Mixed deep- and shallow-water depositional model for the Forties Sandstone Member in the South Central Graben, North Sea

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Dreyer, T., Bujak, J, Brunstad, H., Ramberg, J. & Søyseth, L.: Mixed deep- and shallow-water depositional model for the Forties Sandstone Member in the South Central Graben, North Sea. *Norwegian Journal of Geology*, Vol. 84, pp. 191-233, Bergen 2004. ISSN 029-196X.

The Upper Paleocene Forties Sandstone Member is a prolific hydrocarbon reservoir in the Southern North Sea. It has for decades been regarded as a 'classic' submarine fan depositional system, containing mainly high-density turbidites formed during a period of coeval tectonic uplift of the East Shetland Platform and lowstand deposition in basinal areas to the south and east. This view is partly challenged by the sedimentological, palynostratigraphical, and 3D seismic data presented in this study. A revised model is proposed in which the Forties Sandstone Member in the South Central Graben is interpreted as a deep-marine depositional system, which due to the presence of intra-basinal topographic highs locally was transformed into a more shallow-marine setting. Within the study area, several fault trends and a number of salt diapirs can be shown to have been active during deposition, and marginal- to shallow-marine conditions may have developed in association with these tectonic elements. The sub-basins between the highs became sites of rapid sedimentation of slope to basin plain turbiditic successions. Non-marine to nearshore palynofacies and the presence of root traces and wave-formed structures are the prime indicators of nearshore conditions, with the presence of presumed shallow-water trace fossils and seismic clinoforms possibly indicative of shelf-to-slope transition being secondary arguments.

The shallow-marine lithosomes mainly formed in shoreline and shoreface environments that formed as rims around diapirs and fault block crests. They are sand-dominated and relatively thin, and have a more sheetlike reservoir geometry than their deeper-water counterparts. Hence, thickness anomalies are no longer a pre-requisite for postulating sand in plays involving the Forties Sandstone Member. Moreover, the presence of local coastlines several tens of kilometers east of where it was located in previous models increases the probability of Upper Paleocene reservoir development in the Norwegian sector of the Southern North Sea.

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Introduction

The South Central Graben in the North Sea is a mature hydrocarbon province traversing the UK-Norway sector boundary (Fig. 1). Many of the hydrocarbon discoveries in the area have been made within the Upper Paleocene stratigraphic interval, with the Forties Sandstone Member as the main reservoir unit (Mudge & Bujak 1996a,b). Despite the large amount of well and seismic data in the South Central Graben, no detailed sub-regional study of depositional conditions for the upper Paleocene succession has been published. On a more regional scale (den Hartog Jager et al. 1993; Vining et al. 1993) and in reservoir-scale studies of individual fields (e.g. Kessler et al. 1980), the Forties Sandstone Member and its time-equivalent deposits have been placed within a large-scale submarine fan system. Results based on examination of large amounts of seismic-, sedimentological-, and biostratigraphical data performed in the current study seem to be partly at odds with this established depositional model. Hence, it is the aim of the present paper to document a revised geological model for the Upper Paleocene succession in the South Central Graben. This model will be discussed within a high-resolution sequence stratigraphic framework, and its effect on hydrocarbon prospectivity in the Norwegian sector of the study area will be highlighted.

Our database includes wireline logs from all of the wells on Fig.1, sedimentological core descriptions and biostratigraphic data from those wells marked with a blue circle, 3D seismic surveys covering all of the Norwegian part of the study area and also the neighbouring blocks on the UK side, and a number of N-S and E-W oriented 2D seismic lines extending across the entire study area.

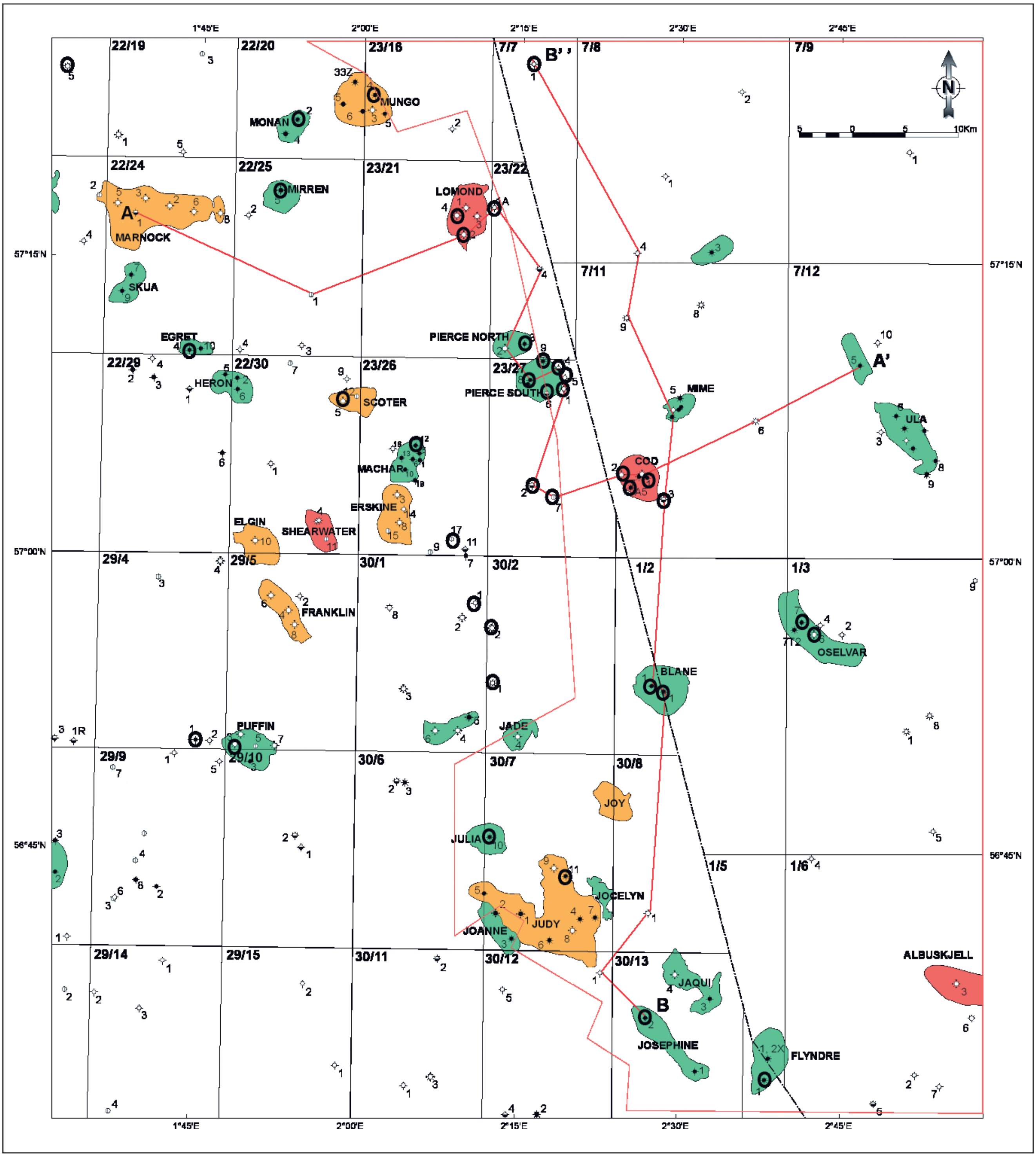


Fig. 1. Study area in the southern North Sea. Oil fields in green, gas fields in red, condensate fields in yellow. The orange frame shows the area where 3D seismic data was available, while the circles around some of the wells indicate cores investigated in the present study. Correlation lines A-A' and B-B' will be discussed in the text.

Geological setting

The area of interest in the present study lies in the Central North Sea, more specifically in the East Central Graben, bounded by the Jæren High and Hidra High to the east and the Forties-Montrose High and the Josephine High to the west-southwest (Fig. 2). In the greater study area, the Central Graben is split into two branches, commonly referred to as the West Central Graben and East Central Graben, with the shallower Feda Graben taking over as the branches start to merge towards the south. The East Central Graben represents the main Paleocene depocentre in the study area, and contains several sub-basins due to the presence of

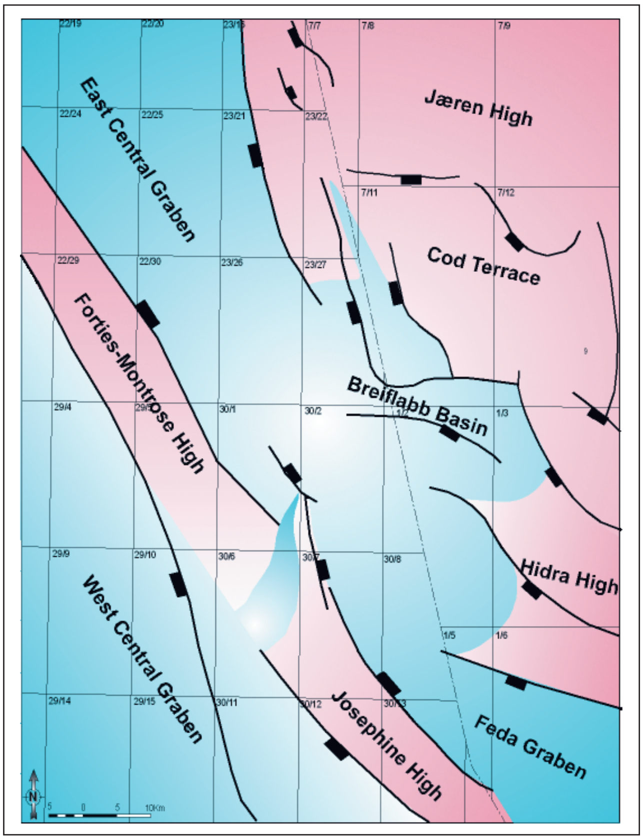


Fig. 2. Main Paleocene structural elements of the study area. Blue areas are deep, pink areas are shallow, shading gives an indication of relative structural amplitude. The various sandstone members are shown in orange.

smaller-scale structural elements such as faulted terraces and salt diapirs.

A stratigraphic scheme of the Paleocene to lowermost Eocene sediments in the study area is shown in Fig. 3. It is based on Isaksen & Tonstad's (1989) scheme for the Tertiary in the Central North Sea, although we prefer to display the sandstone units within the Våle, Lista, Sele and Balder formations as members since they occur as local to semi-regional 'sandstone tongues'. The sequence stratigraphic subdivision employed in the current study is also outlined on Fig. 3, and will be discussed in a later section. At the base of the studied succession (red box), burrowed greenish grey to red mudstones of the upper part of the Lista Formation occur. This interval corresponds to the top of the Andrew Formation of the British sector. Locally, the mudstones are interbedded with intraclast breccias and massive to parallel stratified sandstones believed to have formed in a submarine fan setting (e.g. Pauley 1995; Holmes 1999). However, one of these sandstone units, occurring in association with the Forties-Montrose High, is remarkably thin and laterally continuous, and may have a different origin than the turbiditic sandstones and mass-flow breccias seen elsewhere in the Lista Formation (see discussion below).

