Regional controls on Lower Tertiary sandstone distribution in the North Sea and NE Atlantic margin basins

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Abstract: Widely distributed deep-water fan sandstones of early Tertiary age form the reservoir for one of the most successful and prolific plays in the North Sea and NE Atlantic margin. Stratigraphic interpretation of a large well database provides the basis for mapping sand distribution and depositional environments in these two hydrocarbon provinces. Sand thickness maps for five Paleocene–Lower Eocene plays illustrate the intimate relationship between pre-existing structural features and sand distribution and facies in the North Sea. Large-scale depositional environment mapping gives an insight into the similarities and differences between basin evolution and sand distribution in North Sea and NE Atlantic margin basins. Both provinces were affected by the same succession of pre-break-up and syn-break-up tectonic and magmatic events that led to early Eocene continental separation and the formation of the NE Atlantic. The impact of these events was muted within the North Sea, which was protected from Paleocene rifting on the NE Atlantic margin by the Scotland–Shetland hinterland and from Paleocene–early Eocene volcanism by its more distant location. However, it was the combination of tectonic and thermal uplift of this clastic source area that contributed the large volumes of sand that accumulated in both these provinces.

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Lower Tertiary sandstone reservoirs deposited in deep-water submarine fan systems are widely distributed in the North Sea Basin, occurring in three broadly defined areas of sand accumulation: Moray Firth–Central Graben, South Viking Graben–Beryl Embayment and East Shetland Basin (Fig. 1). Two categories of fan are recognized, each with a different geometry and prospectivity (den Hartog Jager et al. 1993). The Paleocene fans are large-scale systems with sheet-like geometries that form major elements of basin fill (Bowman 1998). In contrast, the younger late Paleocene–early Eocene fans are more localized and smaller in size. In both fan systems, a close relationship is seen between sand thickness distribution and pre-existing structural features, including the north–south South Viking Graben and East Shetland Platform margin faults, the Halibut Horst and the north–south line of intrabasinal Utsira, Jæren and Sørvestlandet highs (Fig. 1).

This paper builds upon previous stratigraphic analysis and lithofacies mapping of Paleocene and lower Eocene sandstones in the North Sea Basin (Mudge & Bujak 1996b, 2001). Reservoir distribution is a key geological element in the evaluation of Lower Tertiary plays in the North Sea, and the main objective of the sand thickness and depositional environment mapping presented here is to provide the regional context for more detailed evaluations of these fan sandstones at field and play fairway scales (Kilhams et al. 2014; Thomas & Hartley, this volume, in press). These maps, which have been produced for five Paleocene–Lower Eocene stratigraphic intervals, are based on a large interpreted well database. They illustrate changing patterns of sand distribution and facies that correlate with the stratigraphic record of regional unconformities, flooding surfaces and the microfossil acmes and extinctions seen in well sections.

The maps and well data are also used to assess the impact of tectonic and magmatic events on early Tertiary basin development and sand distribution in the North Sea and to examine the nature and causes of Paleocene–early Eocene uplift in the Scotland–Shetland hinterland, which separated the North Sea Basin from the Faroe–Shetland and NE Rockall basins located on the NE Atlantic margin (Fig. 1). This uplift produced a high-relief source area that contributed large volumes of clastic material to both the North Sea and NE Atlantic depositional provinces. The North Sea Basin is separated from the Møre Basin by the Møre–Trøndelag Fault Zone; gravity and magnetic anomaly mapping shows that this structural feature continues southwestwards as the faulted NW margin of the Scotland–Shetland hinterland (Kimbell et al. 2005). This fault zone bears a close affinity to other major Caledonian shear including the Walls Boundary Fault and Great Glen Fault, located within the Scotland–Shetland hinterland.

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which were reactivated in the Mesozoic (Dore’ et al. 1997).

The extension, uplift and volcanism that affected North Sea and NE Atlantic margin basin development during the Paleocene–early Eocene are related to two phases of tectonism and magmatism that preceded continental break-up and the start of seafloor spreading in the NE Atlantic during chron 24r at c. 54 Ma (Ahmadi et al. 2003; Coward et al. 2003; Lundin & Dore’ 2005; Passey & Hitchen 2011). The Paleocene pre-break-up phase involved NE–SW rifting in the Faroe–Shetland and NE Rockall basins, accompanied by an episode of volcanism and sill intrusion along a north–south zone extending from Greenland to the Hebrides (Lamers & Carmichael 1999; Roberts et al. 1999; Linnard & Nelson 2005; Lundin & Dore’ 2005). The late Paleocene–early Eocene syn-break-up phase involved replacement of rifting by passive infill of the basins associated with an episode of much more voluminous volcanism prior to plate break-up. In the more distant North Sea Basin, pre-break-up extension led to reactivation of old north–south Mesozoic faults, while the syn-break-up phase can be recognized in the change to passive basin infill during the early Eocene. Here the record of volcanic activity is limited to the deposition and reworking of airfall tuffs.

Data and methodology

In this paper a large interpreted well database, added to and revised over a period of more than thirty years, forms the basis for Lower Tertiary stratigraphic analysis and mapping in the North Sea, Faroe–Shetland, NE Rockall and Møre basins (Fig. 2). In the North Sea, interpretation of more than 2200 wells has been used to establish a detailed Paleocene–Lower Eocene stratigraphy based on the recognition of a series of regional unconformities and marine flooding surfaces (Fig. 3). Biorstratigraphical dating and correlation of these surfaces is important for hydrocarbon exploration because of

Fig. 1. North Sea and NE Atlantic margin basins showing present-day distribution of Paleocene–Lower Eocene sediments and volcanics. BE, Beryl Embayment; CG, Central Graben; MF, Moray Firth; ESB, East Shetland Basin; HH, Halibut Horst; JH, Jæren High; SH, Sorvwestlandet High; SVG, South Viking Graben; UH, Utssira High; GGF, Great Glen Fault; HBF, Highland Boundary Fault; WF, Walls Fault; CH, Corona High; FSB, Faroe–Shetland Basin; JL, Judd Lineament; MR, Munkagrønnur Ridge; WSSF, West Shetland Spine Fault; WTL, Wyville–Thomson Lineament; COB, continent–ocean boundary.
their intimate association with reservoir sandstones, with the base of each sandstone package being marked by unconformity and the top by a high-gamma mudstone. Using this stratigraphic control, sand thickness maps have been produced for five Paleocene–Lower Eocene hydrocarbon plays in the North Sea: Maureen–Andrew, Balmoral/Heimdal, Forties, Dornoch/Sele and Beauly/Balder.

