A record of Eocene (Stronsay Group) sedimentation in BGS borehole 99/3, offshore NW Britain: implications for early post-breakup development of the Faroe-Shetland Basin

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Synopsis

A punctuated Eocene succession has been recovered in British Geological Survey borehole 99/3 from the Faroe-Shetland Basin. The borehole was drilled close to the crest of the Judd Anticline and penetrated 110.5 m into the post-breakup Stronsay Group. The borehole proved 23.8 m of Ypresian–earliest Lutetian paralic to shallow-marine deposits, unconformably overlain by 43.85 m of mid-Lutetian lower shoreface to shallow-marine shelf deposits, in turn unconformably overlain by 42.85 m of late Bartonian–Priabonian mass-flow (slope apron) and basinal deposits. At the borehole site, the Ypresian–earliest Lutetian sediments were subaerially exposed in early Lutetian times; these deposits were subsequently transgressed by the mid-Lutetian shelf – itself eroded in the late Lutetian with reworked material transported northwards and redeposited in the Mid-Eocene basin-floor fan complex in Quadrants 213 and 214. The eroded mid-Lutetian shelf was subsequently downlapped and buried beneath prograding late Bartonian–Priabonian slope apron-to-basinal sediments as the borehole site subsided. Integrating the borehole data with the regional seismic-stratigraphy indicates three major intervals of regression – early/mid-Lutetian, late Lutetian and late Bartonian – which, it is suggested, coincide predominantly with tectonic activity, particularly compressional

deformation, possibly linking the early post- breakup development of the Faroe-Shetland Basin to the evolution of the adjacent Norwegian Basin.

Introduction

The Faroe-Shetland Basin is one of a series of NE–SW trending Cretaceous–Cenozoic depocentres between Ireland and Mid Norway, including the Rockall Basin and the Møre and Vøring basins, which developed as precursors to continental break-up between NW Europe and Greenland (Doré et al. 1999; Roberts et al. 1999). The main phase of extension in the Faroe-Shetland Basin occurred during the Cretaceous (Dean et al. 1999; Lamers & Carmichael 1999; Larsen et al. 2010), though continental break-up – to the north and west of the Faroe Islands – was not achieved until the Early Eocene (54.8–54.5 Ma) (Passey & Jolley 2009). Break-up was accompanied by extensive volcanism, which exploited weak spots in the increasingly thinned and rifted lithosphere of the NW European plate, including the Faroe–Shetland region (Passey & Hitchen 2011).

In common with passive margins throughout the NE Atlantic region, it is becoming increasingly apparent that the Faroe–Shetland region has experienced tectonic movements during the post- breakup Cenozoic interval, manifest as significant departures from the expected post-rift pattern of decaying subsidence due to cooling (e.g. Steckler & Watts 1978), including episodes of accelerated subsidence and uplift that were, at least in part, coeval (e.g. Andersen et al. 2000; Praeg et al. 2005; Ritchie et al. 2011). The most visible consequences of these tectonic episodes are the Fugloy, Munkagrunnur and Wyville Thomson ridges, all of which form major present-day bathymetric highs (Fig.1). The disposition of the Eocene succession, which is folded about the axes of these uplifts, implies that this major phase of folding and/or uplift occurred during late Palaeogene/early Neogene times (Boldreel & Andersen 1993; Andersen et al. 2000; Johnson et al. 2005; Stoker et al. 2005b; Ritchie et al. 2008; Ólavsdóttir et al. 2010). Concomitant subsidence and the instigation of the deep-water Faroe-Shetland and Faroe Bank channels is revealed by the onlapping character of the overlying Oligocene and Miocene basinal sequences (Fig 2).

The western and southern bounding limit of the Faroe-Shetland Basin was especially deformed by these vertical movements; thus, neither the present-day shape nor the physiography of the continental margin likely reflects the early post- breakup setting of the basin. On the basis of the occurrence of marginal deltaic systems, channelized incision of the contemporary shelf, and episodic shelf-margin progradation, particularly around the southern margin of the basin, previous workers have concluded that for most of the Eocene the Faroe-Shetland Basin was a semi-enclosed basin with no deep-water outlet to the south (Robinson 2004; Ólavsdóttir et al. 2010; Stoker & Varming 2011; Stoker et al. 2013). By way of contrast, it has recently been suggested that the onset of deep-water overflow from the Norwegian-Greenland Sea into the North Atlantic, interpreted to represent the onset of a modern-style North Atlantic Deep Water mass, was established only 6 m.y. after break-up (at the Early/Mid-Eocene boundary) (Hohbein et al. 2012), which is up to 15–25 m.y. earlier than has been previously proposed (e.g. Davies et al. 2001; Stoker et al. 2005a, b). Significantly, this interpretation invokes the presence of an Early/Mid-Eocene deep-water passageway cutting across the Faroe–Shetland region, akin to the present-day Faroe-Shetland and Faroe Bank channels, which, according to Hohbein et al. (2012), accumulated up to 900 m of Middle to Upper Eocene deep-marine contourite drift deposits.

In view of these highly conflicting ideas on the early post- breakup structural setting and palaeogeography of the Faroe-Shetland Basin, this paper focuses on the Eocene succession at the southern end of the basin; specifically, British Geological Survey (BGS) borehole 99/3, which was acquired on behalf of the BGS Rockall Consortium (see Acknowledgements), and which penetrated an unconformity-bounded sequence of Lower, Middle and Upper Eocene post- breakup sedimentary rocks (Hitchen 1999). However, despite initial shipboard observation and reporting to the Rockall Consortium (recently summarised in Stoker & Varming 2011), no further work was undertaken on this borehole. On the basis that borehole 99/3 penetrates that part of the Eocene succession recently interpreted by Hohbein et al. (2012) as a deep-water contourite sediment drift, it was decided to re-visit this borehole in order to shed new light on the early post-rift depositional environment along the southern margin of the Faroe-Shetland Basin. To achieve this objective, we have re-logged the Eocene succession in BGS borehole 99/3 in terms of its sedimentology, and fully integrated the results with both legacy and new (autumn 2012) biostratigraphical and palaeo-environmental analyses. Considered together with the regional seismic-stratigraphical architecture of the Eocene succession, we show that BGS borehole 99/3 provides important constraints on the reconstruction of the early post- breakup development of the Faroe-Shetland Basin.

Geological setting of BGS borehole 99/3

BGS Borehole 99/3 is located at the south-western end of the Faroe-Shetland Channel (60^{o} 24.8' N, 4^{o} 39.1' W) (Fig. 1). It was drilled on the lower part of the West Shetland Slope at a water depth of 983 m, and targeted Eocene strata that, through a combination of structural inversion and Neogene–Quaternary bottom-current erosion (Stoker et al. 2003; Smallwood 2004), occur locally at, or near to, sea bed in this part of the Faroe-Shetland Channel (Fig. 3).

This key stratigraphical borehole penetrated 56 m of Quaternary glacially-influenced mass-flow deposits (Davison & Stoker, 2002) overlying 110.5 m of Eocene post-rift sediments and sedimentary rocks belonging to the Stronsay Group (Knox et al. 1997), and was terminated at a depth of 166.5 m below sea bed (Fig. 4).

The inversion structure into which the borehole was drilled is termed the Judd Anticline (Fig. 3). This is one of a number of Cenozoic inversion structures widely developed throughout the Faroe–Shetland region, and which has developed in response to a series of intermittent pulses of enhanced growth linked to tectonic compression since the late Early Eocene (Ritchie et al. 2003, 2008; Davies et al. 2004; Smallwood 2004). Growth of the Judd Anticline is one manifestation of a regional pattern of intra-Eocene post- breakup deformation, which also included episodic uplift and erosion of the flanks of the Faroe-Shetland Basin, as well as intrabasinal highs, e.g. Flett High (Robinson 2004; Robinson et al. 2004; Ólavsdóttir et al. 2010; Stoker et al. 2010; Stoker & Varming 2011). The net result of this deformation is an inverted Eocene stratigraphy that is punctuated by several unconformities of regional extent, expressed on seismic profiles as seismic reflectors T2a to T2d (Figs 2, 3, 5). This set of seismic reflectors was first proposed by Stoker & Varming (2011), and was used to establish a provisional seismic-stratigraphical subdivision of the Stronsay Group comprising intra-Eocene units FSP-2a to FSP-2d, which is summarised in Table 1. All of these reflectors and units were tested by borehole 99/3; however, on the basis of new and reappraised legacy biostratigraphical data (Table 2), the ages of the reflectors (and thus the intra-Eocene units) have been revised (Table 3). This new revised stratigraphical framework replaces the previous scheme proposed by Hitchen (1999), and summarised in Stoker & Varming (2011: their Table 5), which failed to differentiate fully between rocks of early Mid-Eocene (Lutetian) and late Mid- to Late Eocene (Bartonian–Priabonian) age.

A key observation – first demonstrated by Lamers & Carmichael (1999: their Fig. 5) – is that the Eocene succession thins southwestwards along the axis of the Faroe-Shetland Basin. What is also clear from the work of Lamers & Carmichael (1999), as well as the present study, is that the Middle and Upper Eocene sequences onlap, are variably folded by, and are locally cut-out on the flanks of, growth structures at the SW-end of the basin, including the Judd Anticline (Fig. 5). Regional seismic-stratigraphical correlation between Quadrants 204 and 214 (Lamers & Carmichael 1999; Robinson 2004) has also revealed that the well-established Middle Eocene basin-floor fan deposits in Quadrants 213 and 214 (cf. Brooks et al. 2001; Davies & Cartwright 2002; Davies et al. 2004), which occur in the upper part of unit FSP-2c, are not present at the site of borehole 99/3; moreover, these basin-floor fan deposits are overlain by a major late Mid- to Late Eocene slope apron (FSP-2b) (Fig. 5) that locally interdigitates with younger basin-floor fans (Stoker & Varming 2011; their Fig. 102). It should be noted that in a recent review of the Eocene succession in the Faroe–Shetland region, Stoker & Varming (2011) incorrectly jump-correlated the basin-floor fan deposits within these two separate units, whereas the present study supports the superposition of these units as previously proposed by Lamers & Carmichael (1999) and Robinson (2004). It is also apparent that Ólavsdóttir et al. (2010) have similarly mis-correlated their Munkagrunnur Ridge Delta (within the Faroese sector) with the Middle Eocene fan deposits; seismic-stratigraphical mapping related to the present study indicates that this delta – derived from the Munkagrunnur Ridge – is of Early Eocene age, equivalent to similar units in the UK sector contained within unit FSP-2d (Figs 3, 5).

