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Sedimentology of the Eocene succession in BGS Borehole 99/3

Marine Geoscience Programme

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BRITISH GEOLOGICAL SURVEY

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Sedimentology of the Eocene succession in BGS Borehole 99/3

A Leslie, K Hitchen and M Stoker

Keywords

Sedimentology, Eocene, Faroe-Shetland Channel.

Offshore Reference

Centre point 60° 24.8183N, 4° 39.0639W

Map

Judd, 1 : 250 000 offshore map series.

Front cover

Photograph of bioturbated Eocene mudstone from Borehole 99/3.

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Foreword

This report is the product of a study by the British Geological Survey (BGS) investigating the sedimentology of the Eocene succession in BGS Borehole 99/3. The report draws on work by the original cruise geologists, R Gatliff, D Tappin and M Williams. Dating of the rocks was originally published in Hitchen (1999) and Stoker (1999).

This work was carried out for the BGS Rockall Consortium during 2010.

Acknowledgements

In addition to the BGS staff acknowledged in the Foreword, H Johnson contributed to the production of this report, and Eileen Gillespie and Craig Woodward drafted the figures.

Thanks are also due to Dr M Huuse of the University of Manchester for discussion on aspects of the sedimentology.

Contents

1 Summary

The evolution of the Faroe-Shetland Basin during the Eocene is currently the subject of considerable interest. Subsidence during the Eocene has produced a succession in which shelf and slope deposits, some of which might have potential as hydrocarbon reservoirs, overlie non-marine and shallow marine sedimentary rocks. The rate of subsidence in the basin, and identification of the exact depositional environments in which the sediments were deposited, have some bearing on the interpretation of the time of onset on North Atlantic deep water circulation.

The sedimentology of the Eocene succession in BGS Borehole 99/3 is of some relevance to this discussion as it has been interpreted to be part of a contourite drift, implying that deep marine circulation was active. The mudstones and muds in the core, however, contain little definitive evidence for contour current activity, nor have any down-slope depositional events been identified.

2 Introduction

BGS Borehole 99/3 was drilled in the south-western end of the Faroe-Shetland Channel (licence block 204/17) between the 20th and 24th June 1999. It was drilled on the lower slope of the West Shetland Shelf in 983 m water depth (Figure 1) and targeted folded Eocene strata that are at, or near to, sea bed in parts of the Faroe-Shetland Channel.

The borehole penetrated 54 m of Quaternary sediments (Davison & Stoker, 2002; Davison, 2004) overlying 112.5 m of Eocene sediments and sedimentary rocks with TD at 166.5 m. The Eocene succession has been subdivided into Early, Mid and Late Eocene units separated by unconformities at 63.0 and 142.7 m (Hitchen, 1999).

In 2010 the Eocene succession was re-examined to determine details of the depositional environment in which the rocks were formed and to investigate evidence for water depth during deposition. The evolution of the Faroe-Shetland area during the Palaeogene has been subject to some debate, in particular the paleogeography of the area around 99/3 during the Eocene (Sørensen, 2003; Smallwood, 2004). The project was instigated partially to investigate claims that some of the Eocene succession was deposited by contour currents (Hohbein, 2006). This has implications both for the evolution of the Faroe-Shetland Basin and for the development of deep-water circulatory systems within the North Atlantic Ocean and Norwegian Sea.

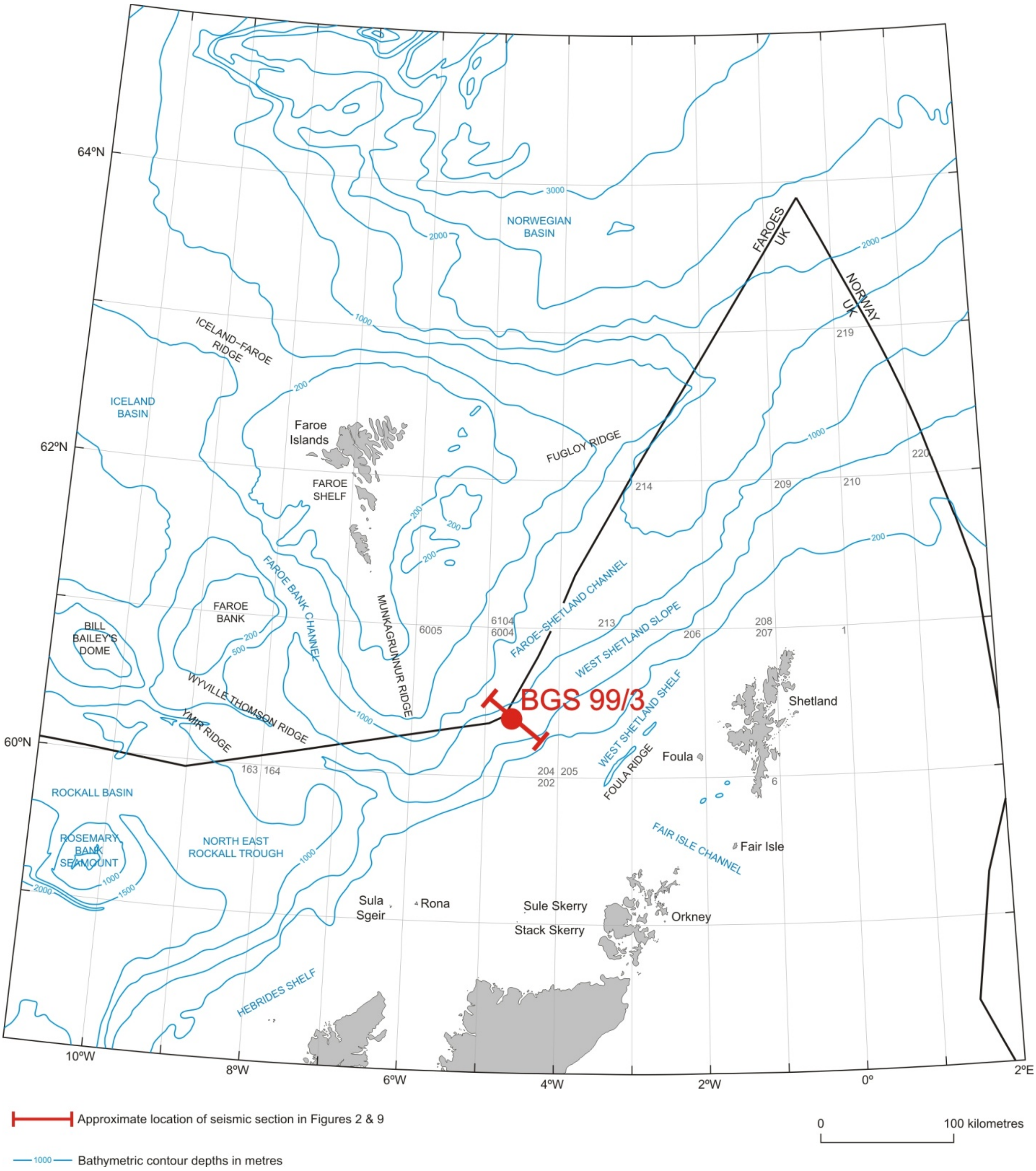

Figure 1. Location map of Faroe-Shetland Channel area, including the main bathymetric features (GEBCO digital atlas bathymetric data courtesy of British Oceanographic Data Centre (BODC), NERC) and the approximate location of BGS Borehole 99/3 and the section shown in Figure 2.