These regional surfaces also occur in the Faroe–Shetland stratigraphic record, and can be identified in the NE Rockall and Møre basins (Waddams & Cordingley 1999; Mudge & Bujak 2001). Integration of a further 200 interpreted wells from these NE Atlantic margin basins with the North Sea stratigraphic database has provided the basis for regional mapping of Danian–Lower Ypresian depositional environments.

**North Sea and NE Atlantic margin stratigraphy**

The stratigraphy of Paleocene–Lower Eocene rocks in the North Sea and Faroe–Shetland basins is shown in Figure 3. This interval contains the Danian, Selandian, Thanetian and lower Ypresian stages. The North Sea lithostratigraphy has been established in a series of papers by Deegan & Scull (1977), Isaksen & Tonstad (1989), Mudge & Copetake (1992a, b) and Knox & Holloway (1992). A largely separate lithostratigraphical nomenclature has been erected at formation level for the Faroe–Shetland Basin (Knox et al. 1997).

Detailed biostratigraphical analysis using dinocysts, spores and pollen, agglutinated and planktonic foraminifera, diatoms, and radiolarians shows that the succession of bioevents is the same in both basins, demonstrating that they share a common chronostratigraphy and that they were connected during Paleocene–early Eocene time (Mudge & Bujak 2001). Comparison of the stratigraphical ranges of the dinocysts in North Sea and Faroe–Shetland wells with those of onshore NW Europe stratotypes and reference sections provides the basis for this Paleocene–Eocene chronostratigraphy (Mudge & Bujak 1996a, b). Planktonic foraminifera are also used in the Danian interval. This scheme ties the succession to the global planktonic foraminiferal (P) and nannoplankton (NP) zones and hence to the geological timescale and stage nomenclature of Gradstein et al. (2012).

A Paleocene–Lower Eocene sequence stratigraphy based on regional unconformities and maximum flooding surfaces has been developed in a series of papers by Mudge & Bujak (1996a, b, 2001). These papers show that there is a consistent relationship between these surfaces and the distribution of microfossil and microfaunal assemblages across the North Sea and Faroe–Shetland basins. Six regional unconformities are recognized, with sandstones, reworked chalks or tuffs overlying these surfaces in many platform, slope and basin well sections (Mudge & Jones 2004). In addition, biostratigraphical dating indicates that section is missing below these unconformities, even in wells drilled in the deepest parts of the basin. Geological

Fig. 2. Location of wells used in the study.
Fig. 3. Paleocene–Lower Eocene stratigraphy of the North Sea and Faroe–Shetland basins. Slope basin sandstones shown in orange; shelf/coastal margin sediments in yellow; non-marine sediments in brown; mudstone in grey; lavas in red; tuffs in pink. T–M, tectonic–magmatic phase. Absolute ages after Gradstein et al. (2012).
cross-sections based on well profiles for the Moray Firth–Central Graben and Beryl Embayment–South Viking Graben are shown in Figures 4 and 5.

Biographical analysis allows these sequences to be correlated with the ‘T’ sequences of Jones & Milton (1994) in the North Sea Basin and Ebdon et al. (1995) and Goodwin et al. (2009) in the Faroe–Shetland Basin. These BP sequences are also bound by maximum flooding surfaces and unconformities interpreted from wireline log and seismic data calibrated with microfaunal and microfloral biostratigraphy. Much useful information on Faroe–Shetland stratigraphy is provided in a BGS report by Stoker & Varming (2011). A geological cross-section of the Faroe–Shetland Basin is shown in Figure 6. The stratigraphic distribution of maximum flooding surfaces, unconformities and sandstones is illustrated in four wells from the North Sea and Faroe–Shetland basins (Fig. 7).

Basalt lavas cover a large part of the Faroe–Shetland–Hebrides–NE Rockall region (Fig. 1). A combined thickness of more than 6.5 km of lavas, hyaloclastites and subordinate volcaniclastic rocks has been mapped at outcrop and drilled in the Lopra-1, 1A and Vestmanna-1 boreholes on the Faroe Islands (Berthelsen et al. 1984; Hald & Waagstein 1984). These extrusive rocks form the Faroe–Islands Basalt Group, which is subdivided into seven formations (Passey & Jolley 2009). The lower basalts were extruded during chron 26r to 25n, while the middle and upper basalts are of chron 24r age (Waagstein 1988). Radiometric K–Ar dating has given ages of 56.5 ± 1.3 Ma to 58.9 ± 1.3 Ma for six basalts from the Lopra and Beinisvørð formations, consistent with the palaeomagnetic evidence and indicating extrusion during latest Selandian–Thanetian time (Waagstein et al. 2002). These two lava formations represent extrusion during the pre-break-up volcanic phase; they are separated from the much more areally extensive Malinstindur and Enni lavas by a thin unit of coal-bearing sediments overlain by tuffaceous sandstones and mudstones (Prestfjall and Hvannhagi formations). These younger lavas are of early Ypresian age and were extruded during the syn-break-up volcanic phase. 40Ar/39Ar dating has been used to extend the age range of the Beinisvørð and Lopra lavas from 56.8 ± 0.6 to 60.1 ± 0.6 Ma in the Lopra borehole, and to give ages of 54.9 ± 0.7 Ma to 55.2 ± 0.7 Ma for the Malinstindur and Enni lavas (Storey et al. 2007).

Vaila Formation volcaniclastic sandstones of Selandian age occur in several wells in the NE Rockall Basin, for example, 154/1-1 and 164/28-1A, where they are succeeded by lower and upper Rockall lavas and hyaloclastites yielding early Thanetian and Ypresian biostratigraphical dates, respectively. The lower Rockall lavas occur within the Lamba Formation and rest on the Mid-Paleocene unconformity in this area, for example, in well 164/7-1 (Archer et al. 2005). Further evidence for the regional presence of Thanetian lavas comes from well 219/21-1 drilled to the south of the Brendan volcanic centre (Jolley 2009). In well 6005/15-1 in the Faroe–Shetland Basin, the Vaila Formation contains thin lava flows interbedded with volcaniclastic sandstones and siltstones (Smallwood & Harding 2009). These volcaniclastics are widely distributed in Vaila sediments in the SW Faroe–Shetland Basin (Ellis et al. 2009).

In the Faroe–Shetland Basin the Lamba Formation contains several Thanetian tuff horizons. The Kettle Tuff Member is equivalent to the Glanis Tuff Member in the North Sea, both units resting on the Mid-Paleocene unconformity (Mudge & Bujak 2001). Younger tuffs also occur within the Lamba Formation in the SW Faroe–Shetland Basin. Flett lavas and hyaloclastites of early Ypresian age have been drilled in wells on the Corona High and in well 205/9-1 in the Faroe–Shetland Basin (Knox et al. 1997; Jolley 2009). Biostratigraphical analysis of extrusive rocks associated with the Erlend volcanic centre have yielded similar ages (Jolley & Bell 2002). Balder tuffs, which are widely distributed across the North Sea and NE Atlantic margin, represent the last phase of extrusive activity before continental separation at c. 54 Ma.