BGS borehole 99/3

Borehole 99/3 was drilled close to the crest of the Judd Anticline, and penetrated 110.5 m into the post- breakup Eocene Stronsay Group beneath a cover of Quaternary sediment (Fig. 4). Biostratigraphical analysis indicates that at least three main phases of Eocene deposition are represented in the borehole, constrained within the following biozone ranges: NP12–14 (mid-Ypresian–early Lutetian); NP15–early NP16 (mid-Lutetian); and NP17–21 (late Bartonian–Priabonian) (Table 2). The major Lutetian and Bartonian biostratigraphical breaks are confidently correlated with reflectors T2d and T2c (Figs 3 & 4). In contrast, any hiatus that might be represented by reflector T2b is not as well resolved at the borehole site, though it is evident on the seismic data (Fig. 3); thus, the age of the reflector can be confidently re-interpreted as a late Bartonian/Priabonian horizon (Table 3). Nevertheless, there is a clear lithological distinction between all four seismic-stratigraphical units, and in general terms the cored Eocene succession at the borehole site preserves an upwards-deepening transition from a deltaic/proximal marine setting (unit FSP-2d) that is overlain by a transgressive shallow shelf (unit FSP-2c), which, in turn, is buried beneath slope apron to basinal deposits (units FSP-2b and 2a).

A lithological description of the Eocene succession is presented below (in ascending stratigraphical order), and shown graphically in Figure 4. All borehole depths cited in the text are referenced with respect to the sea bed. Ichnofabric recognition of key trace fossils (Table 4) is based on Reineck & Singh (1980), Wetzel (1984) and McIlroy (2004).

Lithological description

Unit FSP-2d (142.7–166.5 m TD). The basal unit in the borehole consists predominantly of pale olive grey (5Y 5/2) (Munsell ® colour code), medium- to very fine-grained, thick- to very thick-bedded, massive to laminated sandstone with variable mud (silt and clay) content. The majority of the grains (60–80%) are quartz, but feldspar, mica, lithic grains, glauconite, sporadic ferromagnesian minerals, sparse basaltic grains, glassy volcanic fragments and abraded bioclastic (shell) material are all present. The grains are sub-rounded and well sorted, and commonly cemented by ferroan calcite, though several sections of sand and muddy sand, up to 0.6 m thick, are devoid of any cement and have not been fully lithified. Dark patches and knots of presumed organic origin occur sporadically in the core, and a sporadic green-grey colouration might represent the presence of chlorite derived from volcanogenic clasts. Moreover, minor fine-grained, euhedral, zeolite crystal development is observed in some open pore spaces, which may reflect diagenetic derivation from volcanic materials, including glass.

The sandstone generally has a massive, homogenous appearance, which might reflect a pervasive bioturbation of the sediment, though individual burrows are also distinguishable within the unit, and include *Planolites* and *Chondrites* ichnofabrics (Table 4). Between 165.64–166.22 m and 149.51–152.48 m, however, sedimentary lamination is well preserved, and consists of thick to very thick laminae (2–5 mm) comprising alternations of sandstone, mudstone and sandy mudstone. The laminations vary from planar to wavy in form and display sharp contacts. In the upper interval, the laminations are wavy, consist predominantly of very fine-grained sandstone with scattered very coarse sand grains, and resemble small-scale current ripples. These ripples are asymmetric, with a height of up to 1 cm, and width between about 3 and 8 cm, with superposed ripple sets (1–3 cm thick) displaying opposing flow directions.

The top of unit FSP-2d is marked by an unconformity at 142.7 m (reflector T2d), below which the uppermost part of the unit (recovered interval 142.7–143.0 m) is marked by a strongly weathered zone of rubbly and friable, iron-stained muddy sandstone.

Unit FSP-2c (98.85–142.7 m). Unit FSP-2c comprises a basal conglomerate, about 10 cm thick, overlain by a predominantly argillaceous sequence of sandy mudstone (Fig. 4). The conglomerate is ferruginous, very poorly sorted and contains angular to very well rounded, matrix-to-clast-supported, granule to pebble grade clasts, including layered iron-stained concretionary clasts, quartz and lithic grains, glauconite and bioclastic material, set in an iron-stained matrix of silty to very fine-grained sandstone (Fig. 6). The matrix is pale yellow (2.5Y 8/4) whereas the ferruginous clasts are more generally brown (7.5YR 5/3). Uncommon sub-horizontal lenses of grey sandy mud, 0.8 cm in thickness and up to 9 cm in length, might reflect bioturbation in the core. The bioclastic material includes arenaceous agglutinated foraminifera (Table 2), up to medium sand grade, and sharks teeth; the latter are up to 1.5 cm long (Fig. 6) and the long slender blade is characteristic of a Sand Tiger Shark (http://www.elasmo-research.org/education/evolution/guide_f.htm).

The conglomerate is overlain conformably by a 0.05 m-thick unit of very thin-bedded alternations of pale brownish grey (2.5Y 6/2), very fine-grained sandstone and granule to small pebble grade layers (Fig. 6). The latter include clasts of iron-stained sediment that are matrix-to-clast-supported, very poorly sorted, and with no obvious grading. This transitional bed marks an upwards-fining from the basal conglomerate into a very fine-grained, pale yellowish brown (2.5Y 6/3) muddy sandstone, and eventually (above 138 m) sandy mudstone (Fig. 4).

The muddy sandstone is generally massive, but with sporadic, thick to very thick laminae of sandy mudstone, 1–4 mm in thickness; these laminations are commonly slightly darker in colour than the surrounding sandstone, and have sharp bases and tops. The sandstone contains 70% quartz, with uncommon mica, feldspar and lithic grains, and scattered matrix-supported grains (as in the transitional bed) of coarse sand to granule grade. Patches of cemented material up to 5 mm in diameter are also found within the sandstone; the cementing mineral is soft and non-reactive to hydrochloric acid, and is possibly a zeolite. The sandstone is bioturbated with burrows similar to *Chondrites* in form (Table 4).

Between 138.0 and 98.85 m, unit FSP-2c consists predominantly of massive, variably coloured – pale yellowish brown (2.5Y 6/3), pale olive brown (2.5Y 5/3), pale brownish grey (2.5Y 6/2 and dark greyish brown (2.5Y 4/2) – sandy mudstone, which locally grades into muddy sandstone (Fig. 4). The fine-grained sand component includes quartz, mica, feldspar, lithic grains and glauconite. Whilst much of the unit is consolidated, there is no evidence for cementation by calcite and calcium carbonate bioclasts are fragmentary and very uncommon. Bed contacts are generally poorly resolved in the core, but surfaces at 134.61, 127.54, 126.18, 125.55, 124.89 and 104.40 m indicate changes in sedimentary style. At 104.40 and 134.61 m, relatively planar surfaces are overlain by discrete, very thin to thin-bedded mudstone, which grade upwards into sandy mudstone. At 127.54 m, a colour change reveals a planar contact that is overlain by medium-bedded, upwards-coarsening, muddy sandstone, itself in sharp contact with the overlying sandy mudstone. At 124.89, 125.55 and 126.18 m colour changes highlight a series of sharp, undulating surfaces with a relief of up to 20 mm, due either to erosion or bioturbation.

The main variations in texture and structure of the sandy mudstone are revealed by subtle changes in the style of bioturbation, which includes *Chondrites*, *Planolites*, and *Skolithos* ichnofabrics throughout FSP-2c, with a single occurrence of *Zoophycos* observed at 126.8 m. The intensity of bioturbation appears to be consistent throughout unit FPS-2c, with burrows common within the core, but not enough to obscure sedimentary contacts. In addition to discrete burrows, there appears to be a varying amount of biodeformation, where the sediment has been disturbed but not displaced (cf. Akhurst et al. 2002), leaving the existing lamination preserved. Sporadic fractures are also observed at several levels within this unit (Fig. 4), marked by dark, planar surfaces oriented at 35–45° relative to the core axis.

Unit FSP-2b (ca. 95.0–98.85 m). The distal edge of unit FSP-2b was penetrated in borehole 99/3, which proved a massive, pale olive brown (2.5Y 5/3), unconsolidated, soft, pebbly mud resting in sharp contact with the underlying, darker coloured and lithified unit FSP-2c. Although the mud displays general mottling, bioturbation appears to be uncommon. The main characteristic of this unit is the inclusion of matrix-supported outsized pebble-grade clasts of siltstone, 5–7 cm maximum dimension. As there is a core gap between 97.75 and 92.0 m, the boundary between units FSP-2b and FSP-2a is placed arbitrarily at 95.0 m.

Unit FSP-2a (56.0–ca. 95.0 m). This unit is characterised by poor recovery of massive, soft, unconsolidated, very slightly sandy mud. At the top of the unit, the sediment is brownish yellow (10YR 6/6) to dark yellowish brown (10YR 4/4) whereas towards the base it is dark greyish brown (2.5Y 4/2). The mud is fine grained, and contains uncommon very fine-grained sand (quartz, mica, lithic fragments) and bioclasts including benthic foraminifera and echinoderm spines. Bioturbation is difficult to identify and appears to be uncommon, though small ovoids, 2–3 mm in diameter and containing slightly darker mud, are present indicating some biogenic activity.

Interpretation

Unit FSP-2d: The association of bi-directional ripple lamination, sporadic shell material and common bioturbation suggests that the sandstones of unit FSP-2d were deposited in a subaqueous environment with intermittent (at least) tidal influence. Micropalaeontological data comprise both indigenous marine- and terrestrially-derived forms (Hitchen 1999) (Table 2), which implies a proximal marine setting. On seismic profiles, unit FSP-2d represents an alternating stacked sequence of sheet-like and prograding sub-units (Fig. 3; Table 1); the latter have been interpreted as deltaic bodies in relation to equivalent prograding deposits in the Faroese sector (Ólavsdóttir et al. 2010). It is not inconceivable that the bioturbated sheet-like sub-units – which are penetrated by borehole 99/3 (Fig. 3) – might represent shoreface, deltaic or shallow marine shelf sandstones. The contact with unit FSP-2c is marked by a rubbly, weathered, iron-stained zone that we interpret as a subaerial exposure surface, subsequently transgressed by FSP-2c (see below). On Figure 3, this boundary is marked by an irregular reflection; the presence of similar reflective surfaces at deeper levels within unit FSP-2d suggests that intermittent exposure of this succession might have been relatively common, thereby attesting to a fluctuating deltaic/coastal/shallow-marine setting for unit FSP-2d as a whole. The ichnofabrics documented from unit FSP-2d – *Planolites and Chondrites* – are consistent with a coastal/deltaic setting (McIlroy 2004). It should be noted that the type material for the ostracod species *Leguminocythereis bicostata* and *Trachyleberis spiniferrima* (Table 2) is from the London Clay Formation in southern England, which similarly represents marine conditions, either on an open shelf or a more restricted lagoon or embayment (Keen 1978; Hamblin et al. 1992; Ellison 2004).