The Sele Formation is a dark grey laminated mudstone which in the study area contains numerous cm- to dm-thick sandstone beds. Where these amalgamate into thicker sandstone-dominated units, the stratigraphic term member is employed. Three such units have been recognized in the Sele Formation: the Forties Sandstone Member (Forties Formation of the British sector, belongs to the T70 cycle), the Hermod Sandstone Member (general name for sands of T80 cycle in the Norwegian sector), and the Fiskebank Sandstone Member (local name for T80 sands in the south-eastern part of the Norwegian sector). Locally in the Norwegian sector, an intra-Sele chalk deposit (re-sedimented, see below) is present. Some tuff layers are present in the Sele Formation, but these deposits only become abundant in the overlying Balder Formation.

The studied succession (red box on Fig. 3) has traditionally been interpreted as the distal part of a large submarine fan system, with uplifted areas and shelfal systems associated with the East Shetland Platform as the main source for clastic sediments (Thomas et al. 1974; Kessler et al. 1980; Kulpecz & van Geuns 1990; Carman & Young 1981; Stewart 1987; den Hartog Jager et al. 1993; O'Connor & Walker 1993; Vining et al. 1993; Pauley 1995; Galloway 1998). A shelf-slope passive margin setting is invoked by most of these workers, with a broad deep marine basin plain occupying the present study area. However, this simple model has some discrepancies when observations of syn-sedimentary tectonism in the Paleocene North Sea Basin are taken into account. This tectonism, which led to large-scale uplift of the source area to the east, occurred in association with the Thulean volcanic phase and the opening of the Atlantic Ocean (Nadin & Kusznir 1995; Mudge & Bujak 1996b; den Hartog Jager 1993). Moreover, this Late Paleocene tectonic pulse is believed to have triggered fault reactivation and a complex pattern of differential subsidence in the greater North Sea Basin (i.e. O'Connor & Walker 1993; Vining et al. 1993; Dore & Jensen 1996; Clausen & Huuse 1999). In eastern parts of the study area, listric normal faults within the Paleocene succession are seen in association with old Mesozoic down-to-the-west detachment zones at the boundary to the Jæren High and at the transition to the Breiflabb Basin and East Central Graben (Fig. 2). This Late Paleocene faulting seems to have led to rotation of the Cod Terrace towards the east, with the highest structural elevation along the western fault zone and a low-gradient dipslope towards minor depocentres along the eastern fault zone. As a result, conditions of increased subsidence and perhaps greater water depth are likely to have developed in the immediate hangingwall of these faults. Conversely, a series of bathymetric highs developed on the western margin of the Cod Terrace, arranged in an en echelon fashion along the three main fault strands west of the Cod and Lomond Fields and

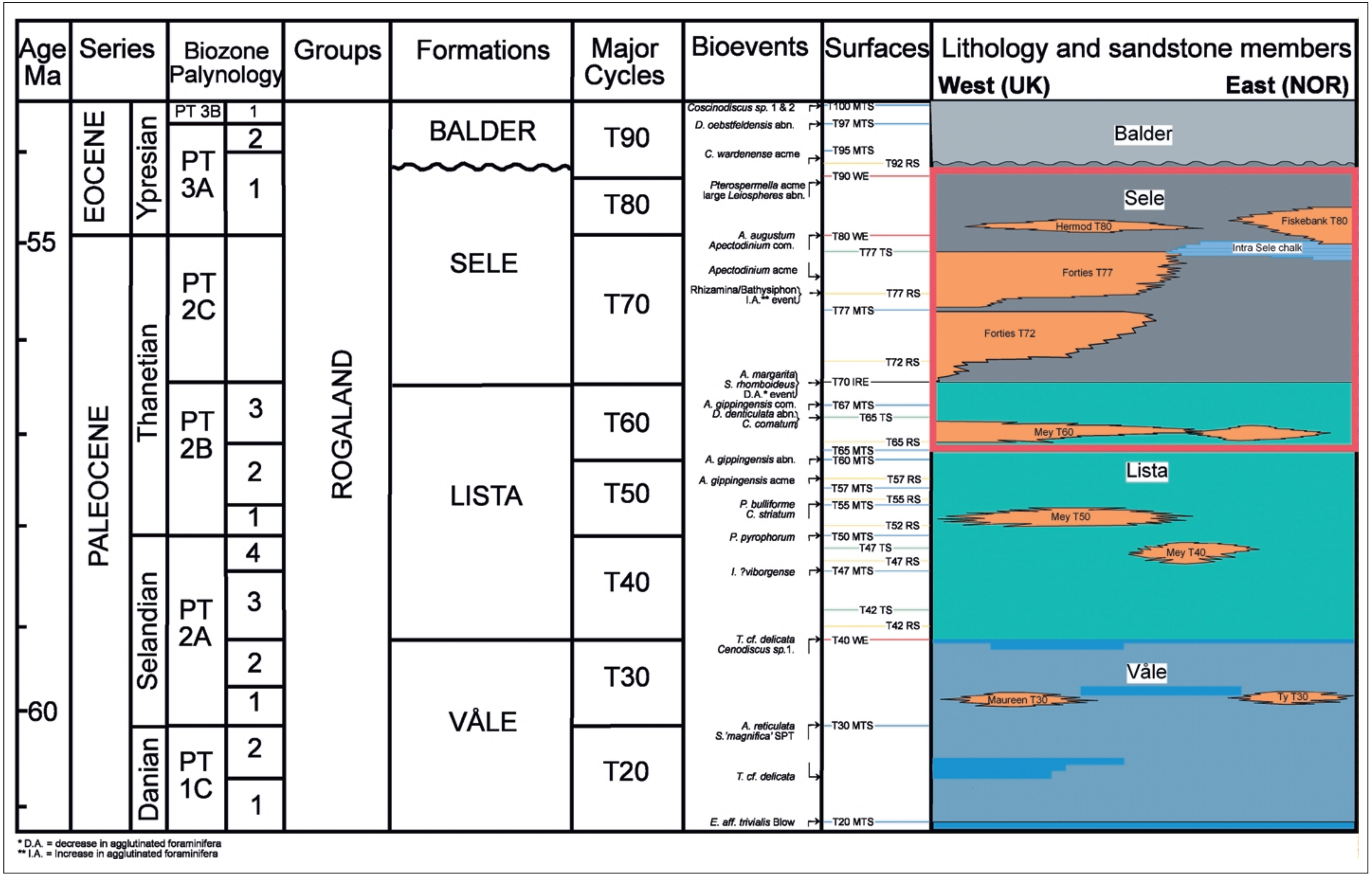


Fig. 3. Lower Tertiary stratigraphy in the study area, with columns for lithostratigraphy, sequence stratigraphy and bioevents. The red box indicates the part of the succession mainly focused on in this paper.

cutting through the Pierce Field. Reduced accommodation and shallower water conditions are believed to have been associated with these crestal areas. Moreover, several salt diapirs in the study area can be demonstrated to have experienced substantial growth during the Late Paleocene (see Davison et al. 2000a, b). By reference to Fig. 1, diapirs with marked Paleocene growth are associated with the Cod, Pierce, Lomond, Mungo, Monan, Mirren, Erskine, and Machar Fields. The combined (and possibly linked) effects of basement uplift and salt diapir growth created a series of syn-depositional basins and highs that are evident on the correlation diagrams and the paleogeographic maps discussed below. On Fig. 2, the reddish colours indicate basement highs that experienced uplift and/or low rates of subsidence in the Late Paleocene, whereas the blue areas represent basinal areas with higher rates of subsidence during this period. The effects of this complex basin physiography relative to deep- and shallow-water depositional conditions will be discussed in a later section.

The paleo-oceanographic conditions of the Late Paleocene North Sea Basin have received a lot of attention in recent years. The two most important events affecting basin morphology and water chemistry were:

i) Semi-enclosure of several basins in the North Atlantic region, including the North Sea Basin, due to regional tectonic and volcanic events that formed sills and land bridges (Bujak & Brinkhuis 1998). This strongly influenced the basin configuration and biofacies, causing a morphologically complex basin markedly different from the previous passive margin setting (Fig. 4), and resulting in assemblages that became particularly endemic during the Late Paleocene.

ii) Global climatic changes resulted in a series of warming events during the Paleocene (Bujak & Brinkhuis 1998). The most significant of these was the late Thanetian warming event, closely associated with the boundary between the Lista and Sele formations. In the North Sea, a marked increase in kaolinite has been documented in cored sections in the lower part of the Sele Formation (Thomas 1993). This is accompanied by the first consistent North Sea occurrence of *Apectodinium*, contrasting with its occurrence in Tethyan strata of Early Selandian age (Brinkhuis et al. 1994). Bujak & Brinkhuis (1998) reviewed worldwide data on *Apectodinium* distribution and suggested that it was a warm-water Tethyan dinocyst that migrated worldwide into high latitudes during the Late Thanetian warming event, which can therefore be recognized in the Faeroe-Shetland and North Sea basins by the *Apectodinium* acme. According to Kennett & Stott (1991), the Late Thanetian warming event lasted at most several hundred thousand years. Its termination is reflected in mid to high latitudes by the disappearance of *Apectodinium*-dominated dinocyst assemblages (Bujak & Brinkhuis, 1998). However, the semi-enclosed nature of the North Sea Basin is reflected by the palynological and micropaleontological assemblages that continued to be highly restricted. The last occurrences of the *Apectodinium* acme and of *A. augustum* coincide with the top of the T70 sequence (see below) within the Sele Formation.