Maureen–Andrew sandstones

The Selandian net sand thickness map combines Maureen and Andrew sandstone distributions for the North Sea Basin (Fig. 8). These were deposited in the Maureen II and Lista I sequences, at the same time as Vaila sandstones in the Faroe–Shetland Basin (Fig. 3). In the North Sea, the sandstones have a general sheet-like nature lacking mound seismic facies (den Hartog Jager et al. 1993). These are interpreted as massive, stacked, submarine fan and channel deposits, which rest unconformably on older Danian sediments. The Maureen II/Lista I sequence boundary is marked by a high-gamma mudstone (p3) containing a distinctive microfauna of coarsely reticulate radiolarians (Mudge & Bujak 1996a). This condensed mudstone, which also occurs in the Faroe–Shetland Basin, represents a significant pause in regional Selandian deposition separating the Maureen and Andrew sand events (Mudge & Bujak 2001).

Maureen sandstones are widely distributed in the Moray Firth–Central Graben and South Viking Graben–Beryl Embayment. However, Andrew sandstones have a more limited extent, being absent over most of the Central Graben and the
Fig. 4. NW–SE well cross-section through Moray Firth and Central Graben, North Sea. Be, Beauly Formation; UDS, Upper Dornoch sandstone; LDS, Lower Dornoch sandstone; Bt, Balder Tuff; Fo, Forties Sandstone Member; Fe, Fergie Sandstone; Bal, Balmoral Sandstone Member; And, Andrew Sandstone Member; Maur, Maureen Sandstone; RWU, Reworked Unit; Eko, Ekofisk Formation. Inset abbreviations as Figure 3, except FP, Forties Platform.
northern part of the South Viking Graben (Figs 4 & 5). The Maureen–Andrew sand system passes laterally into a thin argillaceous facies along its eastern and SW margins. Its NW limits appear to be erosional. The sandstones were laid down exclusively within a slope-basin setting. Later Palaeogene uplift has removed any shelf sediments deposited along the flank of the Scotland–Shetland hinterland to the west.

Two sand systems are recognized: one spreading southeastwards through the Moray Firth into the Central Graben and the other occupying the South Viking Graben and Beryl Embayment. These are separated by a zone of thin sandy sediments over the Fladen Ground Spur. Two extensive channelized sand fairways with an easterly trend are mapped in the Moray Firth, divided by the Halibut Horst, which acted as a sediment bypass zone during the Selandian. In the wide northern fairway, where sandstones reach a net thickness of more than 350 m, both massive and thinly bedded units are seen. South of the Halibut Horst the southern fairway is much narrower, with seismic data showing evidence for incision. The sand fairways merge and thin southeastwards along the Central Graben, shaling out westwards on to the Forties Platform and eastwards across the UK–Norway median line. The easterly shale out on to the Jæren and Utsira highs can be clearly seen on seismic and well data from the Everest and Maureen fields (O’Connor & Walker 1993; Chandler & Dickinson 2003).

The second sand system occupies the South Viking Graben and Beryl Embayment. Sandstone thickening across the north–south South Viking Graben fault becomes very pronounced in the Beryl Embayment, where a depocentre containing more than 600 m of channelized slope fan and slump sandstones is located in the hanging wall of the East Shetland Platform margin fault. Eastwards into the South Viking Graben these deposits interfinger with thinner basin-floor turbidites and mudstones with local fans (Fig. 5). In the Mariner Field (Block 9/11) located on the platform to the west, seismic data display Maureen sandstones preserved in incised east–west channels cut into the Chalk and, in some wells, into the Old Red Sandstone (Ahmadi et al. 2003). To the north of the Beryl Embayment, only minor amounts of sandstone have been drilled in the East Shetland Basin.

Fig. 5. East–west well cross-section across Beryl Embayment and South Viking Graben, North Sea. Od, Odin Sandstone Member; Hd, Hermod Sandstone Member; He, Heimdal Sandstone Member. For other abbreviations see Figures 3 and 4.
Thanetian Balmoral sandstones are widely distributed throughout the Moray Firth and Central Graben (Figs 4 & 9). Biostatigraphical dating shows they are the same age as the Heimdal sandstones that extend northwards through the South Viking Graben into the Beryl Embayment and East Shetland Basin (Fig. 7; Mudge & Copestake 1992b). Both sandstone units rest on the Mid-Paleocene unconformity surface, which marks the Selandian/Thanetian boundary and separates the Lista I and Lista II sequences (Fig. 3). The top of the sandstones is bounded by the p7 high-gamma mudstone that marks the end of widespread Thanetian sand deposition in the North Sea Basin. Younger Lista III sandstones occur locally in the Moray Firth and Central Graben, where they are informally called the Fergie sandstone. The Balmoral/Heimdal sandstone map includes Fergie net sand (Figs 4 & 7). In the Faroe–Shetland Basin, Lamba sandstones correlate with the Balmoral/Heimdal sandstones.

The basinward extent of these deposits is similar to that of the Selandian Maureen–Andrew sand system, with Balmoral sandstones spreading south-eastwards through the Moray Firth into the Central Graben, separated by the structural high of the Fladen Ground Spur from Heimdal sandstones infilling the South Viking Graben and Beryl Embayment. However, there are significant differences in the distribution of the Thanetian sandstones, which are much thicker in the South Viking Graben but thinner in the Moray Firth. These sediments were also laid down in a slope-basin setting with no evidence for the preservation of shelf deposits to the west. The two sand systems merge in the Fisher...
Bank Basin, continuing southeastwards into the Central Graben and pinching out on to the Utsira, Jærren and Sørvestlandet highs to the east.

A new depocentre is mapped in the East Shetland Basin, where more than 800 m of slumped and channelized slope sandstones have been drilled in the hanging wall of the platform margin fault. A large channel is present in the southern East Shetland Basin, occupying a break in the en echelon platform margin fault system. To the south, three large-scale channels can be seen extending eastwards from the East Shetland Platform into the Beryl Embayment. These fed clastics into the South Viking Graben, where thick sands were deposited in basin-floor fans confined by the Utsira High to the east (Jenssen et al. 1993). There is evidence for incision in the Beryl Embayment, where Heimdal sandstones fill channels cut into lower Lista slope mudstones (Mudge & Jones 2004).