Unit FSP-2c: The contact between units FSP-2d and 2c suggests subaerial exposure of the former; however, the fauna within the basal conglomerate of FSP-2c, including teeth of Sand Tiger sharks, is shallow marine (Table 2). In SE England, equivalent rocks containing shark teeth are commonly interpreted to have been deposited in open estuarine to shallow marine environments (Curry 1992). Thus, we interpret the conglomeratic bed of unit FSP-2c as a transgressive lag deposit. This is consistent with evidence of low-angle onlap of reflections within FSP-2c onto T2d (Fig. 3b).

The overlying succession of muddy sandstone and sandy mudstone is bioturbated and contains a trace fossil assemblage (Table 4) that collectively is characteristic of a lower shoreface to shallow-marine setting (Bann & Fielding 2004; McIlroy 2004). On this basis, we interpret the bulk of unit FSP-2c, at the borehole location, as an oxygenated shallow-marine shelf sequence, though the mixing of marine and terrestrially-derived organic facies (Table 2) attests to the proximity of land. Although sandy mudstone is predominant, the sporadic occurrence of beds of coarser-grained muddy sandstone and finer-grained mudstone most probably reflects short-term fluctuations in tidal currents and sea level. In particular, the episodic influx of sandy material and isolated gravel clasts might be indicative of a storm-influenced shelf causing higher-energy conditions in a succession commonly below wave base.

Unit FSP-2b: On seismic profiles, unit FSP-2b represents a major shelf-margin progradation from the West Shetland High into the Faroe-Shetland Basin, which downlaps onto the underlying unit FSP-2c and older strata (Figs 2 and 3). In contrast to the underlying shallow-water shelf facies of unit FSP-2c, the relief on the clinoforms associated with the prograding slope apron of FSP-2b implies water depths at the foot of the prograding wedge in excess of 350 m (Stoker & Varming 2011). Borehole 99/3 penetrated the distal (basin-floor) edge of the slope apron, which has an internal acoustic structure that is characteristic of mass-flow deposits (Nardin et al. 1979; Mulder & Cochonat 1996) (Table 1). The unconsolidated pebbly mud recovered from the borehole is entirely consistent with an origin as a muddy debris-flow deposit.

Unit FSP-2a: Seismic profile data indicate some discordance, at least locally, between internal reflections within unit FSP-2a and the top of unit FSP-2b (reflector T2b) (Fig. 3). This may represent a hiatus. Although there are few diagnostic indicators of water depth, it is assumed – on the basis of the scale of the prograding clinoforms associated with unit FSP-2b (described above), which unit FSP-2a onlaps onto at the foot of the contemporary slope (Figs 2 and 3) – that the unconsolidated mud of unit FSP-2a, as recovered from the borehole, was deposited in a basinal environment that was several hundred metres deep (Stoker & Varming 2011). A significant observation is that the intensity of bioturbation appears to be relatively low, which might be indicative of anoxic or sub-oxic conditions; this in turn might suggest a restricted marine embayment.

Discussion

Eocene stratigraphical framework

At least three main phases of Eocene sediment accumulation are preserved in borehole 99/3, on the southern flank of the Faroe-Shetland Basin: 1) a Ypresian to earliest Lutetian phase of fluctuating paralic to shallow-marine deposition (unit FSP-2d); 2) a mid-Lutetian phase of lower shoreface to shallow-marine shelf sedimentation (unit FSP-2c); and, 3) a late Bartonian to Priabonian phase of slope-apron development, followed by basinal sedimentation (units FSP-2b, -2a) (Fig. 7). The biostratigraphical data (table 2) indicate that these three phases of sedimentation – at the borehole site – are separated by unconformable boundaries (reflectors T2d and T2c) representing hiatuses of 2–3 Ma duration. Although there is a distinct lithological change between units FSP-2b and FSP-2a (Fig. 4), as well as a seismic-stratigraphical indication of onlap of the latter onto the former (Fig. 3), the recognition and duration of any potential hiatus associated with reflector T2b is currently unresolvable (Fig. 7).

The T2d and T2c reflections are stratigraphical boundaries that have been traced throughout the Faroe–Shetland region (Stoker & Varming 2011) (Figs 2 & 5), and provide important palaeoenvironmental information regarding the early post- breakup development of the Faroe-Shetland Basin. The character of the rocks immediately below the T2d boundary is indicative of subaerial exposure at the borehole site in the early/mid-Lutetian, whereas the T2c surface appears to mark a relative deepening of the basin associated with the development of the unit FSP-2b slope apron in the late Bartonian. It should be noted, however, that in borehole 99/3 the T2c boundary most probably represents a composite hiatus that includes a phase of intra-FSP-2c erosion. Figure 5 shows an internal boundary (Intra-FSP-2c) that effectively separates the older shallow-marine shelf deposits cored in 99/3 from an overlying section that includes the Middle Eocene basin-floor fan deposits preserved in Quadrants 213 and 214. In Quadrant 205, this boundary is expressed as an eroded and incised surface with northward-trending channels, up to 200 m relief (Robinson et al. 2004). The significance of these channels is that they appear to feed into the Middle Eocene basin-floor fan deposits. The stratigraphical constraints provided by the FSP-2c and 2b sections recovered in 99/3 suggest that this phase of intra-FSP-2c erosion is probably of late Lutetian age (Figs 5 & 7). If the channels associated with this phase of erosion are feeders for the Middle Eocene basin-floor fan deposits, then the upper part of unit FSP-2c that contains these deposits is also probably of late Lutetian age. Thus, whereas reflector T2c is assigned a late Bartonian age, the hiatus at the borehole site probably encompasses both late Lutetian (intra-FSP-2c boundary) and late Bartonian unconformities.

Palaeogeography

Integration of the observations from borehole 99/3 with regional palaeoenvironmental information has resulted in the selection of five timeslices (Fig. 7), from which we have constructed of a series of schematic palaeogeographical maps that illustrate the Eocene post-breakup development of the Faroe–Shetland region on the basis of this study (Fig. 8). The five timeslices depicted in Figure 8 are: a) late Ypresian–earliest Lutetian; b) early/mid-Lutetian; c) mid-Lutetian; d) late Lutetian; and, e) late Bartonian–Priabonian. These five intervals are summarised below:

Late Ypresian–earliest Lutetian: Figure 8a depicts a restricted Faroe-Shetland Basin shortly after continental breakup, with an initial basin morphology that was likely influenced by the syn- breakup volcanic terrain, including major volcanic escarpments, such as the Faroe-Shetland Escarpment (Robinson 2004) (Fig. 2). A significant depositional element in this interval is the Munkagrunnur Ridge Delta (Ólavsdóttir et al. 2010), the development of which has been attributed to contemporary uplift around the southern margin of the Faroe-Shetland Basin; primarily the Munkagrunnur Ridge but probably also including the Wyville Thomson Ridge (Ritchie et al. 2008; Tuitt et al. 2010). Seismic-stratigraphical and sedimentological evidence from borehole 99/3 implies alternating deltaic and shallow-marine deposition along the southern margin of the basin, and suggests an oscillating relative sea level. Sediment was also being shed from the West Shetland margin (Figure 2). By way of contrast, tuffaceous limestone – with airfall-derived tuff fragments – recovered west of the Faroe-Shetland Escarpment has been interpreted to be indicative of a marine shelf with little derived clastic material, though common terrestrial organic material is taken to indicate the proximity of land (Waagstein & Heilmann-Clausen 1995; Andersen et al. 2000). The westward extent of this marine shelf remains uncertain, though it would have been bounded to the NW by the emergent Iceland-Faroe Ridge (Talwani et al. 1976; Berggren & Schnitker 1983) (Fig. 1).

Early/mid-Lutetian: The borehole site underwent subaerial exposure during this interval (Fig. 8b). Although the overall geographic extent of the area that was exposed remains uncertain, it most probably included much of the southern end of the Faroe-Shetland Basin (bearing in mind the preceding interval) and extending northwestwards along the emergent Iceland-Faroe Ridge (Talwani et al. 1976; Berggren & Schnitker 1983), though the occurrence of isolated paralic basins cannot be discounted (Robinson 2004). Thus, this might represent a major regression. According to Smallwood (2004) and Ritchie et al. (2008), early growth of inversion domes, such as the Judd Anticline, might have been instigated in the early Lutetian.

Mid-Lutetian: The borehole site was transgressed and a lower shoreface to shallow-marine shelf setting was established in the southern part of the Faroe-Shetland Basin (Fig. 8c). The geographic extent of the basinal (>200 m water depth) area most probably increased as the Faroe-Shetland Escarpment gradually became submerged and overlapped (Robinson 2004) (Fig. 2). According to Andersen et al. (2000), there remained a virtual absence of clastic material of western provenance, which they attribute to the presence of a watershed inferred to follow the spine of the Faroe island chain, with most rivers draining to the north and NW of the present-day Faroe Islands; towards the subsiding spreading centre. Thus, the main source of sediment input remained the SE and southern flank of the Faroe-Shetland Basin. The westward extent of the shelf continued to be controlled by the Iceland-Faroe Ridge, which remained emergent at this time as evidenced by subaerial basalts at DSDP site 336 (Talwani et al. 1976; Berggren & Schnitker 1983).

Late Lutetian: In Quadrant 205, the mid-Lutetian shelf deposits that form the lower part of unit FSP-2c (Fig. 5) were incised by channels 80–200 m deep (Robinson 2004; Robinson et al. 2004). The truncation of equivalent deposits in borehole 99/3 suggests that this channelization is part of a wider zone of erosion that extended around the southern margin of the Faroe-Shetland Basin (Fig. 8d). There is no evidence of subaerial exposure of the mid-Lutetian shelf deposits in borehole 99/3, which is consistent with the submarine origin for the channels in Quadrant 205 (Robinson et al. 2004); nevertheless, a fall in relative sea level and some degree of regression is invoked. Robinson et al. (2004) have suggested that this relative sea-level fall might be related to uplift of the Flett High, one of several intra-basinal highs within the Faroe-Shetland Basin (Fig. 1), though a eustatic fall in sea level was not discounted. From a separate consideration of the borehole evidence, it is not inconceivable that further growth of the Judd Anticline, Munkagrunnur Ridge and Wyville

Thomson Ridge might have occurred during this interval. Detritus eroded from the mid-Lutetian shelf accumulated farther north in the pile of overlapping fans – the Strachan, Caledonia and Portree fans – that is the Mid-Eocene basin-floor fan complex (Fig 8d).