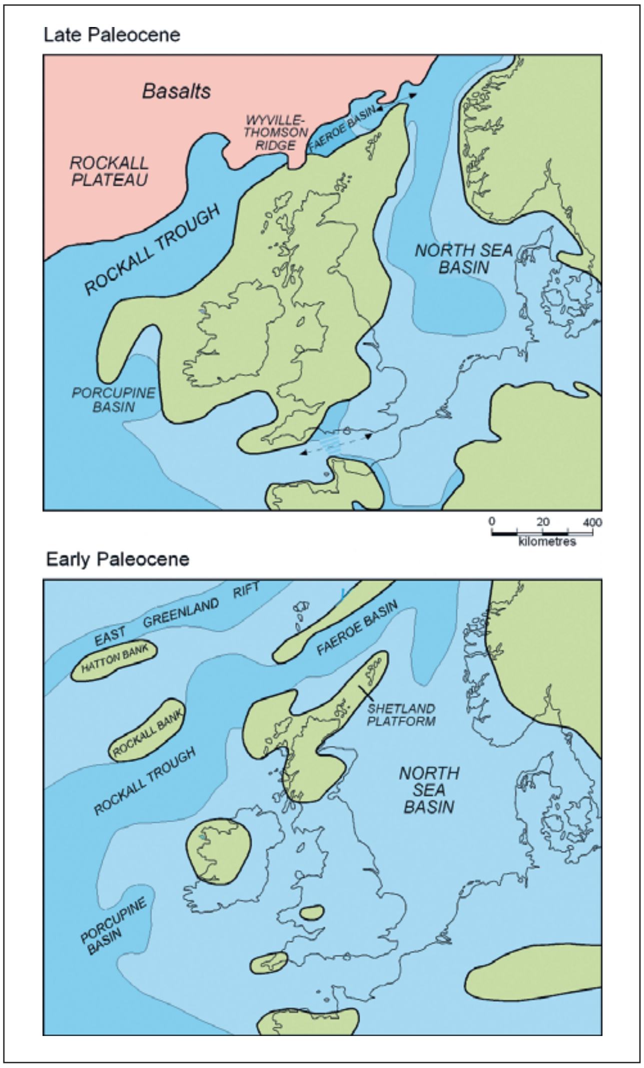


Fig. 4. Contrasting Paleocene palaeo-oceanographic maps. Green/red are landmasses, light blue areas reflect oxygen-rich water masses, whereas dark blue shows postulated areas with anoxic water masses.

Together, the Late Thanetian warming event and the semi-enclosed nature of the Late Paleocene North Sea Basin were responsible for what is termed the 'latest Paleocene to earliest Eocene biotic crisis' (Bujak & Brinkhuis 1998). The stratigraphic interval that formed during this biotic crisis is characterized by highly restricted and unusual marine assemblages encased in mudstones deposited in dysaerobic to anoxic conditions. The initial dysaerobic and subsequent anoxic bottom water conditions caused progressive benthic kill-off and increased the deposition of organic

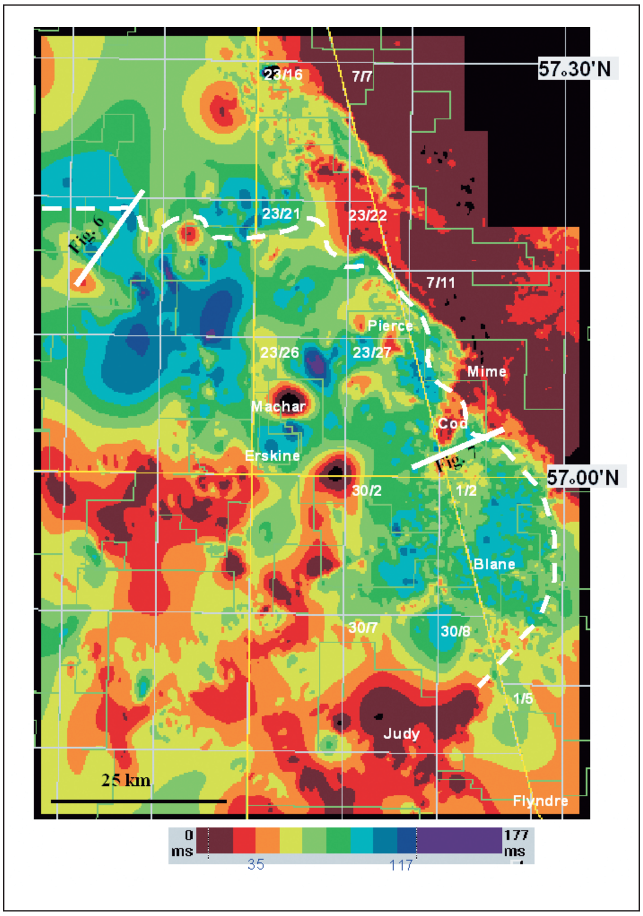


Fig.5. Time isopach map for the Forties Formation (top Lista to top Forties). Note large thickness variations controlled by structural configuration (compare with Fig. 2) and saltdomes (round areas with thin (reddish) isopach). The white stippled line shows the position of the front of the main clinoform breakpoint (see text for discussion).

remains, resulting in a shift to the relatively high gamma ray emission characteristic of the Sele Formation. When re-constructing the depositional model for the Upper Paleocene interval, the semi-enclosed basin configuration and the effects of the biotic crisis on biofacies and mudstone characteristics need to be taken into account.

Seismic observations

The seismic database consists of 3D coverage over all of the Norwegian part of the study area as well as the boundary region (see red box on Fig. 1), whereas the seismic database for the remainder of the UK sector for the most part consists of 2D seismic data of variable quality. The 2D survey CAST 89 is the key survey in the interpretation of the UK sector and the quality of this survey is good. Information from the cored UK wells, highlighted in Fig. 1, have been used when constructing the isopach maps, since the 2D grid on the UK side is very coarse and we needed additional data points in the map generation. The following reflectors have been interpreted over the whole area:

- Top Balder
- Top Forties
- Top Lista
- Top Chalk

The Top Balder and Top Chalk reflections vary in strength and phase but are nevertheless picked with confidence, especially in the 3D coverage area. The Top Forties and Top Lista reflections vary more in strength and character compared to Top Balder and Top Chalk, so the interpretation confidence is somewhat lower.

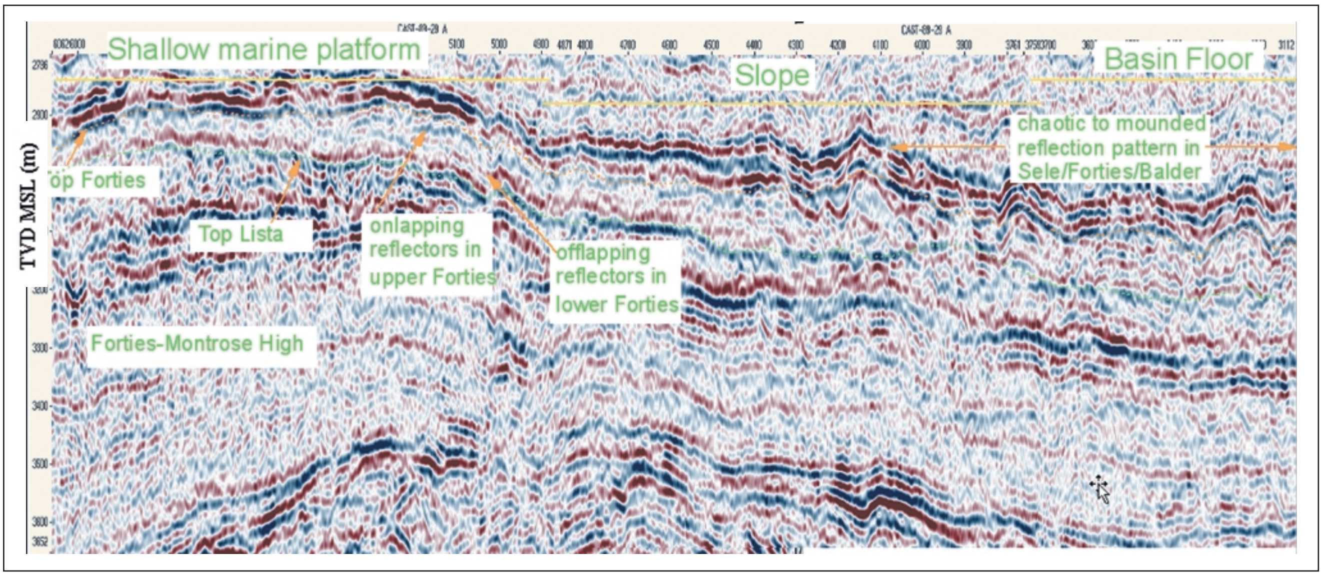


Fig. 6. SW-NE oriented seismic line from the Forties-Montrose High in block 22/24 to the vicinity of the Mirren Field in block 22/25. Note the thickness change in the succession between the top Lista and top Forties reflectors, and the different sedimentary provinces interpreted along this dip transect. See Fig. 5 for location of line.

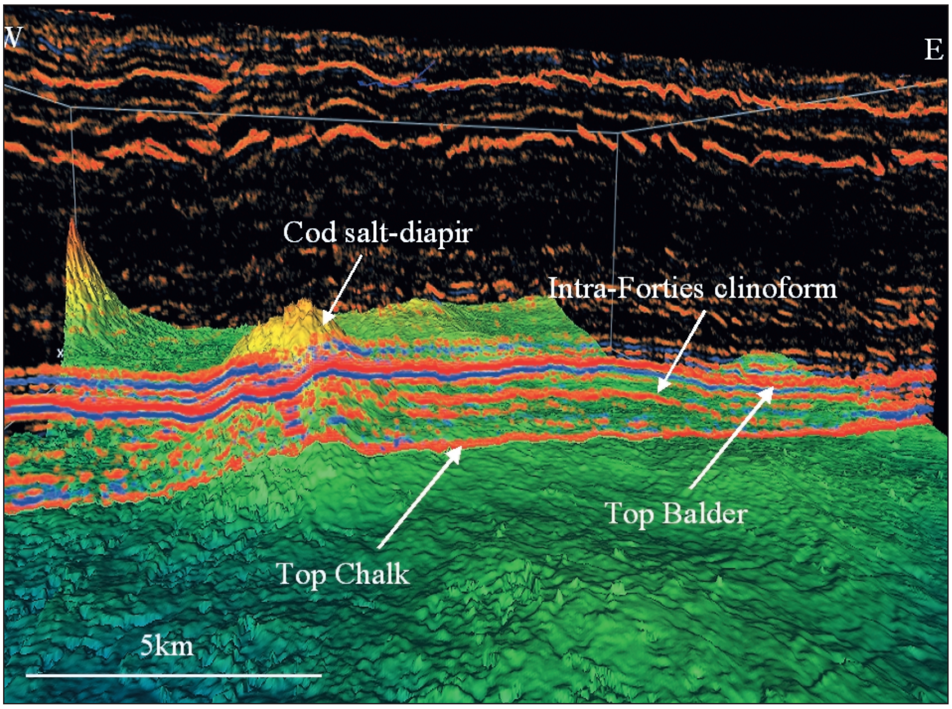


Fig. 7. VoxelGeo image of the Paleocene succession along a seismic transect in the vicinity of the Cod Field (see Fig. 5 for location of line). Everything but the highest seismic amplitudes have been made transparent, and in the succession between Top Chalk seismic reflector and Top Balder reflector these high-amplitude events may correlate with the presence of sand/mud contacts. Note major dipping event labelled intra-Forties shelf-edge clinoform some distance east of the Cod saltdome.