In the Moray Firth, the Halibut Horst again acted as a sand bypass zone with channelized sand fairways located to the north and south of this long-lived basement high. In the Central Graben the western margin of the Balmoral sand fairway is marked by a series of east-trending channels that fed sands into the basin from the Forties Platform. Further south, a separate sand fairway is mapped. Here the sandstones are much thinner and have been deposited in a long narrow channel system trending eastwards from the Forties Platform. Regionally, the seismic character of the Balmoral section suggests the presence of coalescing sheet sandstones that shale out laterally along the fairway margins. In the MacCulloch Field (Block 15/24b), seismic and well data indicate that the upper sandstones were derived from the NW and deposited as massive submarine debris flows within a complex system of stacked channels and levees (Gunn et al. 2003).

The Siri fairway is a sand-dominated channel system extending southwestwards from the Norwegian Platform as far as the Central Graben (Ohm et al. 2006). The Siri channel fill comprises a stacked series of turbiditic channel/lobe sandstones and debris flow layers of Selandian–early Ypresian age. They are included on the Balmoral/Heimdal distribution map as the bulk of the sandstones are believed to be of Thanetian age.
Forties sandstones

Shelf, slope and basin facies have been drilled in the Forties sand system in the North Sea. The shelf sediments belong to the lower Dornoch Formation and the basin/slope sediments to the laterally equivalent lower Sele Formation (Fig. 3). Biostratigraphical analysis enables the Forties to be divided into two sequences separated by the Near Top Paleocene unconformity, which marks the Paleocene/Eocene boundary (Mudge & Bujak 2001). Forties I sediments have only a limited distribution due to widespread erosion beneath this surface. Where preserved, the sequence has a late Thanetian age and rests unconformably on eroded upper Lista sediments. The main development of sandstones occurs within the Forties II sequence, which is of early Ypresian age (Fig. 7). The thick sequence of sand-rich submarine fan deposits in the Central Graben belongs to the Forties Sandstone Member. Further north in the South Viking Graben, these sandstones have a much more limited distribution and have been assigned to various members, for example, the Skadan, Teal and lower Hermod sandstones (Knox & Holloway 1992).

The distribution of Forties sandstones is shown in Figure 10. In the Central Graben the Forties fan system comprises a thick southeasterly-directed lobe with a large-scale sheet-like geometry, connected to the eroded remnants of a shelf and coastal margin wedge in the Moray Firth by a narrow sand-filled channel. Its internal architecture is dominated by stacked sand-prone channels and interchannel interbedded sandstone–mudstone units (Bowman 1998). Many fields produce from this reservoir in the Central Graben, for example, Forties, Nelson, Montrose, Arbroath and Arkwright. Detailed seismic mapping integrated with well-log and biostratigraphical data from these fields provides evidence for the topographic control of sand distribution and facies at both field and fairway scale (Wills 1991; Hogg 2003; Kunka et al. 2003).
The shelf sediments have not been preserved further south along the margin of the Forties Platform. The Central Graben fairway is constrained by rapid thinning and shale out on to the margins of the Forties Platform to the west and the Jæren and Sørvestlandet highs to the east (O’Connor & Walker 1993). Sediment thickness and distribution have also been influenced by halokinesis along the eastern margin. In the Pierce Field (blocks 23/22a and 23/27), Forties deposition was controlled by the growth of two individual salt diapirs (Birch & Haynes 2003). A number of channels are mapped along the western edge of the Forties fairway in the Central Graben (Fig. 10). These channels extend eastwards into the main depositional area, suggesting the sands may be sourced from an eroded shelf area on the Forties Platform to the west (Bowman 1998). The sandstones also shale out southeastwards into basinal mudstone.

In the South Viking Graben, Skadan sandstones are preserved in small basin-floor fans along the graben margin fault (Knox & Holloway 1992). Further north on the East Shetland Platform, a network of deep incised valleys is associated with the Near Top Paleocene and Intra–Upper Thanetian unconformities (Underhill 2001). These cut down into Forties and Dornoch shelf sediments and have coarse fluvial fills succeeded by fine-grained intertidal estuarine backfill deposits. These channels link eastwards across the platform margin fault to channelized slope and basin-floor fan deposits of the Teal Sandstone Member in the Beryl Embayment and Frigg Field area of the South Viking Graben (Fig. 10). In the East Shetland Basin, the lower Dornoch Formation is represented by a prograding shelf package of siltstones and argillaceous sandstones. Further north, the Forties sequence is missing, probably removed during later Dornoch and Balder uplift.

**Dornoch and Sele sandstones**

The Dornoch/Forties sequence boundary is marked by the regional e0 high-gamma mudstone (Fig. 3).
The Dornoch sequence represents a continuation of early Eocene Forties sandstone distribution and facies, with shelf and coastal margin sediments accumulating along the eastern margins of the East Shetland and Forties platforms, and slope/basin channel and fan sands deposited in the basins to the east (Fig. 11). However, the sand-rich shelf deposits, which belong to the upper Dornoch Formation, are much thicker and more extensive than those of the Forties sequence, while in the Central Graben the Forties basin-floor fan system is replaced by a series of narrow sand-filled channels. Dornoch slope/basin sediments, which comprise laminated, occasionally tuffaceous, mudstones and sandstones, are placed in the upper Sele Formation. The sandstones have been assigned to the Cromarty, Flugga and upper Hermod members (Knox & Holloway 1992; Mudge & Copestake 1992).

The upper Dornoch Formation comprises thickly bedded upward-coarsening sandstone units with interbedded siltstones, mudstones and occasional lignites (Mudge & Copestake 1992). Seismic data show that the Dornoch clastics form a prograding wedge that downlaps to the east along a front extending from the Forties Platform across the western Moray Firth and along the margin of the East Shetland Platform as far north as the East Shetland Basin (Rochow 1981; Stewart 1987; Jones & Milton 1994). In the Moray Firth the formation subcrops westwards beneath a transgressive lignite unit that gives rise to a near-horizontal high-amplitude seismic event (Bowman 1998). Further north, wells drilled in Block 9/3 on the East Shetland Platform contain sandstones interpreted as distributary channels and beach ridges deposited on an easterly prograding wave-modified delta (Ahmadi et al. 2003). In the East Shetland Basin, the shelf fairway is limited to the west by erosional truncation and to the east by shale out into upper Sele mudstone.

In the Moray Firth and along the western margin of the Central Graben, the upper Sele argillaceous facies represents progradational slope deposition.
It contains channel sandstones belonging to the Cromarty Sandstone Member. A series of sand-rich slumps and channels have been drilled to the east of the shelf break along this trend; the northern sandstones can be linked to the nearby upper Dornoch shelf, but along the Forties Platform margin to the south, the shelf deposits have not been preserved and the channels are isolated. Flugga and upper Hermod sandstones are present in the South Viking Graben, forming slope channel and basin fan deposits along the line of the graben margin fault as far north as the North Viking Graben (Fig. 11).