3 Geological Setting

The Faroe-Shetland Channel has been a depocentre since the Mesozoic or possibly late Palaeozoic. The channel is currently defined by the Faroe Shelf to the north-west and the West Shetland Shelf to the south-east, and also by Cenozoic inversion structures such as the Wyville-Thomson Ridge (Figure 1) (Ritchie et al., 2003; 2008). One such inversion structure is the Judd Anticline, a north-east trending antiform uplifting the Palaeogene rocks of the Judd Sub Basin which contains at least several hundred metres of Cretaceous and Palaeogene sedimentary rocks (Smallwood, 2004). The Judd Anticline underlies the site of Borehole 99/3 and the uplifted Palaeogene succession formed the target for drilling.

BGS Borehole 99/3 lies close to the junction of the Faroe-Shetland and Faroe Bank channels at latitude 60^{o} 24.8183 N, 4^{o} 39.0639 W in water depth of 983 m (Figure 1). In this location, deep water bodies (the Norwegian Sea Arctic Intermediate water and Faroe-Shetland Channel Bottom water) transport cold water from the Norwegian Sea through the two channels (albeit a single conduit) and into the Rockall Trough and Iceland Basin.

The uppermost 54 m of the borehole are Quaternary sediments, composed of glacigenic debris flow diamicton interbedded with hemipelagic glacimarine mud (Davison & Stoker, 2002). These sediments are part of the Rona Wedge, a late Pleistocene depocentre overlying the Intra-Neogene Unconformity, where glacimarine sediments form a thick prograding wedge extending into the Faroe-Shetland Channel (Figure 2). Borehole 99/3 penetrates the distal part of this prograding wedge. In deeper water to the north-west the Quaternary sediments are being eroded by the bottom currents and older rock is exposed at sea bed.

Between 54 m and 166.5 m (TD), 99/3 penetrated a succession of Eocene sedimentary rocks and sediments (Figure 2). The sedimentology of this succession is discussed in Section 4.

4 Methodology

This study involved examination of the core using a KOYOWA SN132 binocular microscope with magnification of x10 to x20. No additional petrographical or palaeontological work was carried out.

The consolidated rock core was desiccated but this tended to emphasise subtle differences in grain size, in particular where burrows had been filled by mud-rich material, and did not hamper the core description. Unconsolidated sediment core was partially desiccated and degraded. Exposing fresh surfaces was not straightforward even if using an electro-osmotic knife, and so description was more difficult.

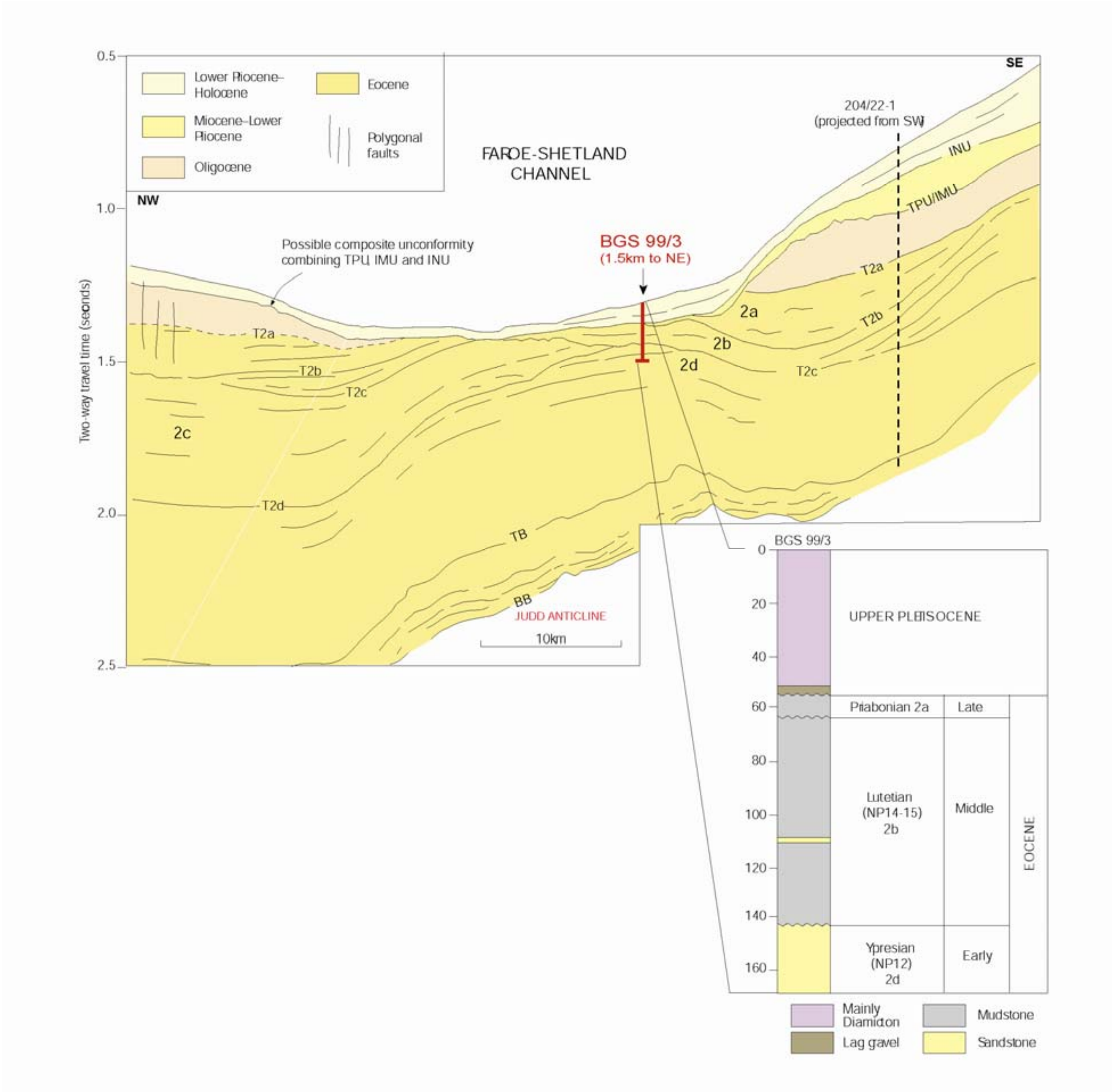

Figure 2. Simplified log of BGS Borehole 99/3 showing subdivision of the Eocene succession and its relationship with the regional seismic stratigraphy. Location shown on Figure 1. TPU: Top-Palaeogene Unconformity; IMU: Intra-Miocene Unconformity; INU: Intra-Neogene Unconformity; TB: Top Balder; BB: Base Balder. Units 2a-2d and surfaces T2a-T2c are shown in Figure 3.