Other internal reflections have been interpreted locally within the 3D dataset.

A time isopach map for the Forties Formation is shown in Fig. 5. The map shows a distinct thinning onto the Cod Terrace (blocks 7/7, 7/8 and 7/11), whereas thick areas (depocentres) are developed in the 'deepest' part of the western arm of the Central Graben (Fig. 2). We also observe a thin Forties isopach on the Josephine High and the Forties-Montrose High even though the total Paleocene isopach in these areas is relatively constant in thickness. There are several salt structures in this area, and the Paleocene is thin to absent over these synsedimenary features. In the sub-basins between the salt diapirs, the Forties interval reaches thicknesses in excess of 150 m. This is indicative of tectonic control (differential subsidence) on deposition during accumulation of the Forties interval. Salt diapirs also show up well as thin 'round' areas on the Forties isopach map, and the presence of local depocentres between diapirs and downflank of the highs is also noticeable.

The seismic character of the interval between the Top Lista and Top Forties reflectors displays a great deal of lateral variation, and there is a marked relationship between structural position, thickness and seismic character (Fig. 6). Structurally elevated areas display a thin Forties isopach with a basal high-amplitude event (top Lista) which appears to have an unconformable relationship with the Lista succession below. Indications of incision are most common at the platform-to-slope transition area on Fig. 6. On the slope portion of Fig. 6,

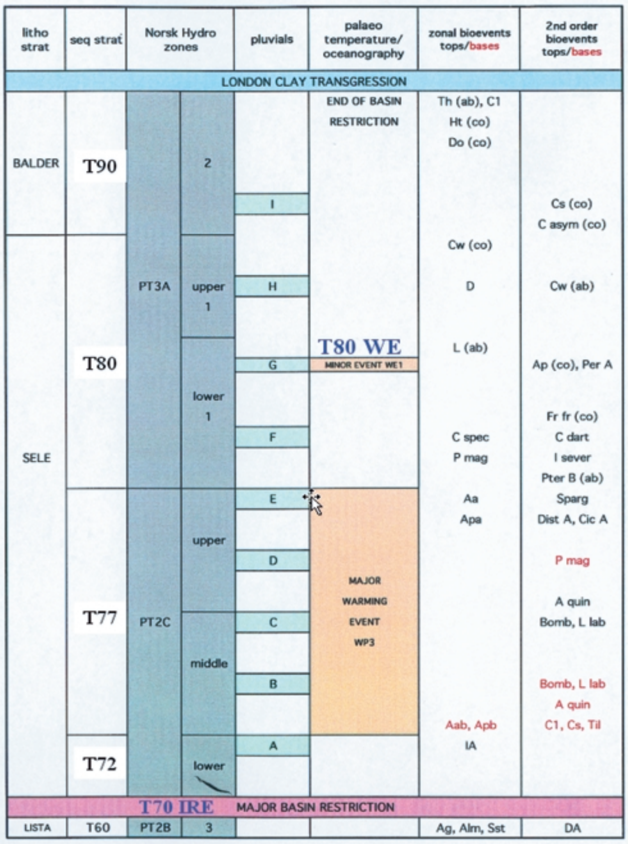


Fig. 8. Detailed Sele - Balder formations palynological zonation with sequences, bioevents, and pluvial events. The biostratigraphical markers are part of a proprietary in-house zonation scheme locally applicable to the study area, and are therefore shown in an abbreviated form without an explanatory index.

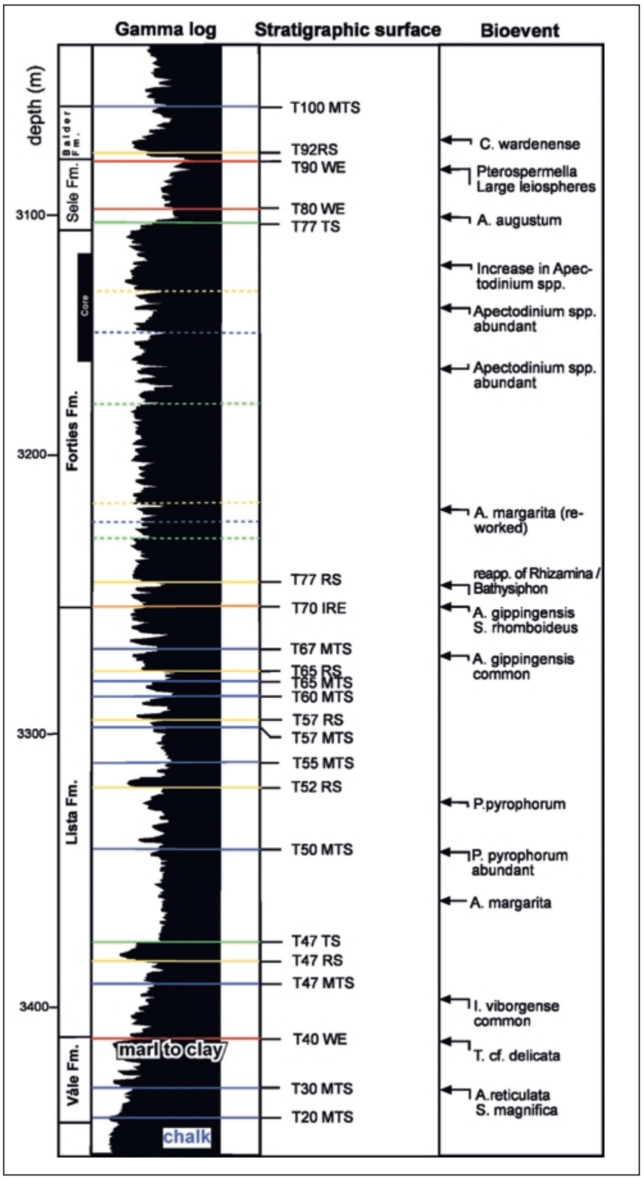


Fig.9. Type well 23/27-2 just west of the UK-Norway boundary, with all the main sequence stratigraphic surfaces shown superimposed on the shaded GR-log. The bioevents primarily used to constrain these surfaces are shown in the right column. See text for surface colour coding and T-cycle nomenclature.

lower parts of the Forties succession thickens considerably and is characterized by an offlapping seismic pattern, whereas the upper parts appear to contain onlapping reflectors which extend onto the platform area. Elsewhere (Fig. 7), the slope areas are characterised by a series of large offlapping reflectors resembling low- to moderate angle clinoforms (2.5-6 degrees of dip). These tend to be developed as a set of discontinuous reflectors in which the basal clinoform tends to stand out as a marked high-amplitude event (Fig. 7). The youngest and most easterly prograded clinoform has an areal extent as shown by the dotted line on Fig. 5. In contrast, structural lows display a mounded to chaotic seismic character alternating with areas of low-relief channelisation and areas with high-amplitude parallel reflectors. These low areas have a thick isopach in the regions containing the mounded, chaotic or channelised reflection patterns and show a marked thinning towards areas of parallel reflectors. These channel-like elements represent NNW-SSE oriented, discrete units that can be followed for several tens of kilometres along the axial part of the sub-basins. Their shape, orientation, onlap relationships and position in depocentres imply that they might represent sand fairways transporting material from proximal areas in the NNW towards distal areas in the Norwegian sector to the SSE.

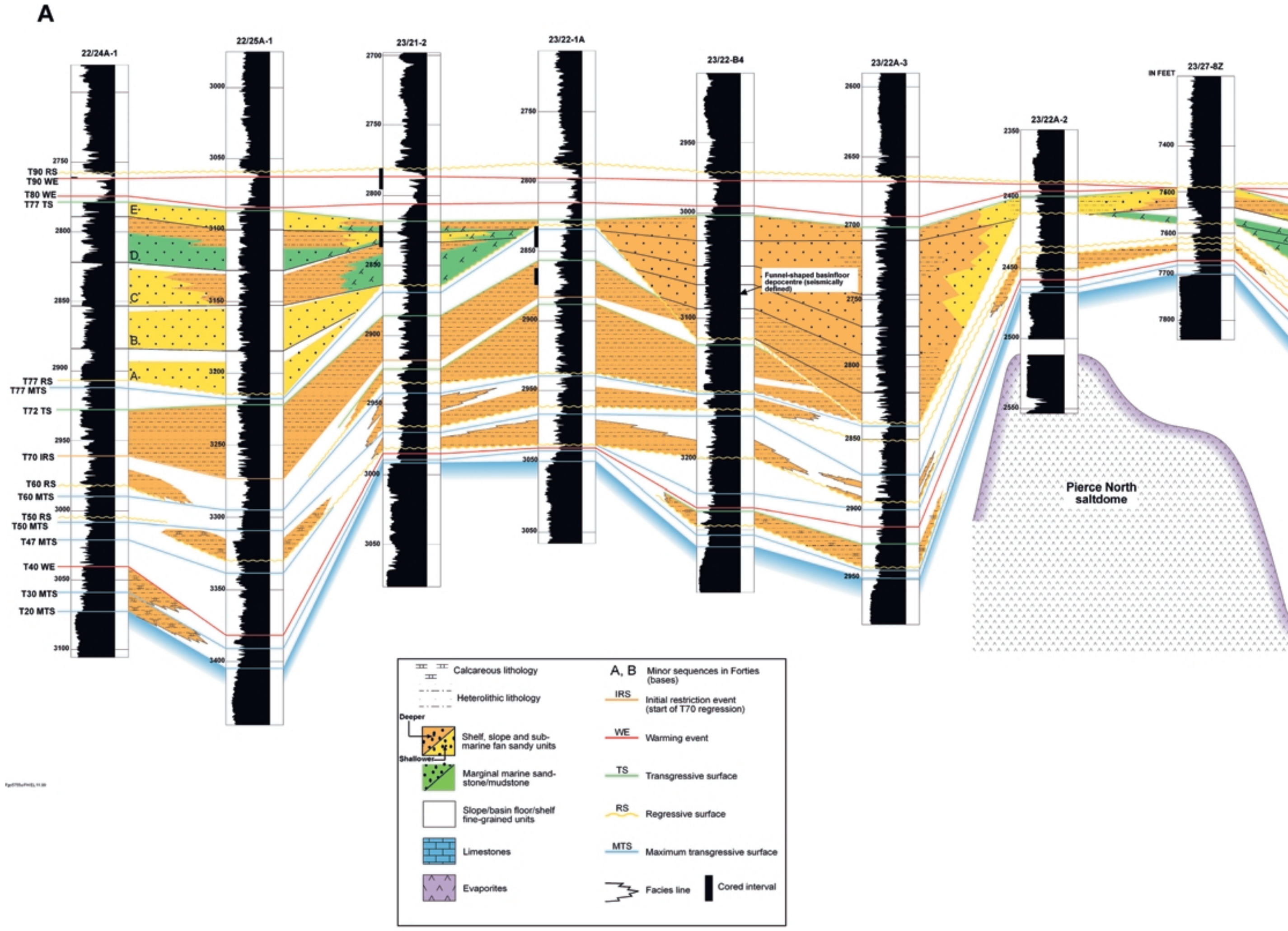
Sequence stratigraphy

Biostratigraphic zonation

A key issue in the development of any sequence stratigraphic framework is the construction of time-lines. In the current study, an extensive biostratigraphic sampling programme was undertaken to ensure that time-lines derived from a high-resolution bioevent scheme existed as a basis for correlation and sequence subdivision. Figure 8 shows the bioevent zonation scheme resulting from quantitative biostratigraphical analysis of 382 samples collected in the studied interval and the overlying Balder Formation. Note that the Forties Sandstone Member is included in the Sele lithostratigraphical unit in Fig. 8. The figure gives an overview of the correlatable bioevents, with highest occurrences (top) bioevents shown in black and lowest occurrence (base) bioevents shown in red. The palynomorph type is shown below in brackets after the event. The figure also provides a tie-in to the palaeo-oceanographic events discussed above, and represents a locally applicable expansion of regional biostratigraphic frameworks for the Paleocene succession published by Powell et al. (1995), Bujak & Mudge (1994) and Mudge & Bujak (1994, 1996 a, b).