In the Beryl Embayment to the east of the Dornoch shelf break and the platform margin fault, the Dornoch sequence is represented by a zone of chaotic seismic reflectors indicative of slope failure and submarine reworking within a slope setting. Two large-scale channels containing upper Hermod sandstones are mapped within this zone. A large upper Hermod fan is also mapped in the North Viking Graben.

Beauly and Balder sandstones

The lower Ypresian Balder and Dornoch sequences are separated by the e1 high-gamma mudstone (Fig. 3). The Balder sequence shows a similar distribution of shelf and slope/basin facies, but the sedimentary succession is thinner and shelf sandstones are absent in the East Shetland Basin and northern part of the Beryl Embayment (Fig. 12). The shelf and coastal margin deposits comprise sandstones interbedded with silty mudstones and lignites, which are placed in the Beauly Formation (Mudge & Copestake 1992b). Lignite beds more than 10 m in thickness commonly occur at the base and top of the formation in the Moray Firth. Here, the upper lignite produces a high-amplitude seismic event defining the upper surface of a basinward-downlapping wedge of shelf/coastal margin sediments that shale out eastwards into tuffaceous mudstones of the lower Balder Formation (Bowman 1998). These tuffaceous beds are widely distributed.
in the North Sea Basin and are overlain by a thin upper Balder mudstone that oversteps the Beauty and Dornoch formations westwards, coming to rest unconformably on the Lista Formation on the East Shetland Platform. The top of the Balder sequence is marked by a well-defined high-gamma log peak ($e^2$) representing the basal Eocene transgressive maximum.

The Balder argillaceous facies contains local developments of Odin sandstone. In the South Viking Graben, these sandstones were deposited in localized, small-scale basin-floor fans along the line of the graben margin fault and further north in the Beryl Embayment. Massive Odin sandstones preserved in areally restricted, steep-sided mounds have been drilled in Harding Central and South fields in the Beryl Embayment between the platform margin fault and the Crawford Spur. Seismic data in this area display a series of individual sandbodies located within a strongly linear north–south fairway, suggesting control by basement structure (Beckly et al. 2003). In the Gryphon Field (Block 9/14) along trend to the north, similar isolated pod-like sandstone bodies are present within a series of sinuous channelized fairways extending eastwards from the platform margin fault (Timbrell 1993). The location of these channel deposits adjacent to the platform margin fault suggests local derivation from reworked Beauty shelf sandstones carried into the Beryl Embayment.

### Upper Danian depositional environments

The Danian depositional history of the NE Atlantic–North Sea region reflects a transition from carbonate to siliciclastic sedimentation. A broad intracontinental seaway connecting the Atlantic and Arctic oceanic provinces extended northeastwards between Greenland and northern Europe (Fig. 13). Open marine circulation reached the North Sea Basin, which was separated structurally from this...
seaway by the Møre–Trøndelag Fault Zone. This long-lived feature continued southwestwards to form the faulted margins of the West Shetland and Outer Hebrides platforms. Igneous activity was initiated in the Hebrides province with the emplacement of volcanic centres on Skye, Mull, Ardnamurchan and Rhum (Mussett et al. 1988; Ritchie & Hitchen 1996).

Uplift and erosion of the Scotland–Shetland hinterland also commenced during the late Danian, marking the start of the pre-break-up phase of regional tectonism and magmatism, with clastics being shed north-westwards across the shelf margins into the NE Rockall and Faroe–Shetland basins and eastwards into the North Sea Basin. Erosion of the Upper Cretaceous–lower Danian chalk and mudstone deposits covering much of the emerging East Shetland Platform led to deposition of reworked chalks and marls with minor sands in the North Sea Basin. There is also evidence for late Danian tectonic activity within the basin, with deposition of calcareous debris flows and slumps of reworked Ekofisk and Tor chalks in the South Viking Graben (O’Connor & Walker 1993). These deposits, which belong to the Maureen Reworked Unit, were derived from the adjacent Jæren and Utsira highs. The upper Danian beds contain rich, cosmopolitan assemblages of dinocysts and planktonic foraminifera indicating open marine conditions with oceanic connections (Mudge & Bujak 1996b). They rest on the Intra-Danian unconformity and belong to the Maureen I sequence (Fig. 3).

In the Faroe–Shetland Basin the shelf was much narrower, and small volumes of both shelf and deep-water fan sands were deposited, separated by the Judd Fault Zone. The basin sandstones are placed in the Sullom Formation, and the adjacent shelf sandstones, which contain abundant bioclastic debris, belong to the Ockran Sandstone Formation (Knox et al. 1997). The beds contain the same North Sea microfossil assemblages, but these are strongly diluted by plant debris, miospores and reworked Jurassic and Cretaceous palynomorphs, providing further evidence for late Danian uplift of the nearby shelf and land areas (Mudge & Bujak 2001). Upper Danian shelf and basin sands were also deposited along the faulted margin of the NE Rockall Basin and in the fault-controlled Kangerlussuaq Basin on the East Greenland margin (Larsen et al. 1999).
Selandian depositional environments

Selandian deposition in the NE Atlantic–North Sea region took place during the early pre-break-up phase of extension and uplift, with thick Maureen, Andrew and Vaila sands accumulating in the North Sea and Faroe–Shetland basins (Fig. 14). Igneous activity was concentrated in five areas along a narrow north–south zone: these are the East Greenland, Faroes, Munkagrunnur, Sula Sgeir and Hebrides volcanic provinces. Volcanism was accompanied by the eruption of basalt hyaloclastites, lavas and tuffs. Uplift and erosion of the Scotland–Shetland hinterland led to large quantities of sand being transported across the East Shetland and Forties platforms and deposited in extensive fan systems in the North Sea Basin. Here, tectonic activity was limited to north–south growth faulting and footwall uplift along the East Shetland Platform margin. In contrast, in the Faroe–Shetlands and NE Rockall, there is evidence for active rifting associated with growth faulting both within the basins and along their NE–SW margins (Dean et al. 1999; Waddams & Cordingley 1999). A narrow fairway of shelf sediments is predicted to have been deposited along the footwall of the Outer Hebrides–West Shetland fault system, while shelf sands are preserved on the footwall of the Judd Fault. Thick sandy fan deposits derived from point sources along the West Shetland Platform margin are preserved in the Faroe–Shetland Basin. In the SW part of the basin these Vaila sandstones have a net thickness of more than 600 m and may have been derived in part from the rising Munkagrunnur Ridge (Linnard & Nelson 2005). Vaila sediments in this area contain volcanioclastics, and the thin lava flows present on the northern flank of the basin suggest extrusion into shallow-water sediments (Ellis et al. 2009; Smallwood & Harding 2009). Tuffs and volcanioclastics, probably derived from the nearby Hebrides volcanic province, are also widely distributed in sediments of Vaila age in the North Rockall and NE Rockall basins.

