
RHFFL2	-0.7	-12.0
RHVSL1	-0.2	-16.2
RHIPL1	-0.4	-16.3
RHSPL1	1.2	-14.2
RHBL1	2.0	-15.6
RHTYL1	-6.9	-16.2
RHTYL2	-4.7	-15.0
RHTBL1	0.4	-15.5
RHTBL2	-2.5	-16.2
RHJL1	-4.3	-15.4
RHJL2	-6.8	-16.7
RHFYL2	-2.6	-13.3

Wild Boar Scar

Sample Name	$\delta^{13}C$	$\delta^{18}O$
WBS1 / BASE	0.2	-8.2
WBS2 / 5M	-2.4	-9.7
WBS3A / 10M	-2.2	-8.1
WBS3 / 10M	-3.5	-8.2
WBS4 / 15M	-4.0	-7.8

A6.2 Brachiopod shell results

Beadnell coast section

Sample Name	$\delta^{13}C$	$\delta^{18}O$
BLALBD1	1.7	-5.1
BLSBBD	1.4	-8.6
BLELBD1	1.9	-7.4

Bowlees Beck river section

Sample Name	$\delta^{13}C$	$\delta^{18}O$
BSFYLBD1	2.8	-5.6
BSFYBD2	2.4	-5.4
BSFYBD3	2.2	-5.5
BSCLBD1	-1.2	-8.0
BSCLBD2	0.8	-9.0

Howick coast section

Sample Name	$\delta^{13}C$	$\delta^{18}O$
HKSBBD1	2.1	-6.3
HKSBBD2	3.7	-4.1
HKSSBD1	-0.3	-7.9
HKSSBD2	0.1	-8.3
HKISBD1	0.9	-6.4

Spittal / Scremerston coast section

Sample Name	$\delta^{13}C$	$\delta^{18}O$
SLSWBD1	-2.8	-9.7
SLDLBD1	-0.3	-5.6
SLOLBD1	0.8	-4.5
SLOLBD2	1.1	-5.8
SLOLBD3	0.2	-5.7
SLOLBD4	2.0	-5.6

Key to sample names:

BLAL	*Beadnell* Acre limestone
BLEL	*Beadnell* Eelwell limestone
BLSBL	*Beadnell* Sandbanks limestone
BSCL	*Bowlees* Cockleshell limestone
BSFYL	*Bowlees* Five-Yard limestone
BSSL	*Bowlees* Scar limestone
HKAL	*Howick* Acre limestone
HKISL	*Howick* Iron Scars limestone
HKSBL	*Howick* Sandbanks limestone
HKSSL	*Howick* Sugar Sands limestone
HQGL	*Height's Quarry* Great limestone
HWGL	*Haltwhistle* Great limestone
HWLL	*Haltwhistle* Little limestone
HWOL	*Haltwhistle* Oakwood limestone
SLAL	*Spittal* Acre limestone
SLDL	*Spittal* Dun limestone
SLSBL	*Spittal* Sandbanks limestone
SLWL	*Spittal* Woodend limestone
RHSL	*Rookhope* Smiddy limestone
RHMSL	*Rookhope* Melmerby Scar limestone
RHGL	*Rookhope* Great limestone
RHFFL	*Rookhope* Four Fathoms limestone
RHVPL	*Rookhope* Upper Smiddy limestone
RHIPL	*Rookhope* Iron Post limestone
RHSPL	*Rookhope* Single Post limestone
RHBL	*Rookhope* Birkdale limestone
RHTYL	*Rookhope* Three-Yard limestone
RHTBL	*Rookhope* Tynebottom limestone
RHJL	*Rookhope* Jew limestone
RHFYL	*Rookhope* Five-Yard limestone
WBS	*Wildboar Scar* (unnamed limestone)

NB 'BD' suffix = brachiopod sample from named limestone