5 Sedimentology of the Eocene Succession

5.1 PREVIOUS WORK

Borehole 99/3 penetrated 112.5 m of Eocene material, between the unconformity with the overlying Pleistocene succession at 54.0 m and TD at 166.5 m (Figure 2). Recovery was moderate to poor in the upper and lower parts and good (>70%) between 98 and 138 m. The majority of the core recovered was consolidated rock and was able to be split for examination. However sections of unconsolidated sediment were recovered throughout the Eocene succession (Figure 2).

The original work on the core interpreted the Eocene succession to comprise 3 units separated by unconformities at approximately 63.0 m and 142.7 m (Figure 2) (Hitchen, 1999). The uppermost unit, from 54.0 – 63.0 m is Late Eocene (Priabonian) in age. Between 63.0 and 142.7 m the sediments and rocks are assigned to the Mid Eocene (Lutetian). The lower unit between 142.7 and 166.5 m (TD) is Early Eocene (Ypresian) in age. The age-determined unconformities within the core correspond with known surfaces identified in seismic records (Figure 2).

The Eocene rocks in 99/3 are part of the Stronsay Group which corresponds to megasequence FSP-2, which has been subdivided into 4 units (Figure 3). In 99/3 it appears that unit 2c is absent and the succession comprises units 2d, 2b and 2a, respectively Ypresian, Lutetian and Priabonian in age (Figure 4) (Stoker et al., 2001). The lower (Bartonian) and upper parts of unit 2a are missing from 99/3.

Robinson (2004) and Huuse (Pers. Comm., 2010) describe a seismic geometry similar to that of sandstone injection structures observed elsewhere in the Faroe-Shetland Basin at a depth of 127 m in 99/3. Hohbein (2006) provided evidence that contourite deposition took place in the Middle Eocene, suggesting that North Atlantic deep water circulation had begun earlier than previously reported.

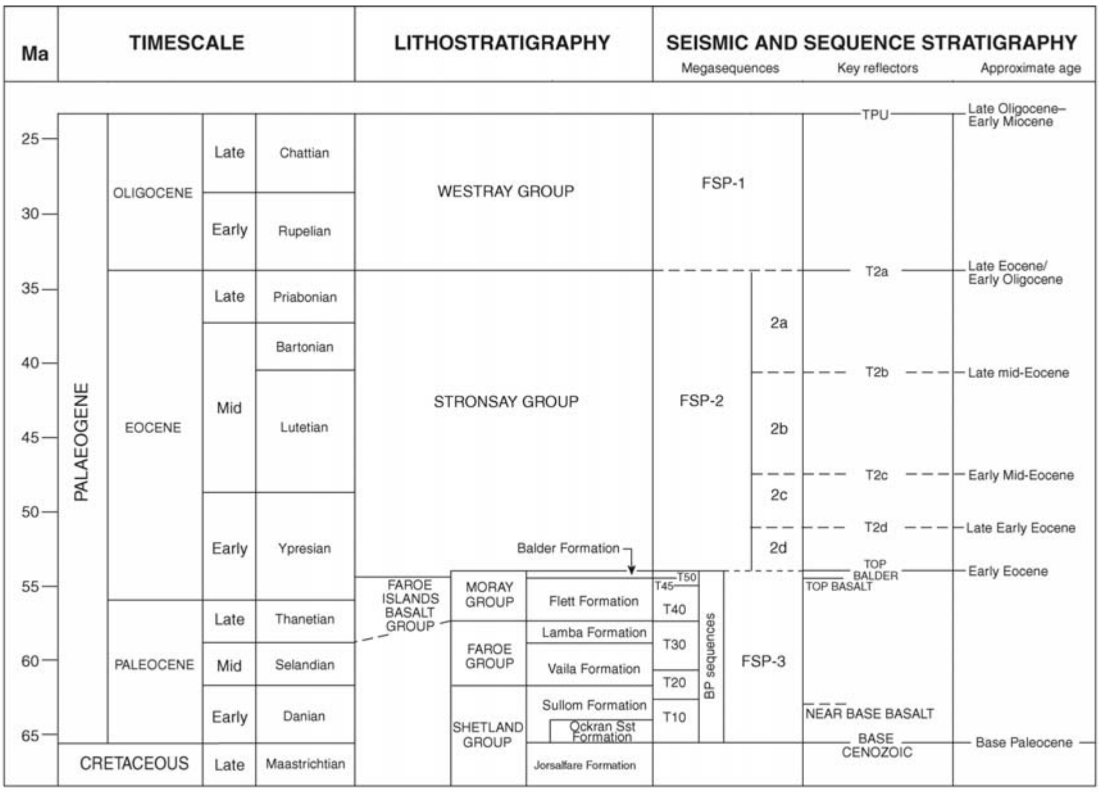

Figure 3. Stratigraphy of the Palaeogene in the Faroe Shetland Basin.