Biostratigraphical analysis shows that the NE Atlantic seaway became increasingly restricted during the Selandian, leading to the Danian oceanic connection being severed between the NE Rockall and Faroe–Shetland basins (Mudge & Bujak 2001). This restriction was associated in part with

Fig. 14. Selandian depositional environments, North Sea, and NE Atlantic margin basins. Greenland shown in 59.2 Ma position; no palinspastic reconstruction of northern Europe basins. Only sands proved by drilling are shown. DP, Darwin Platform; SSVP, Sula Sgeir volcanic province; SSH, Sula Sgeir High. For other abbreviations see Figure 1.
the development of a broad shelf connected to the Faroe Platform and Møre Marginal High to the north and bounded to the SE by a SW–NE line of faulted highs including the Darwin Platform and Corona High. The formation of these highs may have been associated with rift margin uplift reactivating the old Caledonian fault system. At the same time, this SW–NE trend was overprinted by the north–south zone of thermal uplift and volcanism extending from East Greenland to the Hebrides. In the Munkagrunnur Ridge–Sula Sgeir High area, uplift led to the formation of a narrow shelf separating the deep-water Faroe–Shetland and NE Rockall basins. This strong north–south trend, which is displayed by the faulting in this area, is also seen in the Viking Graben and Rockall Basin. It has been interpreted as having a Jurassic origin by Dean et al. (1999) and Keser Neish (2005).

Thanetian depositional environments

The Mid-Paleocene unconformity marking the Selandian/Thanetian boundary is a regional uplift event that can be recognized throughout the NE Atlantic basin system and as far south as SE England (Powell et al. 1996; Mudge & Jones 2004). In the North Sea Basin it is associated with the influx of Balmoral and Heimdal sands deposited in a predominantly basinal setting (Fig. 15). The Lamba sands in the Faroe–Shetland Basin accumulated in a similar deep-water environment, but here, shelf sediments, including sandstones, have also been preserved along both margins of the basin. Reworked Glamis tuffs resting on the unconformity in the Moray Firth can be correlated with Kettla tuffs in the Faroe–Shetland Basin (Mudge & Bujak 2001). Younger Lamba tuffs are also present in the SW part of the basin.

Balmoral and Lamba tuffs are associated with a second, more extensive phase of pre-break-up volcanism of Thanetian age that included the emplacement of new volcanic centres on the Faroe and Outer Hebrides platforms and the Møre Marginal High, associated with the widespread eruption of basalt hyaloclastites and lavas (Fig. 15). By late Thanetian time, thermal uplift and lava eruption had completely closed the seaway between the

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Fig. 15. Thanetian depositional environments, North Sea, and NE Atlantic margin basins. Greenland shown in 56 Ma position; no palinspastic reconstruction of northern Europe basins. Only sands proved by drilling are shown. WLR, West Lewis Ridge. For other abbreviations see Figure 1.
Munkagrunnur Ridge and Sula Sgeir High, leading to a change to non-marine conditions in the SW Faroe–Shetland Basin. The trace of this north–south zone of uplift can be seen on both magnetic and gravity anomaly maps (Kimbell et al. 2005; Ritchie & Ziska 2011), in the north–south faults bounding the Munkagrunnur Ridge and in the reverse faults associated with the Sula Sgeir High and West Lewis Ridge, dated as Thanetian by Tuitt et al. (2010).

The thick fan deposits of Balmoral and Heimdal sands in the North Sea Basin were derived from erosion of the uplifted Scotland–Shetland hinterland to the west. Sand thickness mapping provides evidence for growth faulting along the north–south South Viking Graben–East Shetland Platform en echelon fault system, with a new sand depocentre forming in the East Shetland Basin (Fig. 9). Rifting continued into the Thanetian in the Faroe–Shetland Basin with NE–SW growth faulting within the basin and along its margins. The deep-water sands in the basin were deposited in a narrow fairway extending NE along the axis of the basin; again, these may have been sourced in part from the uplifted Munkagrunnur Ridge.

**Upper Thanetian–Lower Ypresian depositional environments**

Late Thanetian–early Ypresian deposition in the NE Atlantic–North Sea region took place during the syn-break-up phase of tectonism and magmatism, which was dominated by volcanism along the NE Atlantic margin. The North Sea, Møre and Faroe–Shetland basins became isolated from the North Atlantic with only long-distance marine connections to the Arctic and Tethys available (Figs 16–18). This marine restriction, which is represented by a succession of dinocyst and agglutinated foraminiferal extinction events and their replacement by diatom-dominated assemblages, was initiated at the Intra–Upper Thanetian unconformity marking the Lista/Forties sequence boundary (Fig. 3; Mudge & Bujak 2001). At this time, a change from rifting to non-marine fluvio-deltaic passive infill took place in the SW Faroe–Shetland Basin and to anoxic marine sedimentation in the NE Faroe–Shetland, North Sea and Møre basins, while the North Rockall and NE Rockall basins remained connected to North Atlantic oceanic circulation.

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**Fig. 16.** Upper Thanetian–Lower Ypresian depositional environments, North Sea, and NE Atlantic margin basins. Greenland shown in 54 Ma position; no palinspastic reconstruction of northern Europe basins. Only sands proved by drilling are shown. For abbreviations see Figure 1.
The early Ypresian marked the time of maximum uplift and volcanism in the NE Atlantic and North Sea depositional provinces. In the North Sea, continued uplift accompanied by eastward tilting of the Scotland–Shetland hinterland led to accumulation of laterally extensive, prograding lower Dornoch, upper Dornoch and Beauly shelf/coastal margin deposits fringing the Forties and East Shetland platforms. Uplift also occurred along the Møre–Trøndelag Fault Zone where Balder mudstones rest unconformably on the Lista Formation. Sand thickness mapping of the Forties sequence in the North Sea Basin shows that a large volume of channel/fan sands was deposited in the Central Graben, with smaller volumes of slope/basin sands accumulating in the Viking Graben where there is evidence for continuing control of sand distribution and facies along the western graben margin faults (Fig. 10). The Dornoch and Balder sequences show the same depositional pattern but with thicker accumulations of upper Dornoch and Beauly shelf sands and much reduced volumes of slope/basin sands in the Moray Firth and Central Graben (Figs 11 & 12).

The SW Faroe–Shetland Basin became filled with fluvio-deltaic deposits belonging to the Flett and Balder formations. These lignite-bearing sediments interdigitated northwards with shoreline sands in a narrow coastal zone extending from the West Shetland Platform to the Corona High. An area of deeper-water muds with slumped sandbodies lay to the NE of the shelf break. The marine sands are assigned to the Colsay and Hil-dasay Sandstone members (Knox et al. 1997).