In addition to the traditional biostratigraphic events discussed above, Fig. 8 also contains a column for correlatable 'pluvial' events (A to E in the lower Sele zone PT2C, plus F to I in the upper Sele/Balder zone PT3A). Latest Paleocene major warming event WP3 corresponds to pluvials B to E, and a minor earliest Eocene warming event WE1 corresponds to pluvial G. The pluvial events are characterized by an influx of low-salinity dinocysts (see palynofacies section below), and supplement traditional bioevents for correlations within the Forties Sandstone Member. The main reasons for this are:

i) other bioevents tend to be suppressed in this stratigraphic interval due to localized low salinities or a scarcity of certain marker species
ii) the Forties Sandstone Member was formed over a relatively short time-span (1-2 million years).


A
22/24A-1
22/25A-1
23/21-2
23/22-1A
23/22-B4
23/22A-3
23/22A-2
IN FEET
23/27-8Z
T90 RS
T90 WE
T80 WE
T77 TS
T77 RS
T77 MTS
T72 TS
T70 IRS
T60 RS
T60 MTS
T50 RS
T50 MTS
T47 MTS
T40 WE
T30 MTS
T20 MTS
E
D
C
B
A
Funnel-shaped basinfloor depocentre (seismically defined)
Pierce North saltdome
Calcareous lithology
Heterolithic lithology
Deeper
Shallower
Shelf, slope and submarine fan sandy units
Marginal marine sandstone/mudstone
Slope/basin floor/shelf fine-grained units
Limestones
Evaporites
A, B Minor sequences in Forties (bases)
IRS Initial restriction event (start of T70 regression)
WE Warming event
TS Transgressive surface
RS Regressive surface
MTS Maximum transgressive surface
Facies line
Cored interval

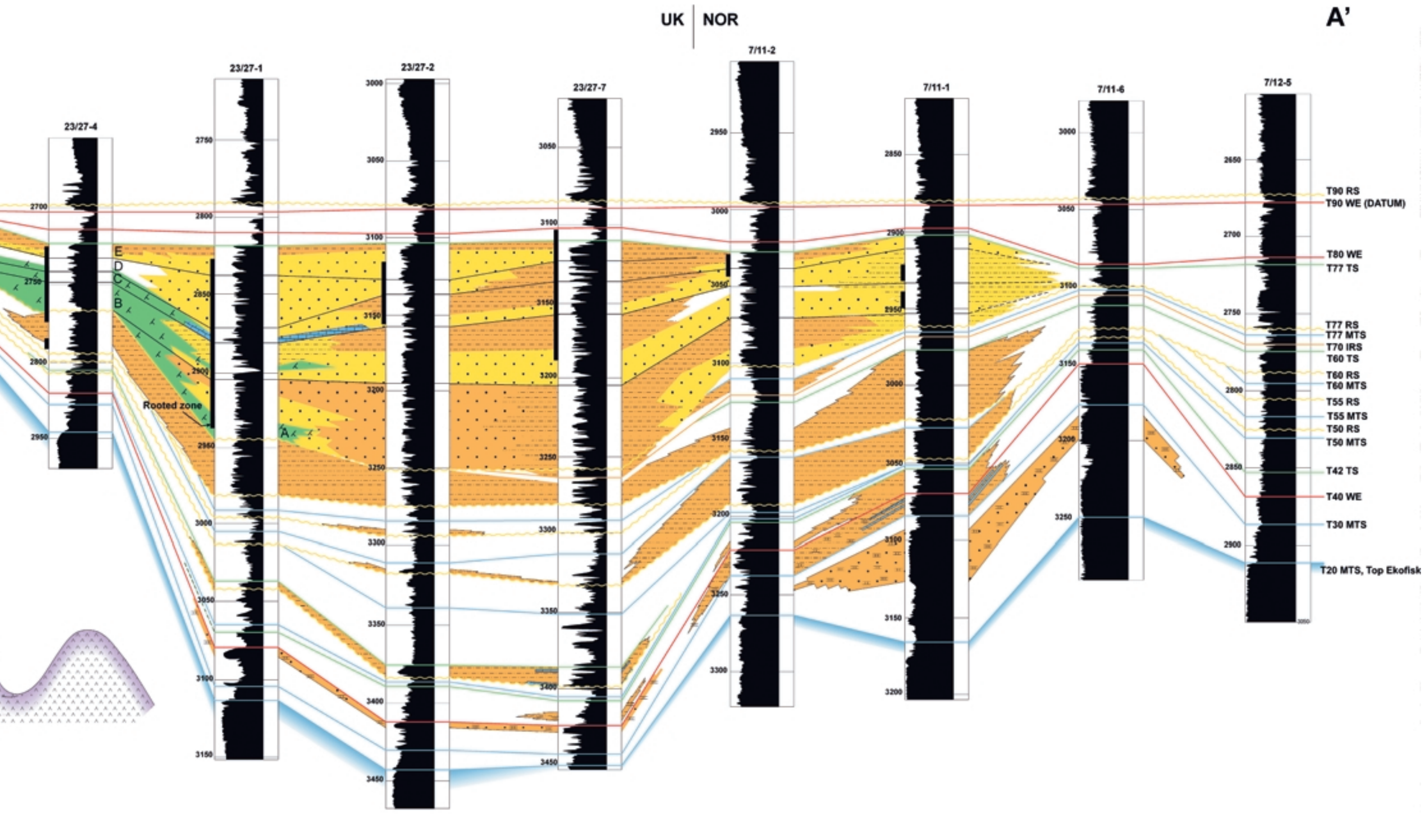


Fig. 10. Correlation line A-A', showing a zigzagging dip-section across the study area (see Fig. 1 for location). The sequence stratigraphic surfaces shown in Fig. 9 form the basis for correlation along with the facies trends outlined in the text and highlighted in a simplified manner in the figure legend. Shaded log represent GR-curves. Note structural control on the thickness and facies development of the Upper Paleocene deposits (see text for discussion).