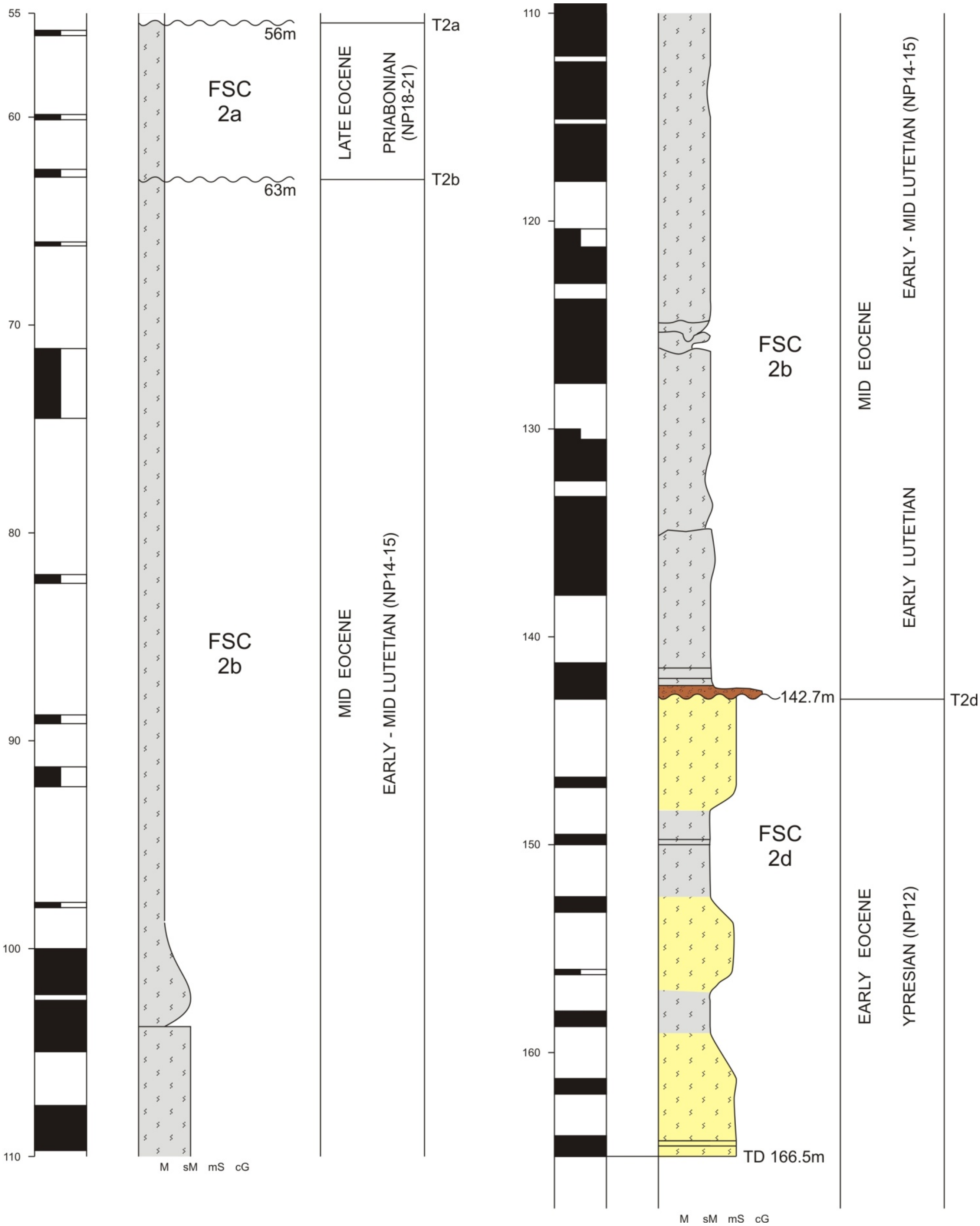

Figure 4. Log of Eocene section of 99/3. The left hand column shows core recovery, where the column is partially filled this indicates a core section in poor condition. The brown interval at 142.7 m is a conglomeratic sandstone, yellow is muddy sandstone, grey is mud, sandy mud or sandy mudstone. Bioturbation occurs throughout the core.

5.2 EOCENE SEDIMENTOLOGY

5.2.1 Unit FSP-2d

Unit FSP-2d was recovered between 142.7 and 166.5 m (TD) and is Early Eocene (Ypresian) in age, corresponding to biostratigraphic zone NP12 (Hitchen, 1999). A total of 4.2 m of core was collected from the interval, giving a recovery of 18% (Figure 4).

The sedimentary rock is a fine to very fine grained sandstone, with variable mud (silt and clay) content. The majority of the clasts (60-80%) are quartz, but feldspar, mica, lithic grains, glauconite and very uncommon ferromagnesian minerals and bioclastic (shell) material are all present. Colour is commonly Munsell® 5Y 5/2 (light olive grey). The green-grey colour might be in part related to the presence of chlorite derived from volcanigenic clasts within the rock. Grains are sub-rounded and well sorted, making the sandstone textually mature. The sandstone could be termed an arkosic arenite, with the most mud-rich rocks close to greywacke. In the upper 0.4 m of the sequence, patches of material of presumed organic origin have formed, presumably through diagenetic processes.

The sandstone is commonly cemented by calcite, but several sections of sand and muddy sand do not contain cement and have not been fully lithified. In these intervals, between 152.30-152.48, 157.80-158.44 and 165.64-166.22, there is no evidence for the presence of carbonate cement but otherwise the sand has the same composition, texture and sedimentary structure as the lithified sections.

The sandstone commonly has a homogenous appearance, related to pervasive bioturbation of the sediment. This process creates sediment in which little structure is visible and individual burrows cannot clearly be delineated and is defined as biodeformation (Akhurst et al., 2002).

Individual burrows are also present within the succession, commonly ovoid in outline, and mud filled with a diameter of 2-12 mm. They are uncommon, taking up under 5% of the sedimentary rock (Figure 5) and are assigned to the *Planolites* form of trace fossil.

Between 161.3 and 152.48 m smaller, lenticular mud filled burrows are present, most abundant around 157.80 m. The orientation of these burrows, assigned to the *Chondrites* form, ranges from sub vertical to 45^{o} inclination. Branches are uncommon but where observed the burrows branch downward in the core.

In two sections between 165.64-166.22 and 149.51-52.48 m sedimentary lamination is seen in the core. These bands consist of alternations of mud and sandy mud, between 2 and 5 mm in thickness, with relatively planar, sharp contacts. In the upper interval, bands of mud become progressively less common upwards, although their thickness does not change. Within these two intervals individual burrows cannot be seen.

Variation in porosity and permeability within the sequence might be related to the cementation of the core, as the cemented sandstone intervals appear to contain the least matrix and fine grained clasts.

The preservation of lamination in some sections of core presumably related to the interaction between rate of sediment supply and intensity of bioturbation.

Figure 5. FSC-2d sandstone containing sparse, mud-filled burrows (arrowed). Core diameter is 80 mm.

5.2.1 Unit FSP-2b

Unit FSP-2b was recovered between 63.0 and 142.7 m and is Mid-Eocene (Lutetian) in age, corresponding to biostratigraphic zones NP14-15 (Hitchen, 1999). A total of 36.18 m of core was collected from the interval, giving a recovery of 48% (Figure 4).

The succession comprises a basal conglomerate underlying a series of muds and sands, which become increasingly consolidated with depth. Below 100 m the core can be termed mudstone and recovery improves markedly.