Late Thanetian–early Ypresian deposition was strongly affected by a major shift in the nature and distribution of igneous activity on the NE Atlantic margin with the extrusion of a thick pile of flood basalts that covered the Faroe Platform and Møre Marginal High (Passey & Hitchen 2011). This second phase of volcanism, which was associated mainly with fissure eruptions, marked the start of continental break-up between Greenland and northern Europe. Basalt lavas with a distinctive oceanic geochemistry flowed northwards across the Greenland margin and southeastwards into the Faroe–Shetland Basin. New volcanic centres formed on the Erlend High to the north of the Shetlands and thick lavas were extruded across the Outer Hebrides Platform. The NE–SW Caledonoid strike of these syn-break-up lavas, which parallels the Paleocene rift trend in the Faroe Shetland–NE Rockall basin.
system, contrasts with the north–south trend of the earlier lavas and volcanic centres that formed during the pre-break-up volcanic phase.

Discussion

The main objective of the sand thickness and depositional environment mapping presented in this paper is to provide the regional context for more detailed evaluation of Lower Tertiary fan sandstones in the North Sea at the field and play fairway scale. These maps, which are based on a large interpreted well database, illustrate changing patterns of sand distribution and facies that correlate with the stratigraphic record of regional unconformities, flooding surfaces, and the microfossil acmes and extinctions seen in well sections. The maps and well data have also been used to examine the influence of tectonic and thermal events on early Tertiary basin development and sand distribution in the North Sea.

The timing and origin of these events is linked to extension, uplift and volcanism associated with two tectonomagmatic phases in the Paleocene–early Eocene that preceded plate separation in the NE Atlantic at c. 54 Ma (Lundin & Döré 2005; Passey & Hitchin 2011). The impact of these processes was less marked in the more distal North Sea Basin than in the Faroe–Shetland and other NE Atlantic margin basins, which were located close to the line of break-up. As a consequence, much more information has been published on Paleocene–early Eocene deposition and volcanism in these proximal basins (see Ritchie et al. 2011 for a useful summary of this literature).

The Faroe–Shetland and North Sea depositional provinces are separated by the Scottish mainland and its northern continuation in the Orkney and Shetland Islands, flanked by broad areas of platform and underlain by Precambrian and Caledonian metamorphic basement with a partial cover of Devonian and younger rocks. The regional uplift affecting this shared hinterland during the Paleocene–early Eocene led to large volumes of clastics being shed into the North Sea and Faroe–Shetland basins. Biostratigraphical dating of the unconformities associated with this uplift shows that they are the same age in both basins and are overlain by sandstones (Mudge & Bujak 2001). The presence

Fig. 18. Lower Ypresian (Balder) depositional environments, North Sea, and NE Atlantic margin basins. Greenland shown in 54 Ma position; no palinspastic reconstruction of northern Europe basins. Only sands proved by drilling are shown. NERB, NE Rockall Basin. For other abbreviations see Figure 1.
of intervening mudstones containing maximum flooding surfaces that are also synchronous, demonstrates that the uplift was not a single event but occurred in a series of pulses separated by periods of subsidence and transgression (Mudge & Jones 2004). The occurrence of the same succession of microfossil extinction and acme events in both basins during the Paleocene–early Eocene indicates that they shared a marine connection, probably via a narrow seaway around the Margarita’s Spur (Mudge & Bujak 2001).

This paper shows that the sand thickness distributions for five Paleocene–Lower Eocene stratigraphic intervals in the North Sea Basin display a close relationship with pre-existing structural features. These include the north–south South Viking Graben and East Shetland Platform margin faults, the Halibut Horst, and the north–south line of intrabasinal Utsira, Jæren and Sorvetsylandet highs. Three broadly defined areas of sand deposition are identified: Moray Firth–Central Graben, South Viking Graben–Beryl Embayment and East Shetland Basin (Fig. 1).

The Moray Firth–Central Graben was the most important locus for North Sea fan sand deposition with development of the Maureen–Andrew, Balmoral and Forties sand systems during Selandian to early Ypresian time (Figs 8–10). Although sand deposition occupied broadly the same area of the Central Graben during this period, a significant decline in clastic input can be seen in the Moray Firth. Here, the maximum areal extent and volume of sand occurred during the Selandian, followed by a progressive shrinking of the depositional area from the west until the early Ypresian, when the Forties fan sand fairway was connected by a narrow sand-filled channel to the eroded remnants of a shelf and coastal margin wedge extending across the Moray Firth. At the same time, the appearance of sand-filled channels along the western margin of the Central Graben fairway suggests increasing clastic input from the Forties Platform to the west.

Structural control of sand deposition was widespread in the Moray Firth–Central Graben area during the Selandian–early Ypresian, although there is no evidence for active faulting (Fig. 4). Sediments thin dramatically over the Fladen Ground Spur, which separated the depositional systems of the Moray Firth–Central Graben and Beryl Embayment–South Viking Graben, while the Halibut Horst had a similar influence on deposition within the Moray Firth. This basement high became a sediment bypass zone, diverting clastic input into northern and southern fairways. Deposition was also constrained by the line of intrabasinal highs marking the eastern margin of the Central Graben.

However, there is clear evidence for active faulting along the north–south margins of the South Viking Graben and Beryl Embayment (Figs 8 & 9). The Maureen sand depocentre, which formed in the Beryl Embayment in the hanging wall of the East Shetland Platform margin during the Selandian, switched to the South Viking Graben during the Thanetian with thick Heimdal sand deposits banked up against the graben margin fault (Fig. 5). The presence of incised, sand-filled Maureen channels on the East Shetland Platform suggests contemporaneous footwall uplift, which jumped eastwards to affect the South Viking Graben margin during Heimdal sand deposition. A new Heimdal sand depocentre also formed in the hanging wall of the East Shetland Platform margin fault in the East Shetland Basin during the Thanetian, representing the northernmost extent of Lower Tertiary fan deposition in the North Sea. Paleocene sand deposition reached its maximum areal extent during the Thanetian. Although the accumulation of thick Forties sands continued into the early Ypresian in the Central Graben, these deep-water deposits represent the last major input of sand into the North Sea Basin (Fig. 10).

The Maureen–Andrew and Balmoral/Heimdal sandstones correlate with the Lower–Upper Vaila and Lamba sandstones in the Faroe–Shetland Basin (Fig. 7). These sand systems overlie the Near Top Danian and Mid Paleocene unconformities in both basins, suggesting that they were associated with the same two uplift events in the Scotland–Shetland hinterland. Synchronous pauses in uplift are suggested by the presence of the coeval Cenodiscus mudstone and upper Lista/upper Lamba mudstones in both basins (Fig. 3).