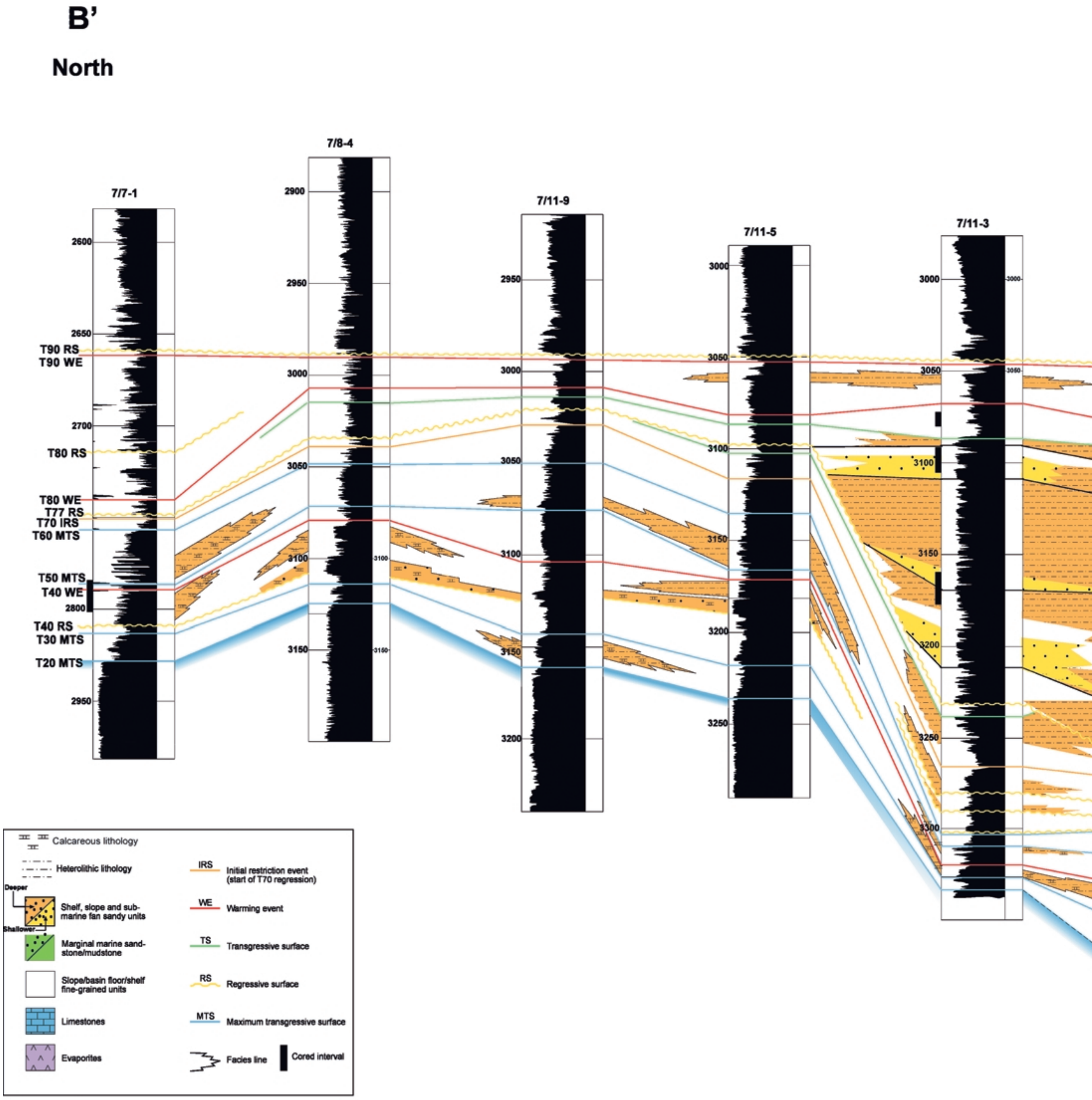


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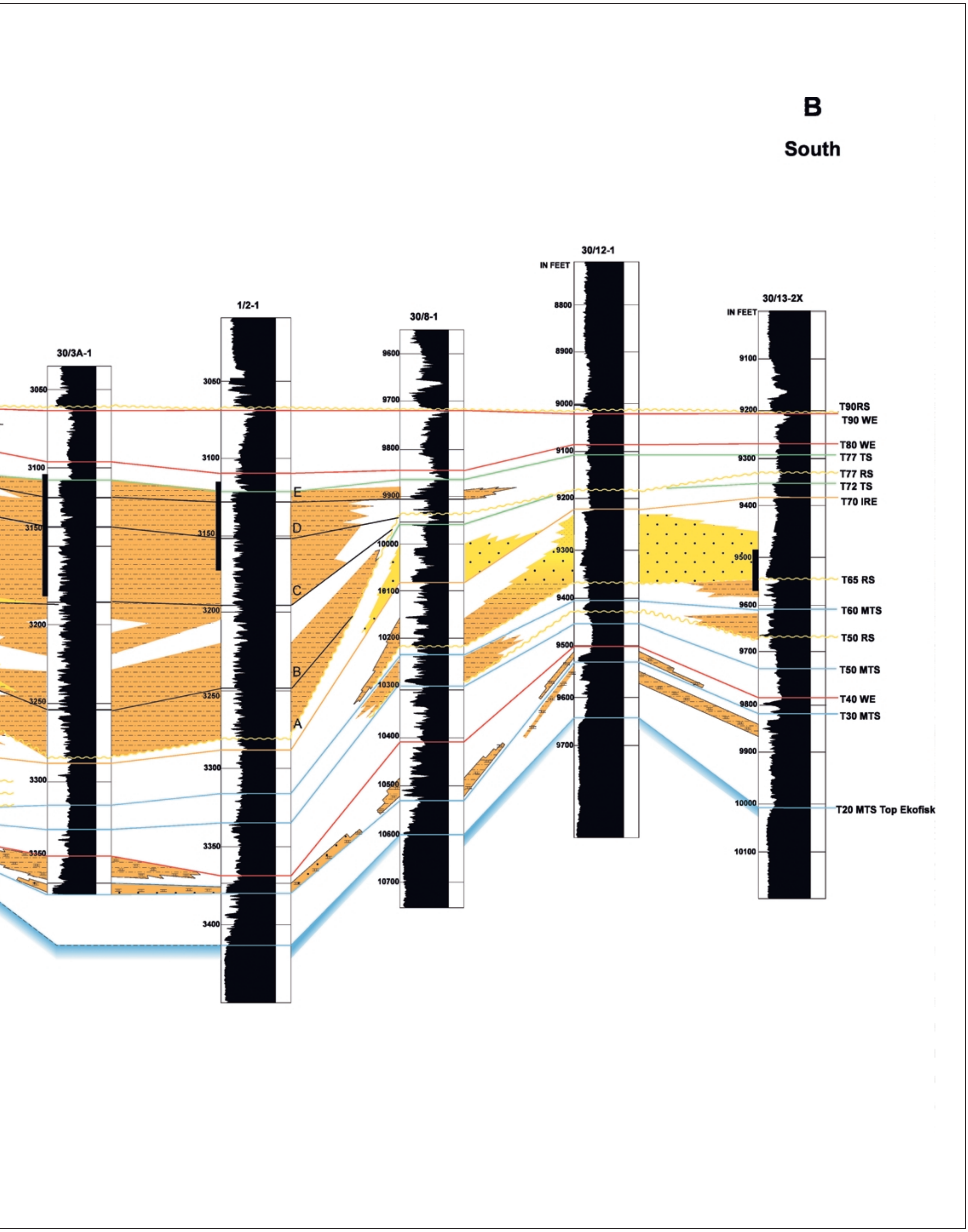
Fig. 11. Correlation line B-B', showing an approximate strike-line in the 'distal' part of the study area, just east of the UK-Norway sector boundary (see Fig. 1 for location). Same comments as for Fig. 10.


B
South
30/3A-1
3050
3100
3150
3200
3250
3300
3350
1/2-1
3050
3100
3150
3200
3250
3300
3350
3400
E
D
C
B
A
30/8-1
9600
9700
9800
9900
10000
10100
10200
10300
10400
10500
10600
10700
30/12-1
IN FEET
8800
8900
9000
9100
9200
9300
9400
9500
9600
9700
30/13-2X
IN FEET
9100
9200
9300
9400
9500
9600
9700
9800
9900
10000
10100
T90RS
T90 WE
T80 WE
T77 TS
T77 RS
T72 TS
T70 IRE
T65 RS
T60 MTS
T50 RS
T50 MTS
T40 WE
T30 MTS
T20 MTS Top Ekofisk

The oldest pluvial phase recognized in zone PT2C occurs near the top of lower PT2C subzone and sequence T72, just below the WP3 warming event. The overlying interval represented by the warming event and sequence T70 is separated into middle and upper PT2C subzones, with pluvials B and C characterizing middle PT2C, and pluvials D and E characterizing upper PT2C. The confidence with which the influx of low-salinity dinocysts is recognized and assigned to a particular pluvial varies. Pluvial A is the most distinctive of the five PT2C pluvials as it pre-dates the *Apectodinium* influx, and can therefore be recognized with a high degree of confidence. Pluvials A to D are all associated with the *Apectodinium* acme. These can be assigned fairly confidently to either middle or upper subzone PT2C, and hence to either undifferentiated B/C or D/E, based on the occurrence of the second-order bioevents shown in Fig. 8.

Assignment to one of the two pluvials occurring in each subzone (i.e. to either B or C, and either D or E) is more difficult and log or seismic correlations may be needed. Nevertheless, sufficient wells were observed in which three or more adjacent pluvials occur to increase the level of confidence regarding the cyclical nature and presence of five distinct pluvial phases, and to assign them to A, B, C, D or E. The following 10 wells were critical in this respect, having three or more adjacent pluvials:

Five pluvials:	22/25b-5 (A, B, C, D, E);
	23/27-1 (A, B, C, D, E)
Four pluvials:	23/21-4 (B, C, D, E);
	23/27-4 (B, C, D, E)
Three pluvials:	22/30a-5 (B, C, D);
	23/27-6 (C, D, E);
	23/27-7 (C, D, E);
	23/27-5 (A, B, C);
	N1/3-7 (C, D, E);
	N7/11-3X (C, D, E).

The five intra-Forties pluvial events were used as time-lines to guide the correlations of the minor sequences within the Forties Sandstone Member (T77A-T77E, see next section).

Sequences and correlation

The Paleocene succession in the study area comprises the T20-T90 cycles (Fig. 3), but as mentioned above only the T60-T80 cycles are discussed in detail. As is common for the North Sea Paleocene (Dixon & Pearce 1995; Mudge & Bujak 1996; Mangerud et al. 1999), prominent mudstone horizons associated with condensation and often high-gamma spikes are used as sequence boundaries (genetic sequences, see Mangerud et al. 1999). Some of these correspond to maximum flooding surfaces whereas others most likely are related to the changes in water chemistry and temperature outlined above.

A detailed overview of the sequence stratigraphic surfaces and corresponding bioevents is given for a single (type) well in Fig. 9 and for some of the other key wells in the study area in the correlation charts of Figs. 10 and 11. Blue surfaces labelled MTS correspond to maximum transgressive surfaces and occur in mudprone intervals, whereas yellow surfaces labelled RS (regressive surface) are in most cases associated with influx of sand. Green surfaces labelled TS (trangressive surfaces) are highlighted only in the few cases where they have correlation potential or where they occur at the top of locally prominent sandstone units. Red surfaces are associated with the three warming events recognized in this study; T40WE, T80WE and T90 WE. These tend to occur at the base of upwards coarsening units, thus signalling the onset of regression in a manner similar to the MTS. The orange surface labelled T70 IRS (initial restriction surface) is, as the name implies, related to changes in water composition, lithology and biogenic content due to onset of tectonically controlled basin restriction (Mudge & Bujak 1996b; Bujak & Brinkhuis 1998). It basically conforms to the Lista/Sele formations boundary (Fig. 3), and precedes the major Forties Sandstone Member regressive phase.

The Paleocene sequences or 'T-cycles' applied in this study are described in some detail in Mangerud et al. (1999), and only the parts pertaining to the T60 and T70 cycles and the base of the T80 cycle will be discussed here. The **T60** cycle has been split into three sub-cycles by Mangerud et al. (1999), and these can also be recognized in the present study area. The base of the cycle is the T60 MTS, which only locally is represented by a high-gamma peak. This surface is linked to the last stratigraphic occurrence of *A. gippingensis*. Above the T65 MTS at the base of the next sub-cycle there is often a sharp drop in gamma values across the T65 RS representing increased sand influx. This vertical transition from a high-gamma shale to a low-gamma sandstone-rich interval is a regionally recognizable surface, probably indicating a major regression, and it occurs just below the top common occurrence of *A. gippingensis*. The transgressive surface, T65 TS, in this sub-cycle is linked to an influx of *C. comatum* and *D. denticulata*. The higher-frequency MTS (T67 MTS) at the base of the upper subcycle is associated with the last stratigraphic occurrence of *A. gippingensis*.

The **T70** cycle represents the most significant regression in the studied interval. The base of the T70 cycle is characterized by a moderately high-gamma shale deposited during the initiation of the basin restriction phase discussed above. This initial restriction event, denoted T70 IRS, is linked to the last stratigraphic occurrence of *A. margarita* and *S. rhomboideus*, as well as a decrease in agglutinated foraminifera. The cycle is at the present stage divided into two subcycles, T72 and T77, separated by a higher-frequency MTS (T77 MTS). These subcycles correspond to the lower and upper/middle part of the Forties Sandstone Member, respectively (Figs. 3 and 9). A dramatic increase in sand influx is indicated in T72 by a sharp drop in gamma values across regressive surface T72 RS. A transition to a generally thin interval of more mud-rich deposits occurs across the T72 TS. The T77MTS separating the two subcycles is locally represented by a high-gamma peak, but in areas on top of and on the margins of salt structures the surface cannot be recognized. This may imply that the surface was eroded or did not develop in areas that had a positive relief on the sea floor (and locally above sea-level) during T77. The regressive surface, T77 RS, is represented by a sharp drop of gamma values related to dramatic increase in sand influx as a result of uplift, forced regression and full basin restriction (Figs. 10 and 11). A change to *Apectodinium* dominated biostratigraphic assemblages occurred subsequent to basin restriction, and is related to the late Thanetian warming event (Bujak & Brinkhuis 1998). The Forties sandstones are overlain rather sharply by mudstones belonging to the Sele Formation, deposited during transgression above T77 TS.