The unconformity surface between units FSP-2d and 2b is presumably at, or just below, 142.7 m and corresponds closely to surface T2c identified in seismic sections (Figure 2). At the location of Borehole 99/3 this surface is a composite unconformity, combined with T2d, and unit FSC-2c is not present in the core. Seismic sections indicate that there was a period of uplift and erosion before deposition of unit FSC-2b, with removal of up to 500 ms TWTT of FSC-2c sediment (Figure 2). This represents one of the phases of compression which are typical of the NW UK margin (Sørensen, 2003; Smallwood, 2004; Ritchie et al., 2008).

The basal core in unit FSP-2b contains 0.3 m of ferruginous conglomeratic sandstone with clasts up to 0.1 m diameter in a strongly iron stained matrix (Figure 6). Colour is variable but Munsell® 2.5Y 8/4 (pale yellow) is typical of the matrix while clasts are 7.5YR 5/3 (brown). Uncommon sub-horizontal lenses of grey sandy mud 8 mm in thickness and up to 90 mm in length might reflect bioturbation in the core. Bioclasts include foraminifera and sharks teeth.

The conglomerate is overlain conformably by 0.7 m of muddy sandstone which fines upwards to a rock intermediate between muddy sandstone and sandy mudstone. Munsell® colour is 2.5Y 6/3 (light yellowish brown). This sandstone contains 70% quartz, with uncommon mica, feldspar and lithic grains and scattered fragments of brown mudstone. This sandstone contains bands of sandy mud 1-4 mm in thickness, commonly slightly darker in colour than the surrounding sandstone. Patches of cemented material 4-5 mm in diameter are found within the sandstone. The cementing mineral is soft and is possibly a zeolite. Small zeolite crystals have been identified within the core in petrographic analysis. The sandstone is bioturbated, with two types of mud-filled burrows, one lenticular, 3-4 mm in diameter and sub horizontal and the second sub rounded and 2-3 mm in diameter. Both burrows are similar to *Chondrites* in form.

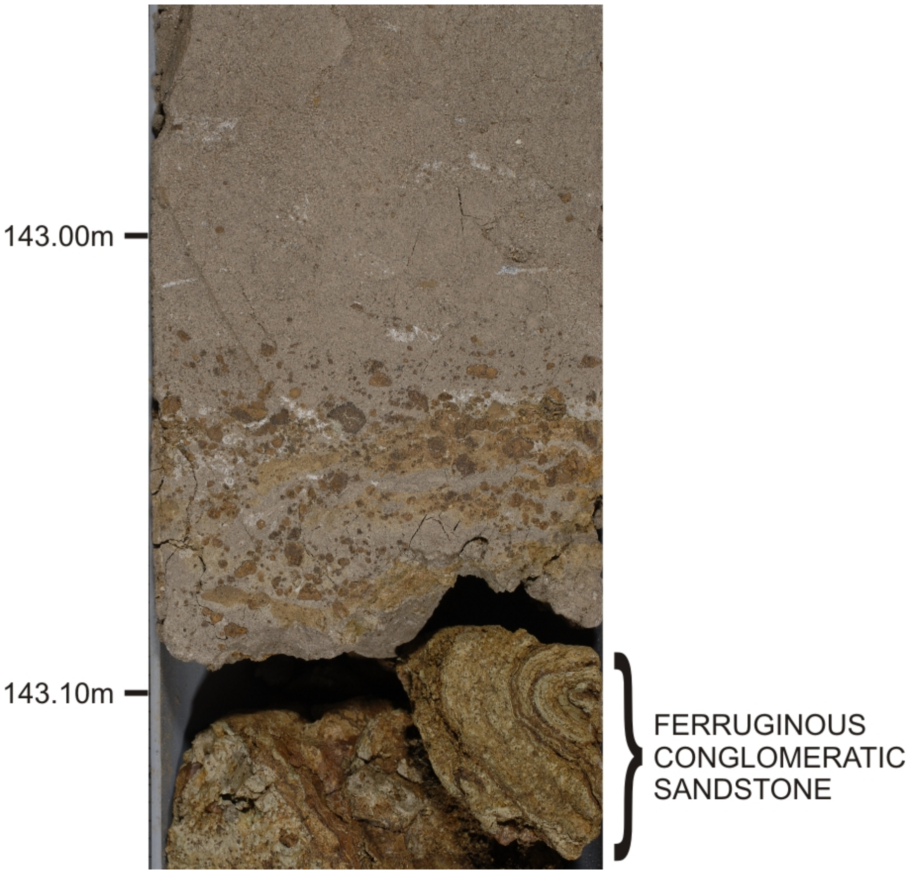

Figure 6. Ferruginous conglomerate and sandstone at the base of unit FSC-2b. Core diameter is 80 mm.

The remainder of unit FSC-2b above 140.0 m comprises muddy sandstone and sandy mudstone that becomes slightly finer grained and less consolidated upwards (Figure 4). Munsell® colour is 2.5Y 6/3 (light yellowish brown) or 2.5Y 5/3 (light olive brown) although undesiccated core material is darker. Generally there is 50-60% of fine grained sand within the rock or sediment, with mica, feldspar, lithic grains and glauconite forming the remainder of the clasts. Between 30 and 50% of the material is silt or clay, making the rock a greywacke. While much of the unit is consolidated, there is no evidence for cementation by calcite and calcium carbonate bioclasts are fragmentary and very uncommon.

Below 138 m the unit commonly shows lamination, similar in scale to that in unit FSC-2d, with mud-prone laminae between 1 and 4 mm in thickness commonly showing sharp bases and tops, although uncommon grading can be observed. The remainder of unit FSC-2b is not laminated, but surfaces at 134.61, 127.54 (Figure 7a), 126.18, 125.55, 124.89 and 104.40 m indicate a change in sedimentary style. At 104.40 and 134.61 m (Figure 7b) a relatively planar surface is overlain by mud or mudstone, which grades upwards into sandy mudstone. The surface at 127.54

m is shown by a planar colour change between two sandy mudstones, while at 124.89, 125.55 and 126.18 m the colour change marks a sharp, undulating surface with relief of 20 mm either due to erosion or bioturbation.