Late Bartonian–Priabonian: The onset of the late Bartonian–Priabonian interval is marked by the instigation of a major phase of shelf-margin progradation – the Mid- to Late Eocene slope apron – building out north-westwards from the West Shetland region (Fig. 8e). The clinoforms associated with this progradation downlap and partially bury the Middle Eocene basin-floor fan deposits. At the borehole site, the recovery of muddy and pebbly mass-flow deposits of unit FSP-2b associated with the distal edge of the prograding slope-apron marks a deepening of this part of the Faroe-Shetland Basin, though an overall basinward shift in coastal onlap accompanies progradation farther to the NE. The slope-apron interdigitates with locally developed basin-floor fans (Stoker & Varming 2011). The scale of the clinoforms indicates basinal water depths greater than 350 m (Stoker & Varming 2011), though probably not in excess of 500 m (Thiede & Eldholm 1983). This water-depth range is consistent with the identification of stacked series of subaerial–deltaic channels, several tens of metres deep, cut into the adjacent topset deposits of the prograding wedge (Robinson et al. 2004).

The increased water depth on the southern flank of the Faroe-Shetland Basin is consistent with the deposition of basinal mud associated with unit FSP-2a, which overlies the slope-apron, probably following a brief hiatus. However, this deepening is likely to have represented an enclosed embayment that was fed, in part, by northward-draining deltas, including the Wyville Thomson Ridge Delta (Fig. 8e), which is a late Mid- to Late Eocene delta preserved on the northern flank of the ridge. In common with deltaic deposits of equivalent age on the Rockall Plateau (Stoker et al. 2012), the Wyville Thomson Ridge Delta was sourced from the ridge in response to local uplift – continued growth – of this inversion dome. East of the Faroe Islands, the upper Middle–Upper Eocene section is reportedly represented by a hiatus (Waagstein & Heilmann-Clausen 1995), which might indicate that the Faroe region was also emergent at this time. Thus, despite the marine embayment and relative deepening of the southern basin margin, there is much evidence of a major regression in late Mid- to Late Eocene times.

Regional controls on early post-breakup sedimentation

There is stratigraphical, sedimentological and palaeogeographical evidence for at least three major regressions preserved within the Stronsay Group around the southern margin of the Faroe-Shetland Basin, including: 1) early/mid-Lutetian subaerial exposure at the 99/3 borehole site; 2) late Lutetian submarine erosion of the southern shelf, and re-deposition of material as basin-floor fans (Mid-Eocene basin-floor fans); and, 3) late Bartonian progradation (Mid- to Late Eocene slope apron) of the West Shetland margin accompanied by a basinward shift in coastal facies (Figs 7 & 8). In the context of a newly developing continental margin, the most likely processes involved in the formation of these unconformities are probably eustasy and tectonic activity, or a combination of the two. The base-level falls that led to late Lutetian erosion and incision of the southern shelf (Fig. 8d), and the late Bartonian progradation of the West Shetland margin (Fig. 8e), might be linked to eustatic sea-level falls according to curves presented by Haq et al. (1988) and Neal (1996), though the late Bartonian minimum is not recognised in the more recent Miller et al. (2005) scheme. The regression associated with early Lutetian subaerial exposure of unit FSP-2d does not correspond to a sea-level minimum on any of these three curves. Such ambiguity concerning the eustatic signal suggests that the magnitude of these depositional events cannot be explained by eustatic sea-level changes alone.

In considering tectonic processes, the growth of inversion domes, such as the Judd Anticline, as well as the folding and/or uplift of the Wyville Thomson, Munkagrunnur and Fugloy ridges (Fig. 1) are testament to the effects of post-breakup compression across the Faroe–Shetland region. The integration of borehole 99/3 with the seismic-stratigraphical framework suggests that the deposition of the sedimentary packages was influenced, to some degree, by this tectonic activity, especially considering that the key unconformities and the enhanced phases of growth of the compressional structures appear to coincide in the early Lutetian and the late Lutetian–late Bartonian intervals (Ritchie et al. 2003, 2008; Smallwood 2004; Johnson et al. 2005; Tuitt et al. 2010).

From a wider perspective, it is worth considering the proximity of the Faroe–Shetland region to the oceanic Norwegian Basin (Fig. 1), the development of which is linked to protracted Palaeogene breakup and spreading events resulting from the failure of the active ridge in the Norwegian Basin – the Aegir Ridge – to join up with the ridge propagating from the southern NE Atlantic; as a consequence, a wide zone of extension and/or transtension developed to the south and SE of the Jan Mayen microcontinent (Mosar et al. 2002; Gaina et al. 2009; Gernigon et al. 2009, 2012). During the Eocene, two major phases of extension and fragmentation occurred on the southern part of the Jan Mayen microcontinent during chrons C21 (c. 48–46 Ma) and C18 (ca. 41–39 Ma); both phases are associated with a change in spreading direction between Greenland and Eurasia, as well as a certain amount of counter-clockwise rotation of the southwestern margin of the microcontinent as rifting (and ultimately ocean spreading) developed between Jan Mayen and Greenland. This rotation has been coupled to local compression on the eastern side of the Jan Mayen microcontinent and the southwestern part of the Norwegian Basin (Gaina et al. 2009; Gernigon et al. 2012). The significance of these plate boundary reconfigurations during C21 and C18 times to the development of the Faroe–Shetland region remains uncertain; however, inspection of Figure 7 might invite speculation concerning a broad correlation between the timing of plate reorganisation events in the Norwegian Basin and the formation of the Eocene unconformities reported in this study.

Implications for an Eocene deep-water gateway in the Faroe–Shetland region

Solely on the basis of seismic interpretation, Hohbein et al. (2012) interpreted the inverted and domed Middle–Upper Eocene succession (comprising units FSP-2a–2c of this study) in the Faroe-Shetland Basin as a mounded deep-water contourite drift –the Judd Falls Drift – and inferred the onset of a modern-style North Atlantic Deep Water mass close to the Early to Middle Eocene boundary. This hypothesis is predicated on the assumption that a deep-water passageway traversed the Faroe–Shetland region at this time. Notwithstanding problems associated with their seismic interpretation, as documented elsewhere (Stoker et al. 2013), we find their hypothesis to be inconsistent with, and in contradiction of, the sedimentological evidence from borehole 99/3, which penetrates their inferred deep-water contourite sequence. Our reasons are based on the following:

- Hohbein et al. (2012) interpret the unconformity at the base of their inferred sediment drift body –their Intra-Eocene Unconformity; our reflector T2d – as a deep-water erosion surface; this study has shown that T2d represents a transgressive lag deposit (basal unit FSP-2c) atop a subaerial erosion surface.

- The sediments immediately overlying the transgressive lag pass into lower shoreface to shallow-marine shelf facies' (main part of unit FSP-2c); they are not deep-water contourite deposits.
- Although units FSP-2b and 2a represent a relative deepening of the depositional setting at the borehole site, there are no discernible indicators of sedimentary structures that commonly occur in contourite deposits, such as sharp and erosive contacts or grain-size cyclicity, which would be expected in response to changes in bottom-current velocity (Faugères et al. 1984; Stow et al. 2002). Moreover, bioturbational mottling, which is generally common to dominant in muddy contourites, is relatively uncommon in these two units. Unit FSP-2b is unequivocally a muddy pebbly debris-flow deposit associated with a slope apron, whereas unit FSP-2a is a homogenous mud most probably deposited in an anoxic, restricted basinal setting.

In addition to the borehole evidence, the palaeogeographical reconstructions (Fig. 8) make it difficult to concur with the viewpoint that, during the Eocene, a deep-water oceanic gateway existed across the Faroe–Shetland region. Instead, the persistent input of southerly-derived sediment into the Faroe-Shetland Basin is probably indicative of the contemporary tectonic activity affecting the southern margin of the basin, which we propose created and maintained a semi-enclosed depocentre with no deep-water outlet to the south. This is consistent with a growing body of biogeographic evidence that a functioning North Atlantic 'land bridge' (between Greenland and Scotland, including the Iceland-Faroe Ridge and adjacent shallow banks and ridges) persisted throughout the Palaeogene either as a terrestrial bridge or island 'stepping stones'; the latter not necessarily separated by vast areas of sea (Xiang et al. 2005; Beard 2008; Tiffney 2008; Denk et al. 2010).

Conclusions

- A revised Eocene stratigraphical and sedimentological framework has been established for the inverted Stronsay Group sediments in BGS borehole 99/3. Ypresian–earliest Lutetian paralic and shallow-marine deposits (unit FSP-2d) are unconformably overlain by lower shoreface to shallow-marine shelf deposits (unit FSP-2c) of mid-Lutetian age, which in turn are unconformably overlain by late Bartonian–Priabonian, deeper-water, mass-flow (slope-apron) (unit FSP-2b) and basinal (unit FSP-2a) sediments. Units FSP-2d and 2c are bounded by an unconformity (T2d) of mid-Lutetian age, whereas the boundary (T2c) between units FSP-2c and 2b is probably a composite unconformity surface at the borehole site encompassing late Lutetian (intra-FSP-2c boundary) and late Bartonian hiatuses.
- Integrating borehole 99/3 with regional seismic-stratigraphical data suggests that the various Lutetian and Bartonian stratigraphical breaks are associated with regressive events, the effects of which are especially well preserved around the southern margin of the Faroe-Shetland Basin. Early/mid-Lutetian subaerial exposure of Ypresian–earliest Lutetian deposits (FSP-2d) at the borehole site was terminated by the deposition of a ferruginous conglomeratic lag deposit (basal FSP-2c) associated with a mid-Lutetian marine transgression. Late Lutetian erosion of the FSP-2c shelf deposits led to redeposition of the eroded material as part of the Mid-Eocene basin-floor fan complex farther north; the unit FSP-2c shelf was subsequently downlapped by the late Bartonian–Priabonian slope-apron deposits of unit FSP-2b, prograding off the West Shetland margin as the borehole site subsided.
- Partial correlation of the regressive intervals to the global sea-level curve might be indicative of a eustatic signal; however, the increasingly apparent record of intra-

Eocene compressional deformation in this region, including the growth of inversion domes, such as the Judd Anticline upon which borehole 99/3 is sited, implies that tectonic activity might also have exerted a control on the stratigraphical architecture of the Stronsay Group. It may be no coincidence that the Faroe–Shetland regressive intervals coincide with chrons C21 and C18, which – from a regional perspective – correlate with episodes of compressive deformation in the Norwegian Basin. This might suggest that the early post-breakup development of the Faroe-Shetland Basin is strongly linked to the tectonic evolution of the adjacent oceanic basin.