The NE–SW rifting that controlled Vaila–Lamba sand deposition in the Faroe–Shetland Basin took place during the Paleocene pre-break-up phase of continental separation in the NE Atlantic between 62 and 56 Ma (Fig. 3). A well profile across the central Faroe–Shetland Basin illustrates the narrowness and depth of the rift zone, which contains 2.4 km of Paleocene–early Eocene sediments in 214/27-1A (Fig. 6). Extension was accompanied by Danian–Selandian volcanism, which was confined to a narrow north–south zone extending from East Greenland to the Hebrides and southwards to Northern Ireland (Fig. 14). During the Thanetian, new volcanic centres developed away from this line on the Møre Marginal High and on the Darwin and Outer Hebrides platforms (Fig. 15).

The synchronicity of fault activity, depositional events and development of unconformities in the Faroe–Shetland and North Sea basins, together with the complicated geographical distribution and different ages of sand entry points and depocentres, suggest a tectonic origin for Danian–Thanetian uplift of the Scotland–Shetland hinterland. Both margins of the uplift area are also faulted and
associated with narrow, deep rift basins (Figs 5 & 6). This conflicts with the commonly held view that hinterland rejuvenation is linked to uplift induced by a thermal anomaly (mantle plume) that developed beneath a proto-Iceland during the Danian (White & McKenzie 1989; Saunders et al. 1997; Ritchie et al. 2011). It is difficult to see why underplating should have caused uplift of the Scotland–Shetland area at the same time as the Faroe–Shetland Basin, positioned between the hinterland and the developing plume, was undergoing rapid extension-related subsidence (Doré et al. 1999). The restriction of the main area of Danian–Thanetian thermal uplift and volcanism to a narrow north–south zone located west of the Scotland–Shetland hinterland is also incompatible with the concept of a thermal dome some 2000 km in diameter being responsible for this uplift (Coffin & Eldholm 1992). An alternative view is that this cross-cutting feature forms the segment of a linear volcanic zone that extends from Baffin Island through the northern and western British Isles, possibly as far as the Massif Central in France (Lundin & Doré 2005).

The transition between the pre-break-up and syn-break-up phases of plate separation is marked by the cessation of basin rifting and the start of voluminous extrusion of lavas along the NE Atlantic continental margin. This transition is seen in Faroe–Shetland Basin wells, which contain two unconformities occurring close to the Thanetian/Ypresian boundary that separate the non-marine and marginal marine Flett Formation from underlying marine Lamba Formation sediments (Fig. 3). The change from marine to non-marine deposition has been attributed to uplift associated with the break-up volcanism (Lamers & Carmichael 1999; Smallwood & Gill 2002), but the restriction of non-marine sediments to the SW Faroe–Shetland Basin, with the NE part of the basin remaining marine, suggests that pre-break-up uplift and volcanism along the Munkagrunnar Ridge–Sula Sgeir High was responsible for severing the connection with NE Atlantic oceanic circulation so that only marine waters from the Møre and North Sea basins were able enter from the NE (Mudge & Bujak 2001). The dating of this uplift and closure is confirmed by the succession of microfossil extinctions seen in SW Faroe–Shetland wells, which shows that basin restriction started in the late Danian but was not complete until the end of the Thanetian (Mudge & Bujak 2001). In the Faroe–Shetland Basin, the syn-break-up phase was terminated by the Basal Eocene transgression recorded in wells by the e2 high-gamma mudstone at the top of the Balder Formation (Fig. 3). However, marine connections to the NE Atlantic via the NE Rockall Basin were not fully restored until after the Eocene.

In contrast to the Faroe–Shetland Basin, the North Sea Basin remained fully marine during the early Ypresian syn-break-up phase. However, the pre-break-up/syn-break-up transition is marked by a significant reorganization of basin architecture and depositional patterns near the Thanetian/Ypresian boundary. This change to syn-break-up passive infill, marked by the same late Thanetian unconformities recorded in the Faroe–Shetland Basin, resulted in the accumulation and preservation of a broad prograding wedge of Dornoch and Beauty Formation sediments along the western margin of the basin (Figs 10–12). Tilting and subsidence of this margin, coinciding with a reduction in hinterland uplift and the cessation of active faulting, led to the build-up of shelf and shoreline deposits, and a reduction of sand supply to the basin (Galloway et al. 1993). The contrast between Thanetian and early Ypresian deep-water sand distribution is also dramatic. While the Forties sand system represents a continuation of Balmoral fan sand deposition in the Central Graben, the thick Selandian–Thanetian sands of the Moray Firth, Beryl Embayment–South Viking Graben and East Shetland Basin are replaced by small, locally distributed slope/basin channel and fans (Fig. 10). By Dornoch–Balder time, deep-water sand deposition over the whole North Sea Basin was reduced to isolated channels and small fans (Figs 11 & 12), representing the final deposits of the syn-break-up phase in this area.

If a tectonic cause is attributed to pre-break-up uplift of the Scottish–Shetland hinterland, it is interesting to speculate on the nature of this uplift. Plate reconstructions for the NE Atlantic region show that major NW–SE extension occurred between Greenland and northern Europe during the Paleocene–early Eocene prior to continental break-up (Mosar et al. 2002). This extension led to active rifting in the NE Atlantic margin basins, controlled by reactivation of the long-lived NE–SW Møre–Trøndelag Fault Zone and other Caledonian faults forming the margins of the deep Faroe–Shetland and NE Rockall basins (Kimbell et al. 2005). In contrast, rifting is confined to north–south faulting along the western margins of the South Viking Graben, Beryl Embayment and East Shetland Basin in the northern part of the North Sea Basin (Fig. 1). The Scotland–Shetland hinterland separating these two depositional provinces also contains major Caledonian shear zones, including the Great Glen and Walls Boundary faults, which show close affinity with the Møre–Trøndelag Fault Zone. It is likely that this Caledonian fault system acted as an accommodation zone protecting the North Sea Basin from the effects of pre-break-up extensional forces along the NE Atlantic margin (Doré et al. 1997). At the same time the sub-parallel trends of the Walls Boundary Fault and the intermittently
active northern North Sea Basin margin faults suggest that lateral and vertical movements within the fault system may have provided the mechanism for uplift of the Scotland–Shetland hinterland.

This pre-break-up phase of limited volcanism associated with widespread fault activity and rapid hinterland uplift was replaced at the end of the Thanetian by the much more extensive and voluminous volcanism of the syn-break-up phase. Rifting was displaced westwards to become concentrated in the break-up zone, while regional uplift affected both the Faroe–Shetland Basin and the neighbouring hinterland. The proximity of the early Eocene line of plate separation suggests that the magmatism may have been an upper mantle response to continental extension and break-up leading to rifting, volcanism and uplift (Doré et al. 1999; Lundin & Doré 2005; Stoker & Varming 2011). At the same time, the slower rate of uplift allowed early Ypresian shelf systems to become established along the western margin of the North Sea Basin.

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