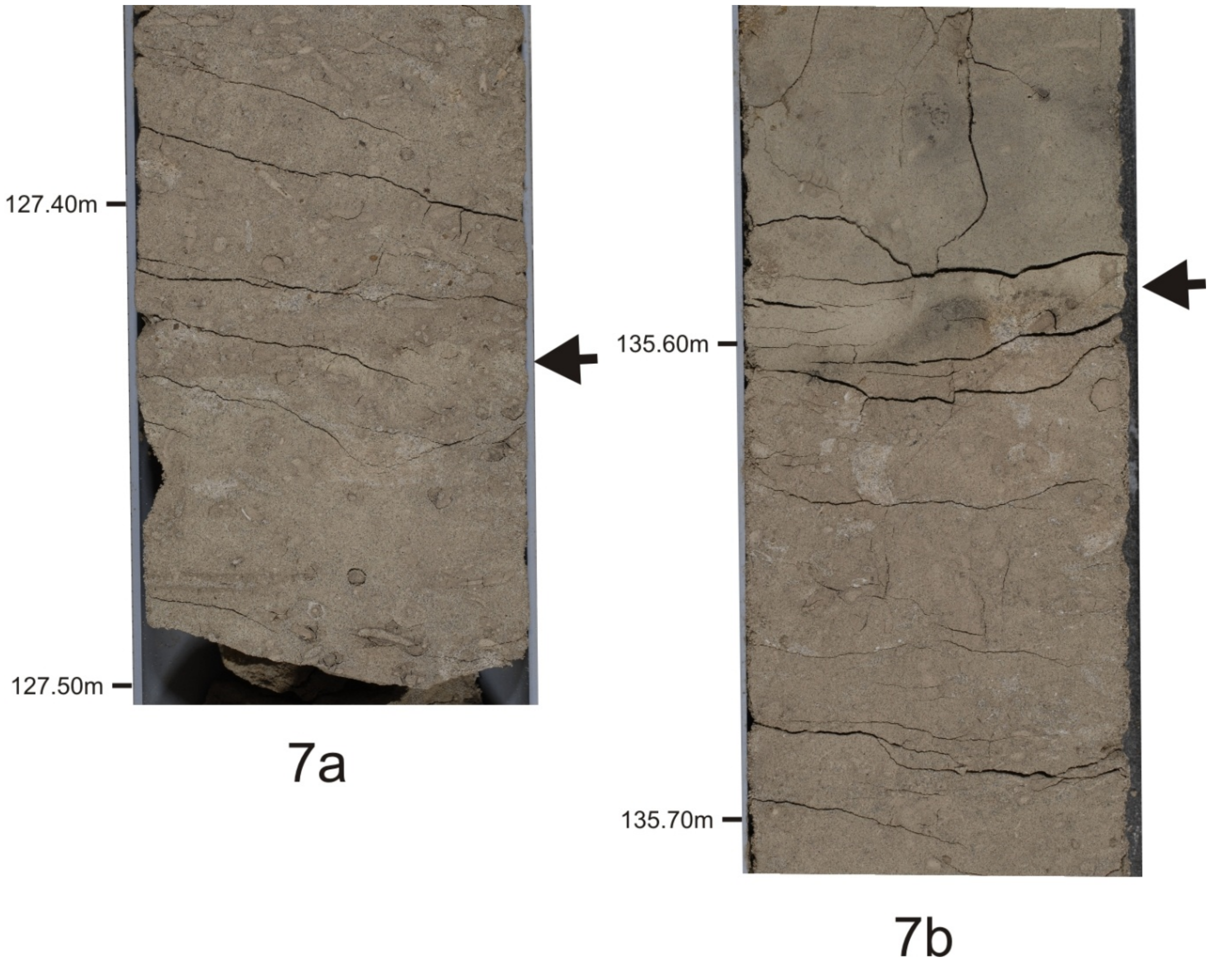

Figure 7. Sedimentary surfaces (arrowed) within FSC-2b. 7a shows a subtle boundary where sandy mud deposition has been interrupted and a bioturbated surface (shown by colour change) is preserved. 7b surface showing bioturbated sandy mudstone overlain by paler mudstone with limited bioturbation across the interface. Core diameters are 80 mm.

In the majority of unit FSC-2c there are subtle changes in character in the rock shown up by changes in the style of bioturbation, but there are no distinct sedimentary surfaces or beds such as sandstones.

In addition to discrete burrows, there appears to be a varying amount of biodeformation, where the sediment has been disturbed but not displaced, leaving the existing lamination preserved.

The following styles of bioturbation are present in unit FSC 2b (Figure 8).

- *Chondrites* (pale mud fill). These burrows are present throughout unit FSC 2b, with a sediment fill of mud with a similar, commonly slightly paler than the surrounding sandy mudstone. Burrows are commonly sub vertical, 2-4 mm in diameter with uncommon downward branching. They are commonly found within *Planolites* burrows and larger, dark mud filled *Chondrites*. Above 89.0 m *Chondrites* is uncommon.

- *Chondrites* (dark mud fill). These are similar in style to the pale mud fill but commonly larger, having a diameter of 3-6 mm. Their abundance is variable and they are common in the unit around 136, 133, 115-110 and 99 m. They commonly rework burrows containing pale mud.

- *Planolites* (mud fill). These are present throughout the unit, comprising lenticular, sub-horizontal burrows, 4-5 mm in diameter filled with mud that is slightly paler than the surrounding sandy mudstone.
- *Planolites* (sand fill). These occur around 136, 132, 116 and 110 m depth and comprise sub horizontal burrows 4-5 mm in diameter filled with pale yellow sand. These burrows are associated with probable silicification of the core at 110 m.
- *Skolithos*. Present, if uncommon, at 137.5, 133, 126 and 116 m, these are vertical burrows 2-3 mm in diameter. At 132 m in the core they thicken upwards to around 4 mm in diameter but it is not certain whether this is a different burrow type.
- *Zoophycos*. One example of a horizontal burrow 4 mm in diameter with a ‘chambered’ backfill, found at 126.8 m.

The variations in bioturbation might have several causes. The intensity of bioturbation appears to be generally similar throughout, with burrows common within the core, but not enough to completely obscure sedimentary contacts between sandy mudstone and the uncommon mud-rich horizons. Burrows infilled by dark mud or sand might indicate the original presence of discrete beds of such sediment, but it is equally likely that the nature of the burrow fill is related to biogenic and diagenetic processes

There is no evidence for the sand identified in the original core log between 109 and 110 m (Figure 2). There is incipient silicification of the core in this interval associated with bioturbation, but the rock does not show any significant grain size variation over this interval.

Evidence for the sediment being contouritic in origin (Hohbein, 2006) is equivocal. The sedimentary rock is oxic and bioturbated, but there is little evidence for erosion or changes in conditions during deposition. Borehole 99/3, however, lies at the margin of the sediment body described as a contourite, and might not be expected to form part of the drift. The suggestion that there might be a sandstone injection structure within unit FSC-2b was made on the basis of seismic records (Robinson, 2004; Huuse, Pers Comm., 2010). The “half-saucer shaped” geometry observed (Figure 9) does not appear to correspond with any change in the bioturbated sandy mudstone around this depth in the core and the preservation of burrows throughout suggests that there has been no significant post depositional movement of the sediment. In addition, the bedding observed between 134 and 124 m is sub-horizontal and does not show a 30^{o} dip as suggested in the seismic section (Figure 9).