- Sedimentological data from borehole 99/3 provides no support for a Mid- to Late Eocene contourite drift, and palaeogeographical considerations suggest that it is unrealistic to assume that a pattern of oceanic circulation, similar to the modern-day North Atlantic Deep Water regime, was active so early in the breakup of the NE Atlantic region.

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Table captions

1. Seismic-stratigraphical characteristics of the Eocene Stronsay Group
2. Summary of Eocene biostratigraphy in BGS borehole 99/3, derived from Ichron Limited (2012) together with a reappraisal of analyses presented in Hitchen (1999)
3. Revised age assignments of Eocene seismic reflectors
4. Key trace fossils recognised in units FSP-2c and 2d

Figure captions

1. Map showing location and present-day physiography of study area, general distribution of the Eocene succession, BGS borehole 99/3, DSDP site 336 and well 214/4-1, and UK Quadrants referred to in text; also, position of profiles shown in Figures 2 and 3. Inset a shows regional setting of Faroe-Shetland Basin. Abbreviation: COB, continent–ocean boundary. Inset b shows detailed layout of profiles in Figure 3 relative to borehole 99/3. Inset c shows early post-breakup structural setting of the southwestern-end of the Faroe-Shetland Basin (from Ritchie et al. 2011). Abbreviations: COB, continent–ocean boundary; ESB, East Solan Basin; RH, Rona High; WH, Westray High; WSB, West Solan Basin; (other) DSDP, Deep Sea Drilling Project. Bathymetric contours in metres.
2. Geoseismic section showing the general structural disposition of the Eocene succession in the Faroe–Shetland region, including the key Eocene (Stronsay Group) seismic boundaries, T2a–T2d. Abbreviations: FSE, Faroe-Shetland Escarpment; IMU, intra-Miocene unconformity; INU, Intra-Neogene unconformity; MEBF, Middle Eocene basin-floor sandstones; TB, Top Balder Fm. Section is located in Fig. 1.
3. Geological setting of BGS borehole 99/3. a) Line drawing showing seismic stratigraphy and structural disposition of Eocene (syn-breakup Balder Formation and post-breakup Stronsay Group) in the area of the borehole (modified after Stoker and Varming 2011); b)

BGS airgun profile 83/04-64 along axis of Faroe-Shetland Channel showing downlap of reflector T2b onto T2c, and concomitant pinchout of unit FSP-2b towards borehole site; c) BGS sparker profile 98/01-9 showing high-resolution seismic stratigraphy at borehole site calibrated to depth in metres, below sea bed, based on a two-way time of 1500 ms-1 for the unconsolidated section above 98.85 m, and 2000 ms-1 for the lithified section below this depth. Location of profiles is shown in Figure 1. Abbreviations: BB, Base Balder Fm; TB, Top Balder Fm; IMU, intra-Miocene unconformity; INU, intra-Neogene unconformity; TPU, Top Palaeogene unconformity.

4. Graphic log of Eocene succession in BGS borehole 99/3 (see text for details). Depth in metres, below sea bed.
5. Schematic section along the axis of the Faroe-Shetland Channel showing the general relationship of the Eocene seismic-stratigraphical units (FSP-2a–FSP-2d) and key reflectors (T2a–T2d; intra-FSP-2c) correlated between BGS borehole 99/3 (Quadrant 204) and well 214/4-1 (Quadrant 214). Abbreviation: TB, Top Balder Formation
6. Basal conglomerate of unit FSP-2c passing transitionally upwards into muddy sandstone. Inset shows shark tooth recovered from the conglomerate. Abbreviation: bsb, below sea bed.
7. Stratigraphical-range and palaeoenvironmental setting of Eocene rocks in BGS borehole 99/3 (see text for details). Circled letters (a) to (e) relate to position of timeslice intervals illustrated in Figure 8. Core depths are cross-referenced to graphic log in Figure 4. Timescale from Gradstein et al. (2012). Abbreviations: Q, Quadrant.
8. Series of schematic palaeogeographical maps showing the inferred spatial and temporal development of the Faroe-Shetland Basin during Eocene times: a) late Ypresian–earliest Lutetian; b) early/mid-Lutetian; c) mid-Lutetian; d) late Lutetian; e) late Bartonian–Priabonian. Palaeogeographical information derived from: Waagstein & Heilmann-

Clausen (1995), Andersen et al. (2000), Brooks et al. (2001), Robinson (2004), Robinson et al. (2004), Smallwood (2004); Ritchie et al. (2008), Ólavsdóttir et al. (2010), Tuitt et al. (2010), Stoker & Varming (2011) and unpublished BGS data (see text for details).

Table 1 Seismic-stratigraphic characteristics of the Eocene Stronsay Group

Seismic stratigraphy	Geometry and acoustic characteristics
Reflector T2a	Represents the top of the Stronsay Group where it is associated with a high-amplitude reflector (Knox et al. 1997) that is locally an angular unconformity (Stoker 1999; Davies and Cartwright 2002). More generally, the Eocene/Oligocene boundary remains poorly defined.
Unit FSP-2a	Poor to moderately reflective basinal section, with sporadic sub-parallel reflections that locally display low-angle onlap onto T2b; locally chaotic reflection pattern on SE flank of Faroe-Shetland Basin, at base of slope apron in Quadrant 204.
Reflector T2b	A high-amplitude reflector that marks the top of the prograding slope-apron (FSP-2b); downlaps onto T2c to both the NE and the SW as the slope apron pinches out laterally along the basin margin.
Unit FSP-2b	Complex sigmoid–oblique reflection configuration associated with a shelf-margin prograding wedge building out into the Faroe-Shetland Basin from the West Shetland margin; locally interdigitates with highly-reflective basin-floor fan deposits in Quadrant 204. Prograding reflectors downlap onto T2c at distal edge of slope apron. Clinoforms separate discrete packages of hummocky, structureless-to-chaotic seismic facies that comprise stacked sequences of lensoid bodies. Internal erosion surfaces, including channels up to several tens of metres deep, reported from topset strata (Robinson et al. 2004).
Reflector T2c	A high-amplitude reflector that marks an angular unconformity, which is especially erosional at the southern end of the basin; reflector is downlapped by clinoforms in the overlying slope apron (FSP-2b).
Unit FSP-2c	At southern-end of the Faroe-Shetland Basin, mid- to high-amplitude reflectors, which display low-angle onlap onto T2d, alternate with acoustically chaotic zones; farther to the NE, the upper part of the unit includes the mounded and highly reflective, acoustically chaotic deposits of the Middle Eocene basin-floor fans, which are thickest in Quadrants 213 and 214. Internal erosion surfaces, including channelised incision up to 200 m deep, have been reported from this unit (Robinson et al. 2004).
Reflector T2d	A high-amplitude reflector that is locally irregular and represents an angular unconformity, which is especially erosional at the southern end of the basin.
Unit FSP-2d	Acoustically well-layered with moderate- to high-amplitude sub-parallel reflections interbedded with stacked units (up to 100 ms TWT in thickness) of prograding oblique parallel-to-tangential clinoforms, particularly around the southern-end of the Faroe-Shetland Basin; common internal and locally irregular erosion surfaces. Unit is strongly folded about the axis of the Judd Anticline.
Reflector TB	The ‘Top Balder’ reflector: an established regional marker that marks the top of the Balder Formation of the underlying Moray Group (Ebdon et al. 1995).

Table 2 Summary of Eocene biostratigraphy in BGS borehole 99/3, derived from Ichron Limited (2012) together with a reappraisal of analyses presented in Hitchen (1999)

Depth in borehole	Biostratigraphical summary	Common age range
56.00–98.85 m	Dinoflagellate cysts: *Heteraulacysta porosa*, *Cerebrocysta bartonensis,Areosphaeridium diktyoplokus, Phthanoperidinium comatum, Systematophora placantha* and *Heteraulacysta* ? *leptalea* Foraminifera: *Pullenia bulloides, Pullenia osloensis, Cassidulina carapitana, Reticulophragmium amplectens, Gyroidana girardana, Uvigerina eoceana* and *Uvigerina germanica* Other comments: reworking of older Eocene (Ypresian–Lutetian) dinocysts, including: *Diphyes Ficusoides, Dracodinium pachydermum, Homotryblium pallidum/tenuispinosum, Eatonicysta ursulae, Aeroligera senonensis,* and *Glaphyrocysta ordinate;* together with common Jurassic and rare Carboniferous dinocyst reworking	Late Mid- to Late Eocene (NP17 and younger): Late Bartonian–Priabonian.
98.85–142.70 m	Dinoflagellate cysts: *Phthanoperidinium regalis, Aerosphaeridium abdoniim, Diphyes Ficusoides, Phthanoperidinium comatum, Selenopemphix coronata, Aeroligera senonensis, Glaphyrocysta ordinate* and *Heteraulacysta* ? *leptalea* Foraminifera: Commonly rare to barren above basal conglomeratic lag; however, concentration of '*Rhabdammina'* sp, *Reticulophragmium* sp, *?Bolivina* sp (possibly *Coryphostoma* sp), *Ammodiscus* sp, *Protobotellina* sp and *Lagena* sp in basal conglomeratic lag Radiolara: Common *Cenosphaera* sp. Diatoms: *Coscinodiscus* sp. 1 Other comments: abundant organic residues dominated by plant tissue and wood fragments; reworking of Paleocene (Thanetian) dinocysts, including: ?*Alisocysta circumtabulata* and *Cladopyxidium saeptum;* together with common Jurassic and rare to common Carboniferous dinocyst reworking. Basal conglomeratic lag includes shark teeth, fish debris and echinoid spines	Mid-Eocene (NP15 to early NP16): mid-Lutetian
142.70–166.50 m	Dinoflagellate cysts: *Dracodinium pachydermum* and *Dracodinium vareilongitudum* Foraminifera: *Cancris subconicus, Vaginulina decorate* (sub sp. A of King), and *Osangularia expansa* Ostracods: *Leguminocythereis bicostata* and *Trachyleberis spiniferrima* Other comments: abundant organic residues dominated by plant tissue and wood fragments; abundant Jurassic and Carboniferous dinocyst reworking	Early to early Mid-Eocene (NP12–14): Mid-Ypresian to earliest Lutetian