The base of **T80** is associated with the first high-gamma peak above the T77 TS at the top of the Forties Sandstone Member (Figs. 9-11). This high-gamma peak is further north related to an uranium-rich section attributed to condensation (Mangerud et al. 1999), but data from the present study area imply that the surface may also coincide with the culmination of the late Thanetian warming event, denoted T80 WE. Just above this surface, the termination of the warming event can be recognized by the last stratigraphic occurrence of *Apectodinium spp*.

The correlation diagrams (Figs. 10 and 11) display the surfaces discussed above, and are in addition colour coded and rasterized to highlight the main lithotypes (see legends on the diagrams and facies section below). The integration of time-constrained correlation lines and broad facies categories make these diagrams ideal as templates for paleogeographical reconstructions (see below). Some of the main features revealed by the correlation diagrams can in general terms be summarized in the following points:

- There is a tendency towards concentration of major sandbodies in the (late) T60 and T70 cycles. In the T20-T50 and the T80-T100 cycles, a limited number of laterally discontinuous clastic units appear to be present.
- The well database indicates that sand content decreases towards the south and east, thus implying sediment supply from the west and north. Within the T60 and T70 cycles, there is a great deal of local variation in sand occurrence, but in general the lower parts of the T77 cycle (sub-cycles A, B and C) tend to be most sand-rich. This stratigraphic interval represents conditions of maximum regression in the study area.
- The large thickness variation of the T60 to T70 cycles is to a large extent controlled by structural position (compare Figs. 2, 5, 10 and 11). In wells located on top of salt diapirs and footwall highs, these cycles are thin or absent, whereas wells in inter-diapir and immediate hangingwall depocentres tend to have thick developments. Well-developed onlap patterns on the flanks of these structures are seen on most of the correlation panels. These relationships lend further support to the above-mentioned notion of syn-depositional structural control.
- As shown by the colour coding, those structural highs not subjected to non-deposition or erosion are associated with Upper Paleocene marginal marine deposits (green on Figs. 10 and 11) and/or shallow-water deposits (yellow). Downflank on these structures, interfingering with deeper-water deposits (orange and white) takes place. This kind of relationship, which is based on core control aided by log-pattern correlation, implies that the basin morphology was quite complex during T60 and T70 deposition, resulting in significant bathymetrical variations that in turn had a marked effect on depositional conditions.
- Although heterolithic, T60 - T70 successions occurring in structurally elevated positions may contain significant amounts of sand despite being relatively thinly developed. The well database and the correlation panels show that every structural high (salt diapir or otherwise) is associated with at least a few meters of T60 (Josephine High) or more commonly T70 sandstone.
- The transition from the T70 to T80 cycle coincides with a regional termination of sand deposition in the study area. This relationship suggests that a major flooding event took place, and by studying the well database and correlation panels it appears that this transgressive event was initiated in the upper part of the T77 cycle. The effects of this event then gradually spread from the axial part of the East Central Graben and onto the more elevated areas to the east and west. This is perhaps best illustrated by the backstepping relationship of the T77D-E cycles in the northern parts of the study area.

Sedimentary facies analysis

The Upper Paleocene succession in the study area has, over the last decades, been interpreted as the distal part of a large submarine fan system sourced from the uplifted East Shetland Platform. Only Knox et al. (1981) specifically mention the possibility for more shallow-water conditions, based on features such as common crossbedding and the presence of *Apectodinium* dinocysts, and states that 'water depths did not exceed a few hundred meters'. However, most of the 'deep-water' models discussed in the previously cited papers envisaged a similar range of Late Paleocene water depths (between 100-500 meters), primarily based on clinoform geometries observed within the upper part of the succession.

As shown above, the study area in Late Paleocene times contained a complex system of sub-basins and structural highs (diapirs and footwall uplifts). A number of cored wells in different structural positions were, in this study, selected for biostratigraphic and sedimentological analyses. (blue circles in Fig. 1). Facies classification is based only on the cores from the T60-T80 stratigraphic interval. Five facies associations were recognized in this succession:

• Facies association 1:	*Massive sandstones and burrowed to laminated mudstones*
• Facies association 2:	*Laminated mudstones with rippled sandstone interbeds*
• Facies association 3:	*Thick sandstone-dominated units with normal graded beds*
• Facies association 4:	*Laminated and cross-bedded sandstones*
• Facies association 5:	*Heterolithic deposits rich in plant material*

Facies association 1: Massive sandstones and burrowed to laminated mudstones

Facies association 1 (FA 1) can be split into a sandstone-dominated variant that is only present in the T77 cycle (main sandstone unit in the Forties Formation) and a mudstone-dominated variant that also occurs in the T60, T72 and T80 cycles. In the T77 cycle, FA 1 is mainly present in the northeastern parts of the study area and in parts of the Breiflabb Basin (i.e. T77A-D subcycles in well 1/3-7, Fig. 12). In the older cycles, however, it has a more widespread occurrence, while it occurs in some wells to the northeast in the T80 cycle. The sandstone-rich variant is characterized by alternations of 2-15 m thick units of fine- to medium-grained sandstones and thinner units of burrowed, massive and occasionally laminated mudstones. In contrast, the mudstone-dominated variant contains only a few scattered sandbodies, up to 20 m thick, and for the most part consists of burrowed to laminated mudstone with thin streaks or lenses of fine-grained sandstone (i.e. upper part of the T77 cycle in the 22/25B-5 well, Fig. 13). The mudstones tend to be dark grey (T77 and T80 cycles) to greenish grey (T60 and T72 cycles), and the alternations between burrowed and laminated zones may in some cases occur on a meter to dm-scale. Trace fossils are mainly *Zoophycus* and *Planolites*, and soft-sediment deformation is occasionally seen. The sandstone lenses are mm-to cm-thick and often display a current ripple formset shape. These lenses tend to sit at the base of cm-scale normal graded massive to laminated beds in which the mudstone component changes from silt to clay from base to top.

The sandstones are well sorted and consist of amalgamated and mostly structureless beds. It is the combined structureless appearance and thick development of bedsets that allow this facies association to be characterized as 'massive'. Individual beds are commonly 0.5-1.75 m thick, with sharp bases, normal graded tops, and rounded mudstone intraclasts lags or floating mudclasts in the lower parts of most beds. Angular mudflake 'breccias' are occasionally seen at the transition to overlying mudstones. Water-escape structures and loading are common, and (fading) current ripples are seen at the top of some beds. FA 1 interfingers with FA 3 in an updip direction, i.e. towards the structurally elevated areas shown on Fig. 2. This transition is quite abrupt in the Breiflabb Basin, as exemplified by well pair 23/27-2 and 23/27-7 (Fig. 10). In the latter well, FA 1 is present in the lower part of the T77D cycle and the upper part of the T77E cycle, whereas it is argued below that corresponding intervals in 23/27-2 contain shallower-water deposits.

Facies association 1 is interpreted as basin plain to lower slope deposits, characterized by intermittent influx of mass-flows onto a variably oxygenated basin floor. The sandstone bodies represent elements of submarine fans, but the level of detail and focus of this study prevent us from being more precise with regard to the geometry of these units. The mass-flow deposits found in the submarine fan units are believed to mainly represent high- to low-density turbidites, based on their normal grading, good sorting, frequent water-escape structures, and the occurrence of traction structures such as current ripples. The burrowed mudstones are regarded as hemipelagic deposits, whereas the normal-graded mudstones with sandlenses probably represent the most distal parts of turbidite flows. Water-depth estimates are speculative, but from the presence of *Zoophycus* traces and the occurrence of this facies association beyond the pinchout of 50-100 m thick clinoform units only may tentatively suggest depths of up to a few hundred meters.

In the above-mentioned studies discussing the sedimentology of the Forties Formation, a depositional setting similar to that currently offered for FA 1 has been presented. Judging by these published accounts, large submarine fan systems occupied the basin floor of the Central Graben and the Outer Moray Firth, pinching out towards the southeast and locally against elevated areas such as the Jæren High. As will be discussed below, however, local deviations from this deep-water depositional model may exist.

Facies association 2: Laminated mudstones with rippled sandstone interbeds

This is the most fine-grained facies association of the studied succession (75-80% mudstone), occurring either as 1-12 m thick muddy intervals in areas where the T77 cycle is sandstone-dominated, or as 5-35 m thick fine-grained units in the T80 cycle and in the T77 cycle in areas outside of the Forties sandstone depocentre (i.e. 29/5A-3 well, Fig. 14). In the latter case, it interfingers with the muddy variant of FA 1, and together these facies types lithostratigraphically corresponds to the Sele Formation. In the former case, interfingering with FA 3 is observed (Figs. 10 and 11). FA 2 has not been observed in the T60 and T72 cycles. The mudstones in FA 2 are dark grey, sapropelic, well laminated, occasionally tuffaceous and frequently normal-graded (silt to clay, Fig. 15). Soft-sediment deformation, often with a high degree of layer contortion, is common, and trace fossils are absent except for a few occurrences of *Planolites*, *Palaeophycus*, and *Chondrites*. Other deformation features associated with sand-mud interlaminations are microloading and sand injection.

Apart from the lack of bioturbation and the common soft-sediment deformation, the main feature that sets it apart from the muddy variant of FA 1 is the nature of the sandstone interbeds. In FA 1, these tend to be structureless and relatively coarse-grained, whereas in FA 2 the sandstone component is finer-grained, laminated and occurs as mm-to dm-thick lenses and beds (i.e. T77E and T80 cycles in well 1/3-7, Fig. 12). The thin sandlenses display fading ripple lamination and ripple formsets, whereas the thicker sand interbeds are dominated by ripple cross-lamination. In the approximately 35 cm thick core section displayed in Fig. 15b, three sandbeds containing ripples grading from asymmetric to more symmetric are seen, with mud-drapes (grey) both on the offshooting to draping foresets and between individual ripple-sets. The ripples with the most well-developed symmetric shape appear to be present in the upper of the three sandbeds. An equally thick core section in Fig. 15c displays well-bedded fine-grained sandstone with siltier drapes (grey) bracketed between mudbeds at the top and bottom. The top and base of the sandbed is characterized by asymmetric ripple crosslamination, whereas the thicker middle part display sub-horizontal to convex-upwards lamination. This kind of structure may be due to a high degree of aggradation of the (climbing ripple) bedform, but effects of oscillatory currents creating small-scale hummocky cross-stratification (HCS) cannot be discounted. Hence, although unidirectional currents may have been instrumental in forming these sandbeds, the offshooting to draping foresets, the presence of relatively symmetric ripple shapes, and the convex-upwards bedding geometries imply that wave-related currents may have been active intermittently.