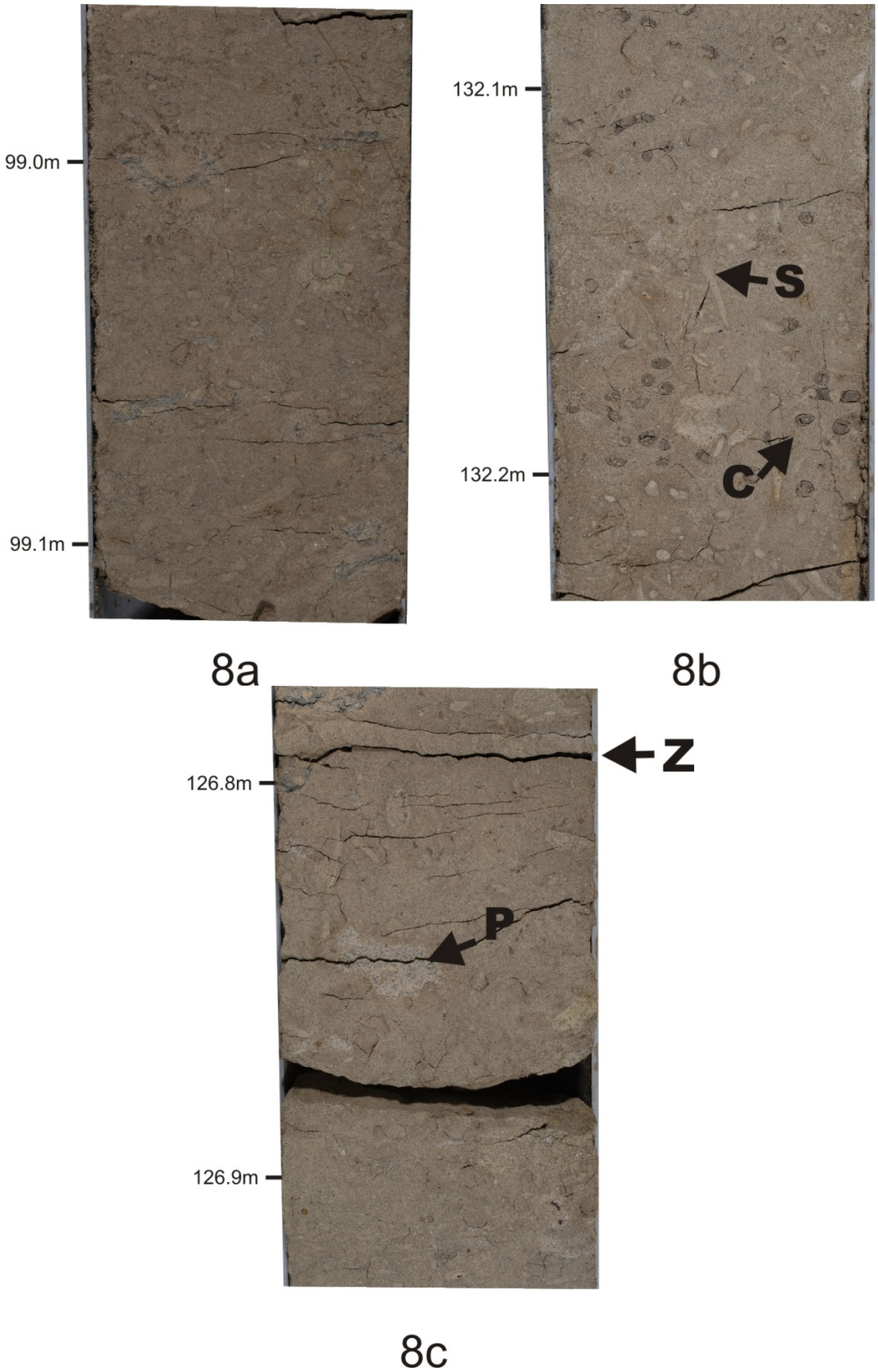

Figure 8. Bioturbation within FSC-2b. 8a shows inter-burrowing of *Planolites* and *Chondrites*. 8b shows *Chondrites* (dark mud fill, C) with several phases of reworking of burrows, and possibly *Skolithos* (S) thickening upwards. 8c shows *Planolites* (sand fill, P) and *Zoophycos* (Z). Core diameters are 80 mm.