Table 3 Revised age assignments of Eocene seismic reflectors

Reflector	Stoker & Varming (2011)	This study
T2a	Late Priabonian/early Rupelian	Late Priabonian/early Rupelian (essentially 'Top Eocene')
T2b	Lutetian/Bartonian	Late Bartonian/Priabonian
T2c	Early Lutetian	Late Bartonian
Intra-FSP-2c*	(Not recognised)	Late Lutetian
T2d	Late Ypresian	Mid-Lutetian
TB	Early Eocene (Top Balder)	Early Eocene (Top Balder)

*Informal term used in this study

Table 4 Key trace fossils recognised in units FSP-2c and 2d

Trace fossil	Description	Unit
Planolites	Ovoid to lenticular, sub-horizontal burrows, 4–12 mm diameter; mud- and sand-filled; locally reworked by *Chrondrites*	FSP-2c & 2d
Chondrites	Rounded to ovoid burrows, 2–6 mm diameter; mainly mud-filled; locally branch downward; commonly found in *Planolites* burrows	FSP-2c & 2d
Skolithos	Vertical/sub-vertical burrows, 2–3 mm diameter, up to 2.5 cm long; locally cross-cuts *Chondrites* burrows	FSP-2c
Zoophycos	Rare horizontal burrow, 4 mm diameter; at least 8 cm long; internal spreiten structure; locally cut by *Chondrites* burrow	FSP-2c

Figure 1

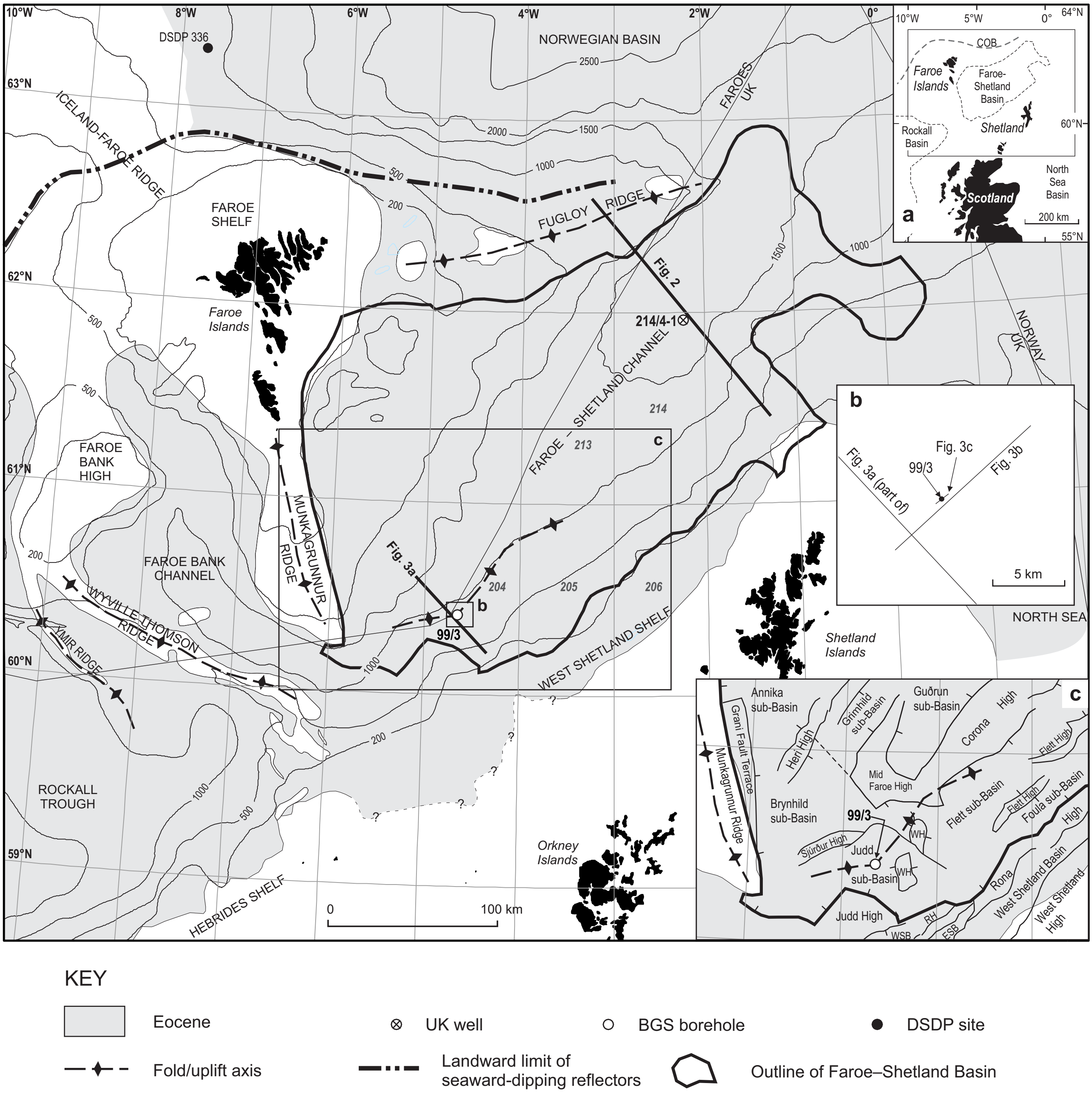

NORWEGIAN BASIN
DSDP 336
ICELAND-FAROE RIDGE
FAROE SHELF
Faroe Islands
FUGLOY RIDGE
FAROES UK
Fig. 2
214/4-1
FAROE – SHETLAND CHANNEL
NORWAY UK
FAROE BANK HIGH
FAROE BANK CHANNEL
MUNKAGRUNNUR RIDGE
Fig. 3a
99/3
WYVILLE-THOMSON RIDGE
YMIR RIDGE
WEST SHETLAND SHELF
Shetland Islands
NORTH SEA
ROCKALL TROUGH
HEBRIDES SHELF
Orkney Islands
100 km
a
COB
Faroe-Shetland Basin
Rockall Basin
Shetland
Scotland
North Sea Basin
200 km
b
Fig. 3c
Fig. 3b
Fig. 3a (part of)
5 km
c
Annika sub-Basin
Grimhild sub-Basin
Guðrun sub-Basin
Corona High
Heri High
Grani Fault Terrace
Munkagrunnur Ridge
Mid Faroe High
Brynhild sub-Basin
Flett sub-Basin
Flett High
Foula sub-Basin
Sjúrður High
Judd sub-Basin
Judd High
Rona
West Shetland Basin
West Shetland High
KEY
Eocene
UK well
BGS borehole
DSDP site
Fold/uplift axis
Landward limit of seaward-dipping reflectors
Outline of Faroe–Shetland Basin

Figure 2

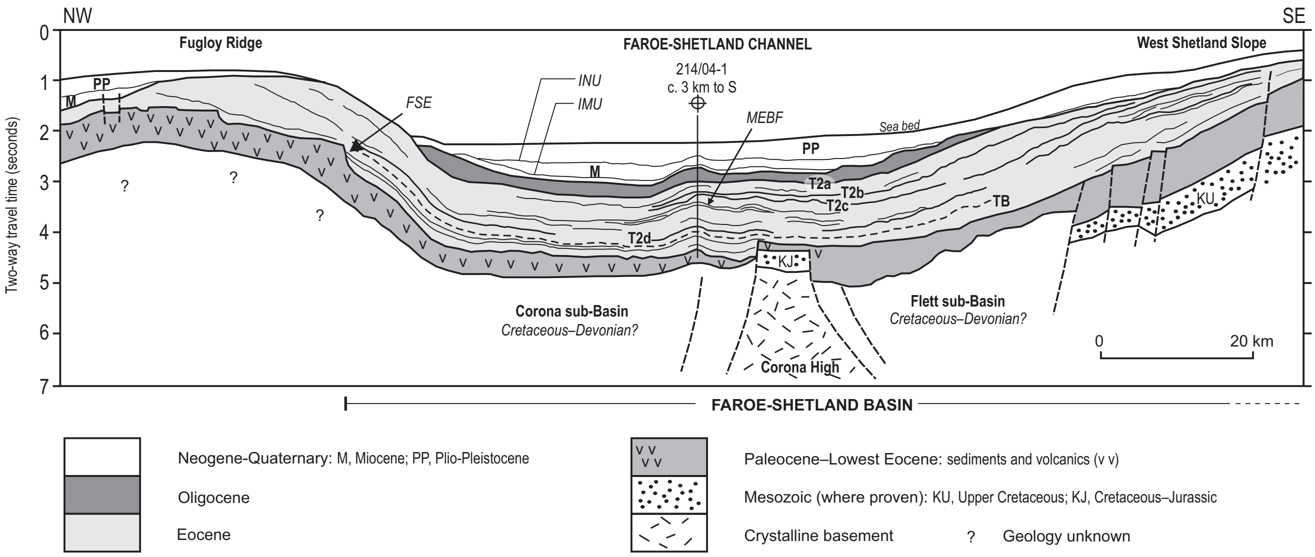
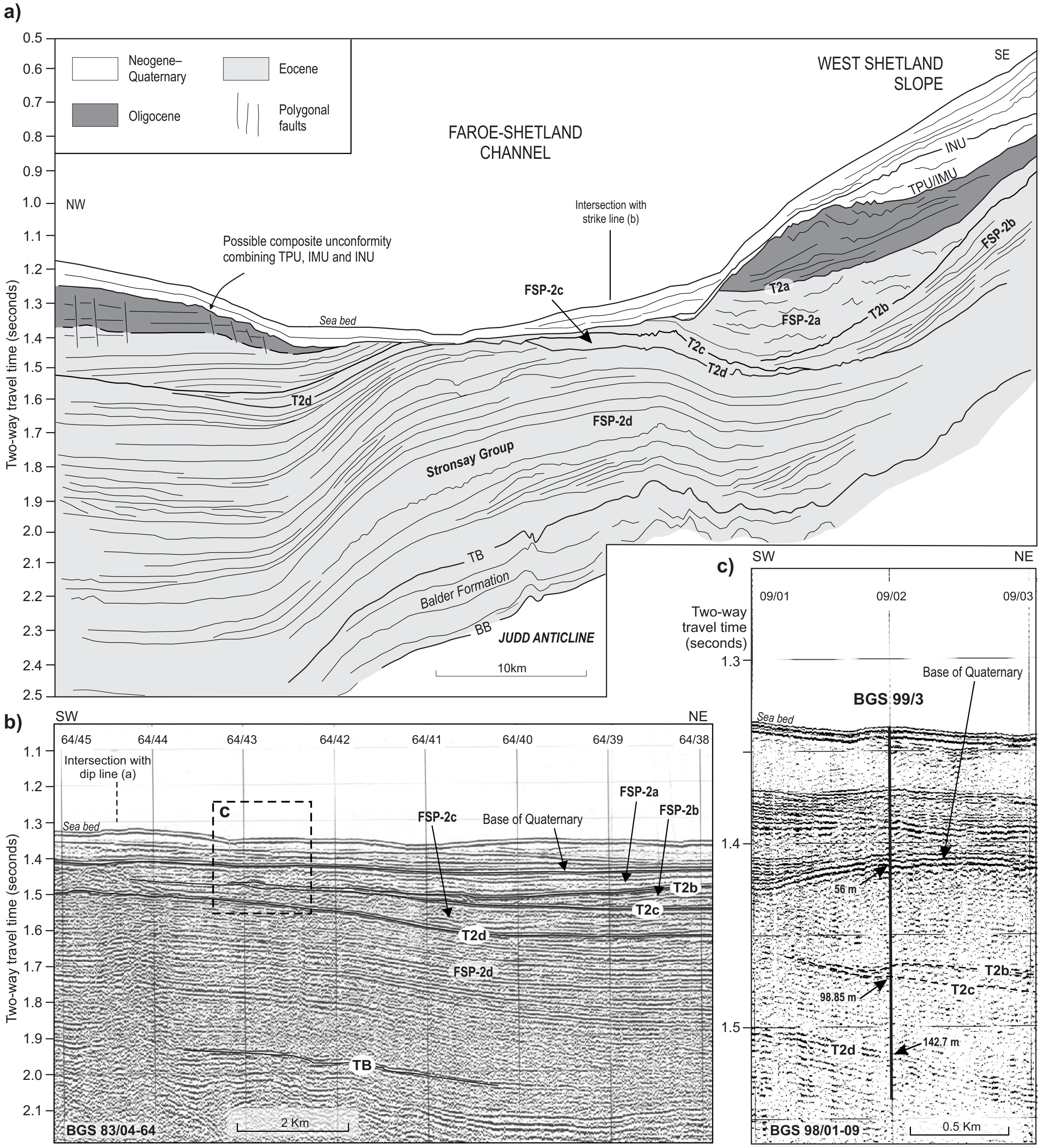
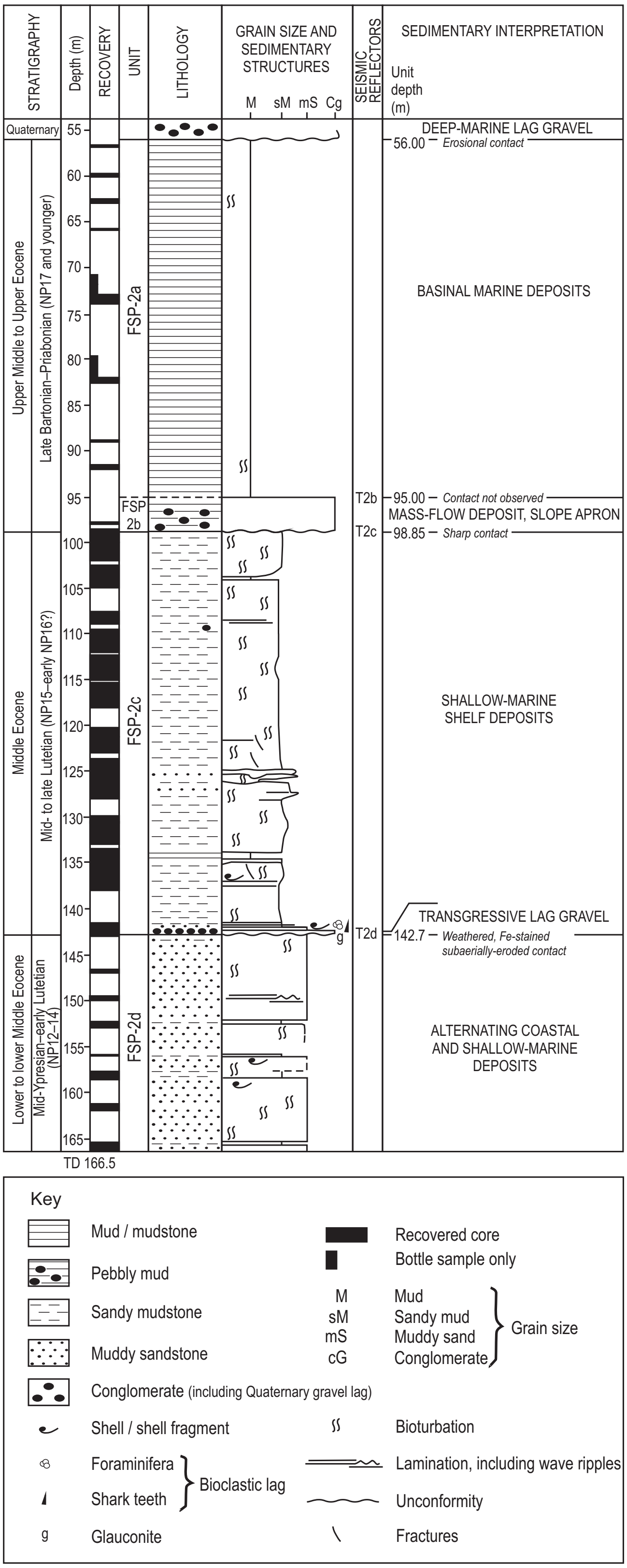

NW
SE
Fugloy Ridge
FAROE-SHETLAND CHANNEL
West Shetland Slope
Two-way travel time (seconds)
0
1
2
3
4
5
6
7
PP
M
INU
IMU
FSE
214/04-1
c. 3 km to S
MEBF
Sea bed
PP
M
T2a
T2b
T2c
TB
T2d
KJ
KU
?
Corona sub-Basin
Cretaceous–Devonian?
Flett sub-Basin
Cretaceous–Devonian?
Corona High
0
20 km
FAROE-SHETLAND BASIN
Neogene-Quaternary: M, Miocene; PP, Plio-Pleistocene
Oligocene
Eocene
Paleocene–Lowest Eocene: sediments and volcanics (v v)
Mesozoic (where proven): KU, Upper Cretaceous; KJ, Cretaceous–Jurassic
Crystalline basement
? Geology unknown

Figure 3



a)
Neogene–Quaternary
Eocene
Oligocene
Polygonal faults
FAROE-SHETLAND CHANNEL
WEST SHETLAND SLOPE
NW
SE
Two-way travel time (seconds)
Possible composite unconformity combining TPU, IMU and INU
Intersection with strike line (b)
Sea bed
FSP-2c
INU
TPU/IMU
FSP-2b
T2a
FSP-2a
T2b
T2c
T2d
FSP-2d
Stronsay Group
TB
Balder Formation
BB
JUDD ANTICLINE
10km
b)
SW
NE
64/45
64/44
64/43
64/42
64/41
64/40
64/39
64/38
Intersection with dip line (a)
Sea bed
C
Base of Quaternary
BGS 83/04-64
2 Km
c)
09/01
09/02
09/03
Two-way travel time (seconds)
BGS 99/3
56 m
98.85 m
142.7 m
BGS 98/01-09
0.5 Km

Figure 4



STRATIGRAPHY
Depth (m)
RECOVERY
UNIT
LITHOLOGY
GRAIN SIZE AND SEDIMENTARY STRUCTURES
M sM mS Cg
SEISMIC REFLECTORS
SEDIMENTARY INTERPRETATION
Unit depth (m)
Quaternary
Upper Middle to Upper Eocene
Late Bartonian–Priabonian (NP17 and younger)
Middle Eocene
Mid- to late Lutetian (NP15–early NP16?)
Lower to lower Middle Eocene
Mid-Ypresian–early Lutetian (NP12–14)
FSP-2a
FSP 2b
FSP-2c
FSP-2d
TD 166.5
DEEP-MARINE LAG GRAVEL
56.00 Erosional contact
BASINAL MARINE DEPOSITS
T2b 95.00 Contact not observed
MASS-FLOW DEPOSIT, SLOPE APRON
T2c 98.85 Sharp contact
SHALLOW-MARINE SHELF DEPOSITS
TRANSGRESSIVE LAG GRAVEL
T2d 142.7 Weathered, Fe-stained subaerially-eroded contact
ALTERNATING COASTAL AND SHALLOW-MARINE DEPOSITS
Key
Mud / mudstone
Pebbly mud
Sandy mudstone
Muddy sandstone
Conglomerate (including Quaternary gravel lag)
Shell / shell fragment
Foraminifera
Shark teeth
Bioclastic lag
Glauconite
Recovered core
Bottle sample only
M Mud
sM Sandy mud
mS Muddy sand
cG Conglomerate
Grain size
Bioturbation
Lamination, including wave ripples
Unconformity
Fractures

Figure 5

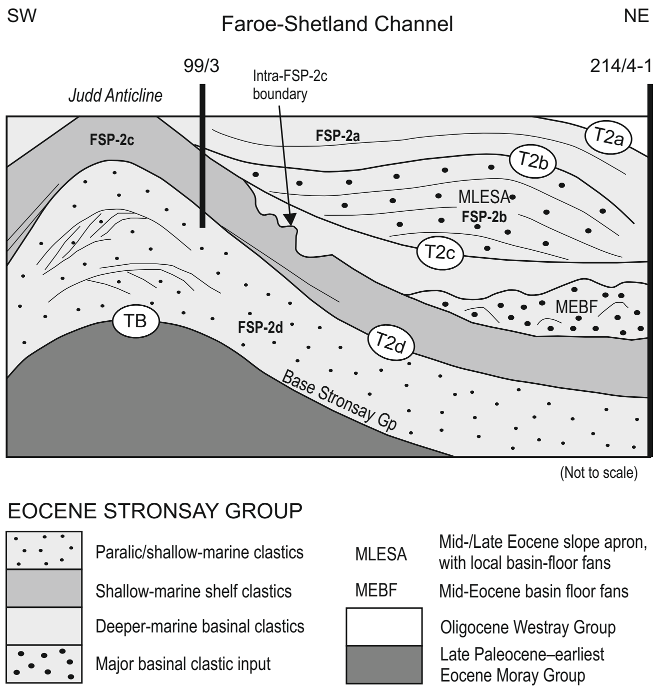

SW
Faroe-Shetland Channel
NE
99/3
214/4-1
Judd Anticline
Intra-FSP-2c boundary
FSP-2c
FSP-2a
T2a
T2b
MLESA
FSP-2b
T2c
MEBF
TB
FSP-2d
T2d
Base Stronsay Gp
(Not to scale)
EOCENE STRONSAY GROUP
Paralic/shallow-marine clastics
Shallow-marine shelf clastics
Deeper-marine basinal clastics
Major basinal clastic input
MLESA
Mid-/Late Eocene slope apron, with local basin-floor fans
MEBF
Mid-Eocene basin floor fans
Oligocene Westray Group
Late Paleocene–earliest Eocene Moray Group