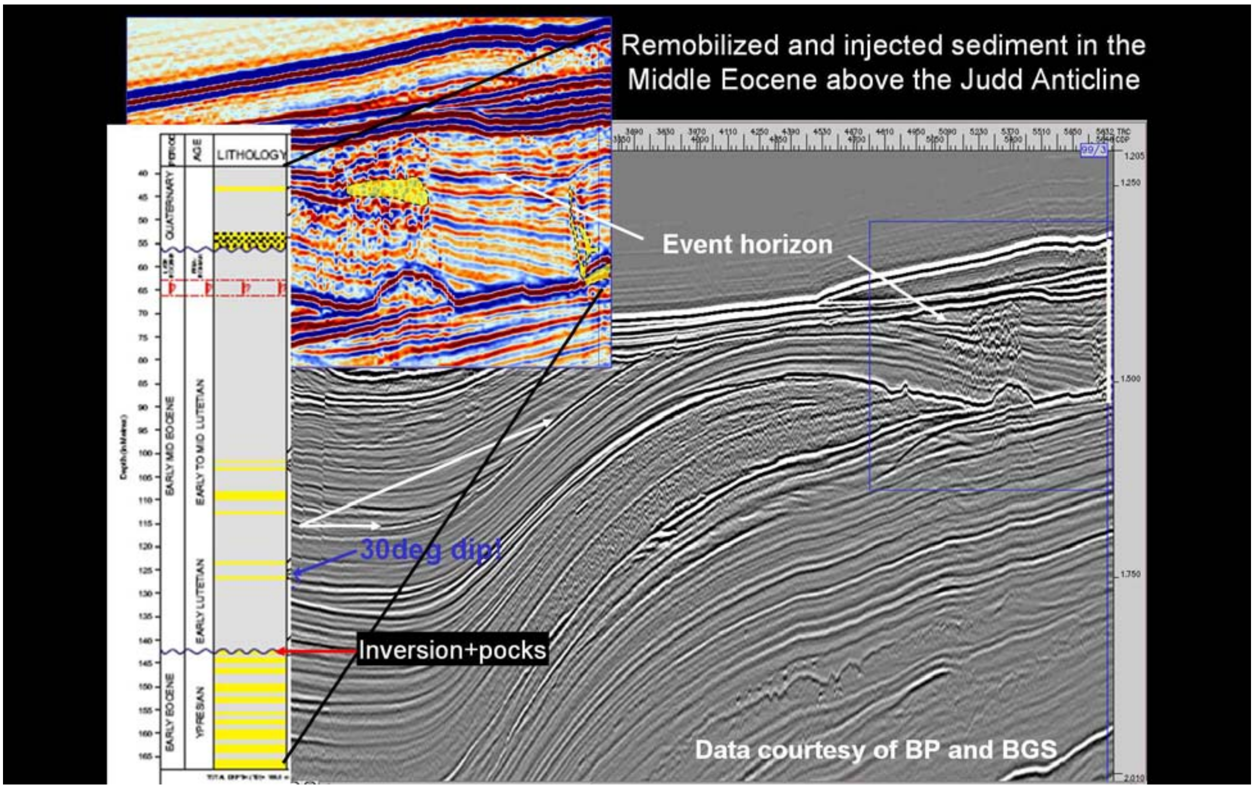

Figure 9. Seismic line showing “half-saucer shaped” geometry proposed to be a sandstone intrusion (image from Robinson, 2004).

5.2.2 Unit FSP-2a

Unit FSP-2a was recovered between 56.0 and 63.0 m and is Late Eocene (Priabonian) in age, corresponding to biostratigraphic zones NP18-21 (Hitchen, 1999). A total of 0.92 m of core was collected from the interval, giving a recovery of 13% (Figure 4).

The succession comprises unconsolidated, undesiccated mud. The section between 56.72 and 57.00 m is Munsell® colour 10YR 4/4 (dark yellowish brown) while the two lower sections of mud are 2.5Y 4/2 (dark grayish brown). The mud is fine grained, and contains uncommon very fine grained sand clasts (quartz, mica, lithic fragments) and bioclasts including benthic foraminifera and echinoderm spines.

Bioturbation is difficult to identify but appears to be uncommon. Small ovoids 2-3 mm in diameter containing slightly darker mud are present, indicating some biogenic activity.

6 Eocene Depositional Environment

6.1 UNIT FSP-2D

The Early Eocene succession appears to represent a shallow marine succession, possibly estuarine or shelfal. The palynomorphs recovered from the sequence (at a depth of 158.63 m) prove a mixed marine and terrestrial flora (Hitchen, 1999). There is little evidence for an unconformity or change in sedimentary style and so it is probable that all of the recovered succession is shallow marine. The lamination preserved in the core might relate to storm events on the shelf, there is little indication that they have formed through down slope depositional events.

Absence of coarse grained material might be related to margin history, where repeated erosion and deposition of sediment has led to a quartz rich, texturally mature sediment which has been reworked into the offshore environment.

6.2 UNIT FSP-2B

Unit FSP-2b is a marine succession, but contains few indicators of absolute depth. Marine palynomorphs and the associated diatoms, radiolaria and foraminifera are characteristic of the early to mid Lutetian but do not indicate a particular water depth. The downlap of reflectors onto the unconformity surface T2c (Figure 2) to the east of Borehole 99/3 indicates significant basin margin topography, with the succession in Borehole 99/3 lying at the base of slope with a relief of approximately 200 m. Water depths of between 100 and 1000 m were suggested for Middle Eocene depocentres further north on the basis of clinoform geometries by Robinson (2004).

The basal conglomerate suggests that there has been uplift and erosion, with removal of a significant thickness of sediment in units FSC-2d and 2c before the conglomerate was deposited. The iron-rich nature of the basal sedimentary rocks suggests aerial exposure during erosion, which is plausible given the scale of uplift, but the fauna within the basal rocks is marine. The time between deposition of FSC-2d and FSC-2b is not great, 2-3 Ma (Hitchen, 1999), and it appears that uplift of the Judd Anticline and Munkgrunnur Ridge, erosion and subsidence took place relatively rapidly.

While sand-prone sediments have been identified in FSC-2b both to north and south (Davies et al., 2004) the succession in 99/3 contains very few distinct bedforms and is composed of bioturbated sandy mud. The few sedimentary contacts observed indicate several short periods during which more mud prone sediment was deposited but there is no evidence of event beds, coarse grained or otherwise, which might relate to down-slope transport of sediment. It is possible that ongoing uplift and erosion in the early Lutetian led to continuing non-deposition at the site of Borehole 99/3 and that the unit records only the upper part of unit FSC-2b, after deposition of the sand-prone submarine fans preserved to the north of 99/3 (Robinson, 2004).

The bioturbated sandy mud that comprises the majority of FSC-2b formed, therefore, in an oxic base of slope environment in which sedimentation was relatively constant. There is no evidence for deposition of sandstone beds from turbidity currents and, other than several thin mudstone beds, no suggestion of significant changes in sediment input. The mudstone units suggest short periods of lower energy conditions and do not resemble distal turbidites. The oxic nature of the sediment suggests some circulation of basinal waters, but there is little evidence for the sedimentary structures that might imply significant changes in bottom current velocity (Stow & Faugères, 2008). In particular if the Mid Eocene was the time of the onset of North Atlantic deep water circulation then a higher energy sedimentary regime would be expected.

6.3 UNIT FSP-2A

The fine grained mud forming this unit formed in a basinal setting with an increasing oceanic influence. As in FSC-2b there are few indicators of absolute depth, but it is assumed that the deepening of the Faroe-Shetland Basin was ongoing. The unconformity surface (Figures 2 & 4) indicates a significant period of non-deposition (approximately 5 Ma), including the upper Lutetian and Bartonian, possibly associated with a phase of inversion of the Judd Anticline.

The upper part of FSC-2a, and any Oligocene to middle Quaternary record, has been removed by erosion associated with further uplift of the Judd Anticline and Munkgrunnur Ridge in combination with the circulation of deep waters through the Faroe-Shetland Channel.

7 Conclusions

The Eocene sedimentary record in Borehole 99/3 suggests a gradual deepening marine environment in which the deposition of three sedimentary units was punctuated by episodes of uplift and erosion.

- The Early Eocene unit (FSP-2d) contains a shallow marine succession of sandstone and mudstone, with reworking of sediment on the shelf producing a mature, quartz rich rock. Lamination in the rocks appears most likely to be related to shelf processes and not to down slope transport of sediment.
- The Middle Eocene unit (FSP-2b) comprises a succession formed at the base of slope below clinoforms defining the slope to the east, in water depths of at least several hundred metres. The sediments formed in oxygenated waters but there are no sedimentary structures that indicate a definitive depositional setting.
- The muds recovered in unit FSP-2a appears to have formed in a deeper, more distal environment, related to ongoing deepening of the basin.
- There is little direct evidence for contourite or turbidite deposition within the Eocene succession.

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British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: http://geolib.bgs.ac.uk.

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