Figure 6

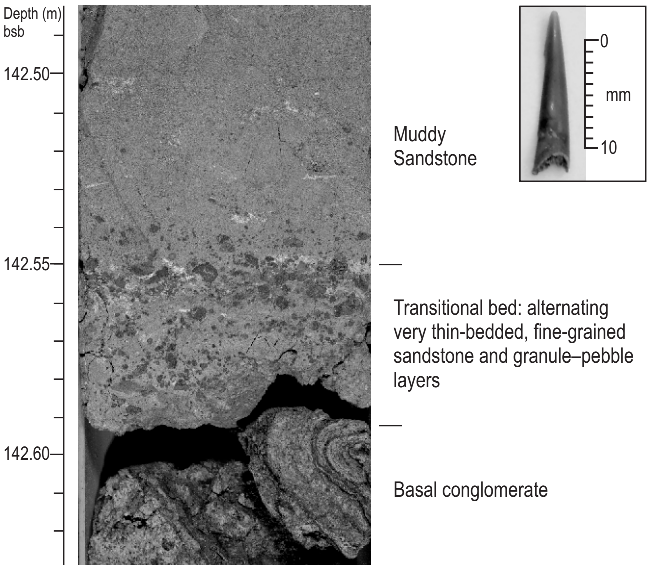
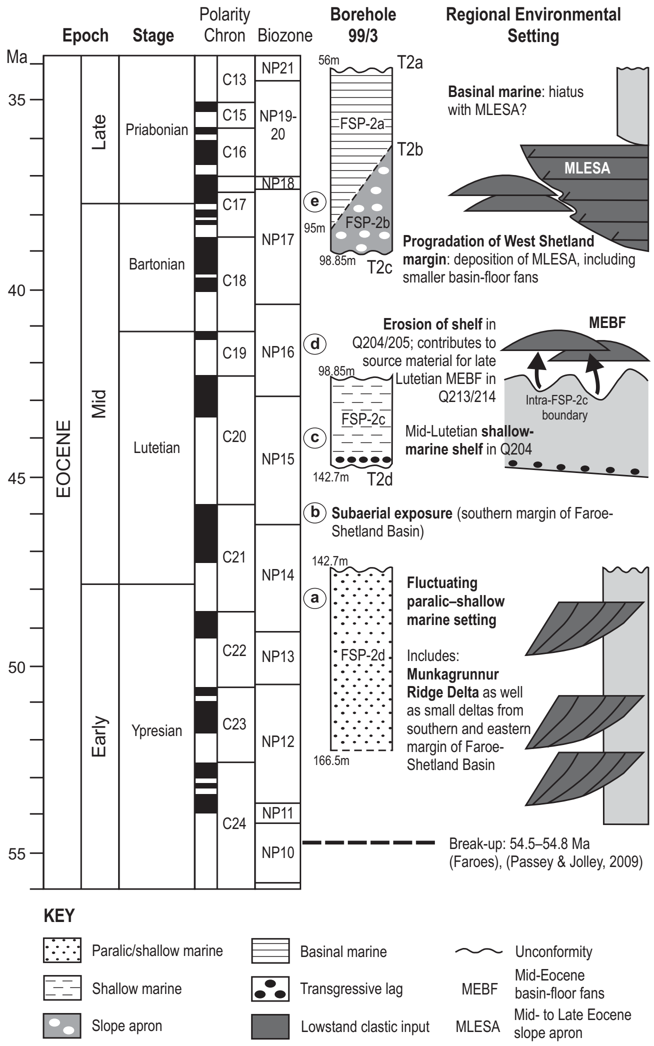
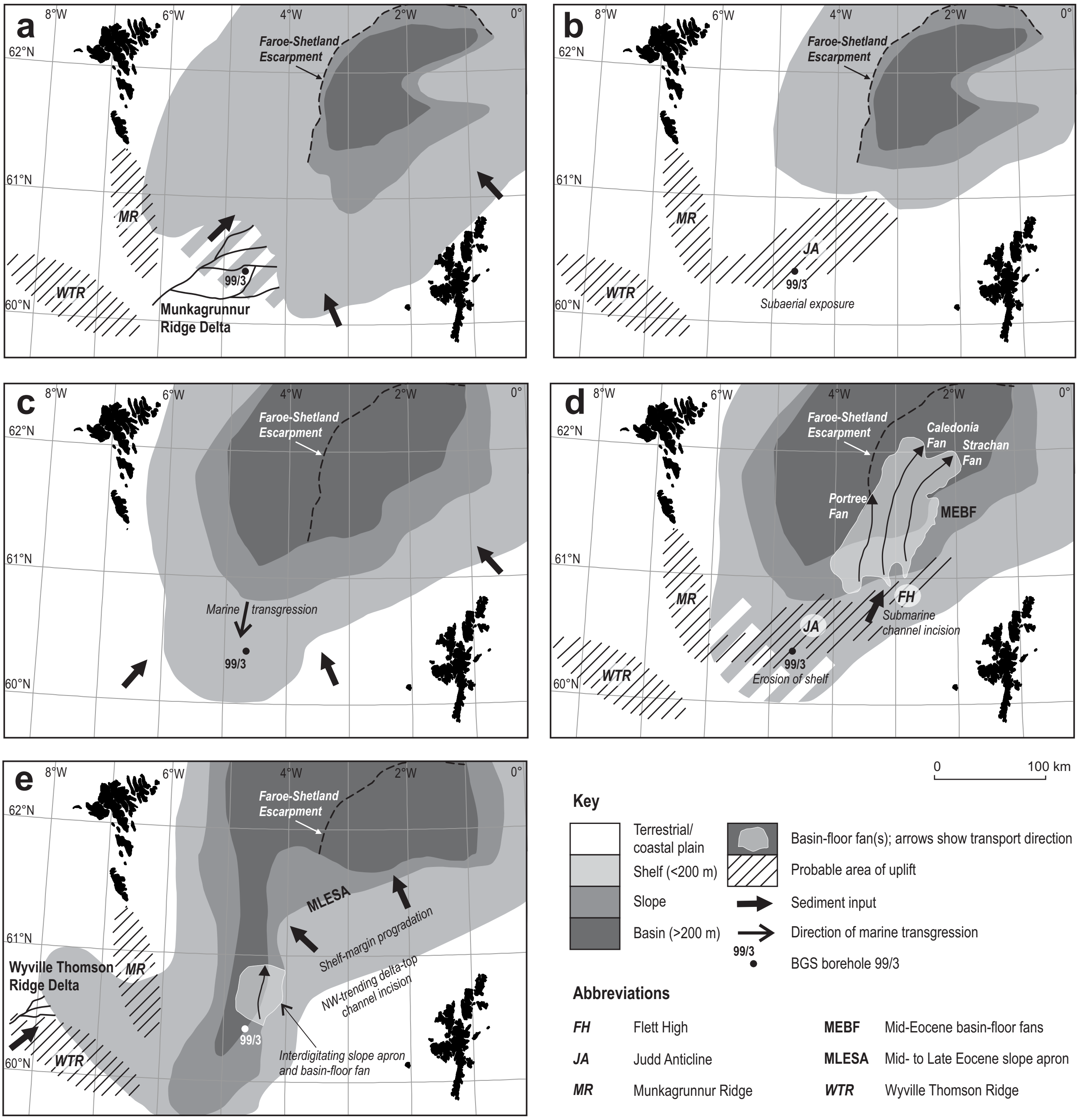

Depth (m)
bsb
142.50
142.55
142.60
Muddy
Sandstone
Transitional bed: alternating
very thin-bedded, fine-grained
sandstone and granule–pebble
layers
Basal conglomerate
0
mm
10

Figure 7



Epoch
Stage
Polarity Chron
Biozone
Borehole 99/3
Regional Environmental Setting
Ma
35
40
45
50
55
EOCENE
Late
Mid
Early
Priabonian
Bartonian
Lutetian
Ypresian
C13
C15
C16
C17
C18
C19
C20
C21
C22
C23
C24
NP21
NP19-20
NP18
NP17
NP16
NP15
NP14
NP13
NP12
NP11
NP10
56m
T2a
FSP-2a
T2b
FSP-2b
95m
98.85m
T2c
Basinal marine: hiatus with MLESA?
MLESA
Progradation of West Shetland margin: deposition of MLESA, including smaller basin-floor fans
Erosion of shelf in Q204/205; contributes to source material for late Lutetian MEBF in Q213/214
MEBF
Intra-FSP-2c boundary
98.85m
FSP-2c
142.7m
T2d
Mid-Lutetian shallow-marine shelf in Q204
Subaerial exposure (southern margin of Faroe-Shetland Basin)
142.7m
FSP-2d
166.5m
Fluctuating paralic–shallow marine setting
Includes: Munkagrunnur Ridge Delta as well as small deltas from southern and eastern margin of Faroe-Shetland Basin
Break-up: 54.5–54.8 Ma (Faroes), (Passey & Jolley, 2009)
KEY
Paralic/shallow marine
Shallow marine
Slope apron
Basinal marine
Transgressive lag
Lowstand clastic input
Unconformity
MEBF Mid-Eocene basin-floor fans
MLESA Mid- to Late Eocene slope apron

Figure 8


a
b
c
d
e
8°W
6°W
4°W
2°W
0°
62°N
61°N
60°N
Faroe-Shetland Escarpment
MR
WTR
99/3
Munkagrunnur Ridge Delta
JA
Subaerial exposure
Marine transgression
Caledonia Fan
Strachan Fan
Portree Fan
MEBF
FH
Submarine channel incision
Erosion of shelf
MLESA
Shelf-margin progradation
NW-trending delta-top channel incision
Wyville Thomson Ridge Delta
Interdigitating slope apron and basin-floor fan
0
100 km
Key
Terrestrial/ coastal plain
Shelf (<200 m)
Slope
Basin (>200 m)
Basin-floor fan(s); arrows show transport direction
Probable area of uplift
Sediment input
Direction of marine transgression
BGS borehole 99/3
Abbreviations
FH Flett High
JA Judd Anticline
MR Munkagrunnur Ridge
MEBF Mid-Eocene basin-floor fans
MLESA Mid- to Late Eocene slope apron
WTR Wyville Thomson Ridge