Facies association 2 is interpreted as basinal deposits formed in a low-energy anoxic setting. Graded mudstone beds probably represent low-density turbidites similar in nature to those discussed in FA 1, whereas the thicker intervals of laminated, ungraded mudstone reflect hemipelagic settling from suspension. Where dominated by asymmetric ripples, the ripple-laminated sandbeds may represent low-density turbidites. However, the presence of possible wave-generated structures in some of the sand interbeds imply that this low-energy setting periodically may have been affected by currents associated with storm waves, and it is thus plausible that parts of FA 2 formed in water-depths of less than 100 m. When these interbeds occur with regularity in intervals up to 20 m in thickness, it seems plausible that they reflect a relatively shallow-water setting, such as at the toe of shoreface. In combination, it is suggested that FA 2 accumulated in a broad spectrum of low-energy environments such as a (relatively shallow) basin floor, the muddy portions of the slope, and in distal shelfal areas during periods of low sediment input or during prolonged quiescent conditions. The high degree of soft-sediment deformation indicates frequent destabilization, and probably reflects deposition in the slope sub-environment.

Facies association 3: Thick sandstone-dominated units with normal graded beds

This is the volumetrically most common facies association in the studied succession, and corresponds to the majority of the orange-coloured 'deeper-water' deposits on Figs. 10 and 11. It consists of 3-45 m thick sandstone-dominated units in which stacked normal-graded sandstone beds are the main component (i.e. T77C/D cycles in well 22/30A-5 and well 30/3A-1, Figs. 16 and 17). Cm- to dm-thick interbeds of mudstone to silty fine-grained sandstone occur between the graded sandstone units. FA 3 interfingers with both FA1 and FA2 as well as FA4, and displays a great variety in grain-size (silt to granules). Sandstone beds are moderately sorted and may be normally graded throughout, in which case a basal granule to mudclast lag is commonly present, or they may display normal grading only in the topmost part. Bases are sharp and slightly erosional, and tops tend to display fining up into very fine-grained sandstone and siltstone with parallel lamination, ripples, bioturbation (mostly *Planolites* and *Chondrites*) and lenticular bedding (Fig. 18b). However, the top surfaces can also be erosional,

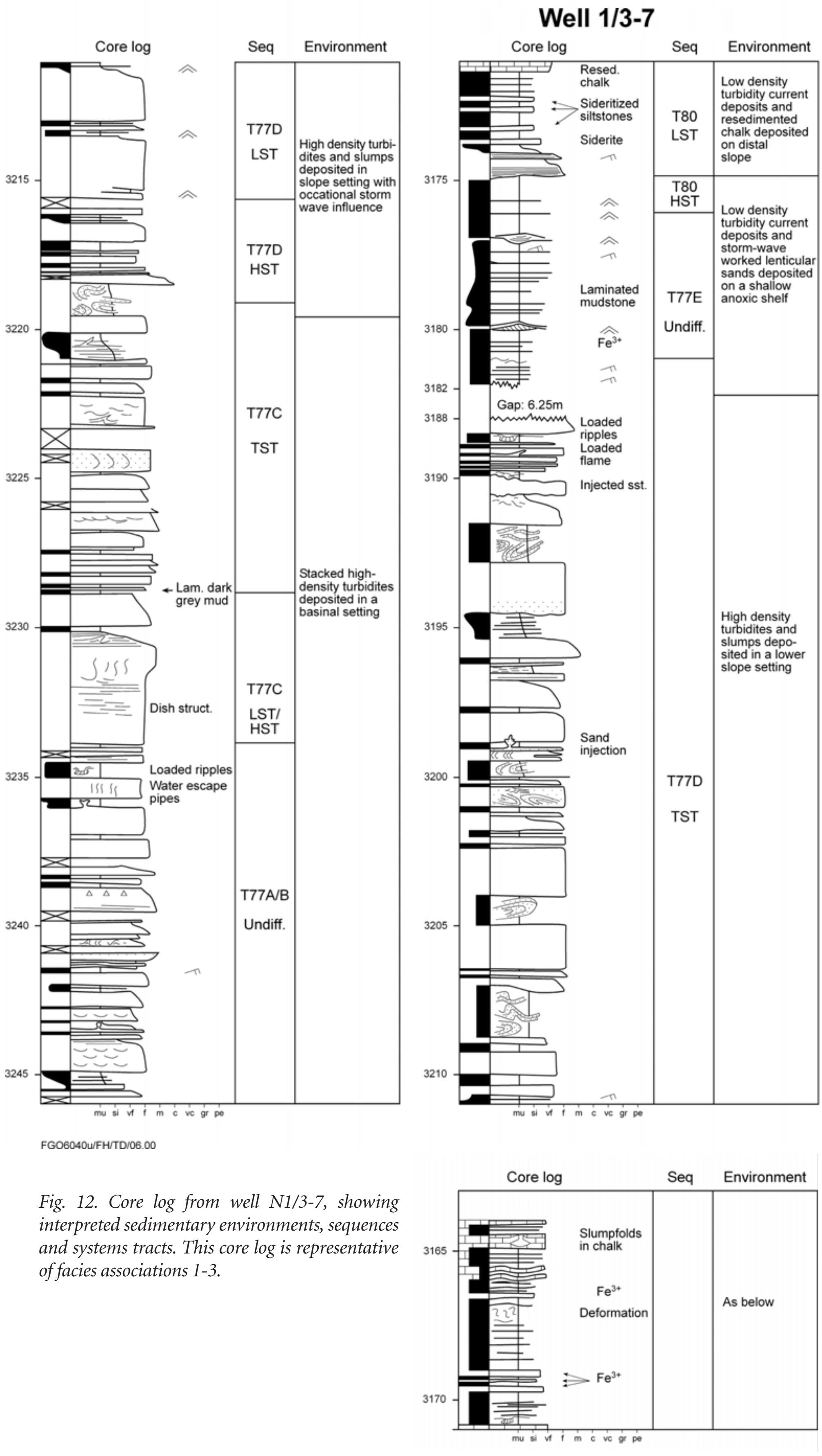


Fig. 12. Core log from well N1/3-7, showing interpreted sedimentary environments, sequences and systems tracts. This core log is representative of facies associations 1-3.

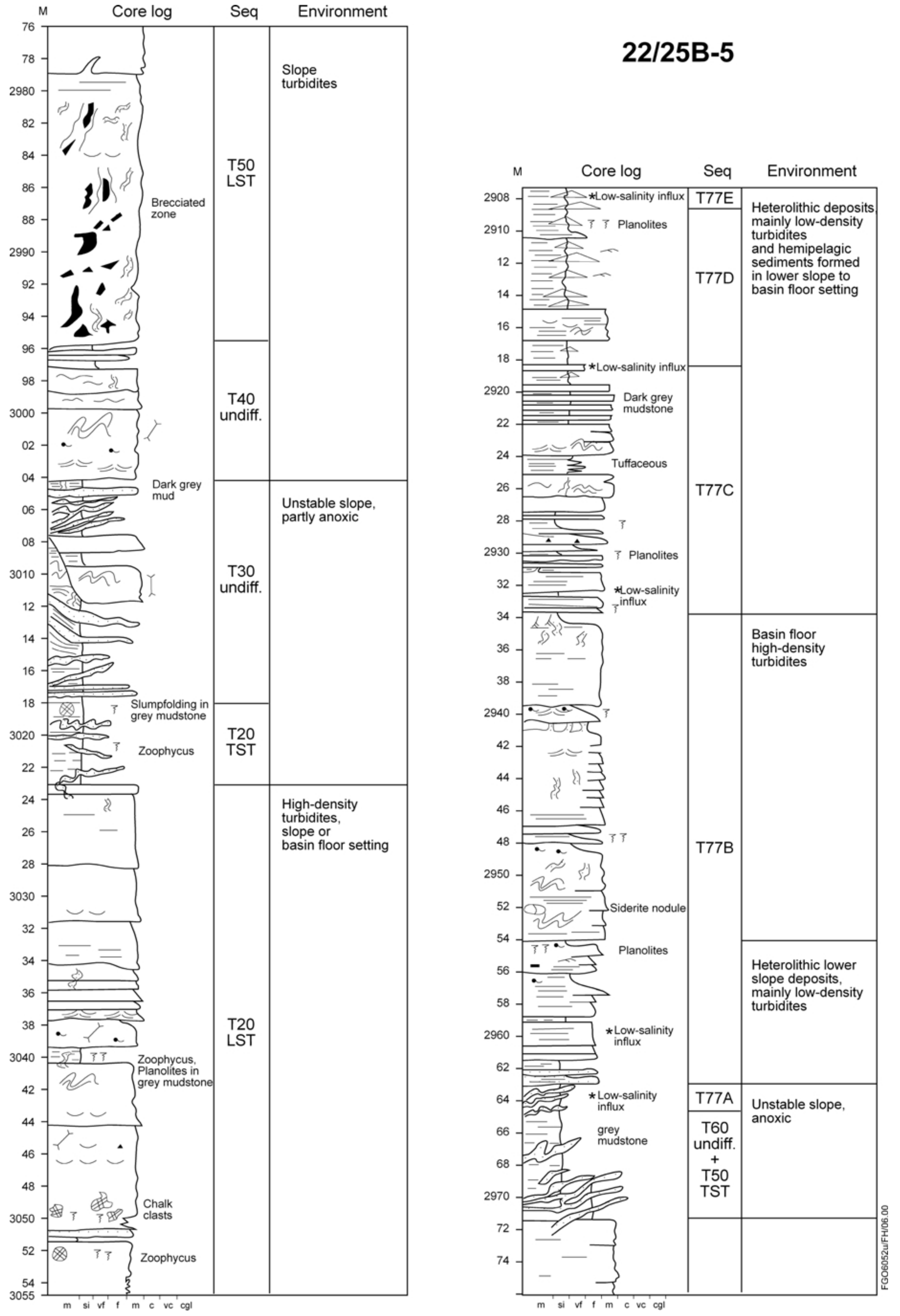


Fig.13. Core log from well 22/25B-5, showing interpreted sedimentary environments, sequences and systems tracts. This core log is representative of facies associations 1-3.

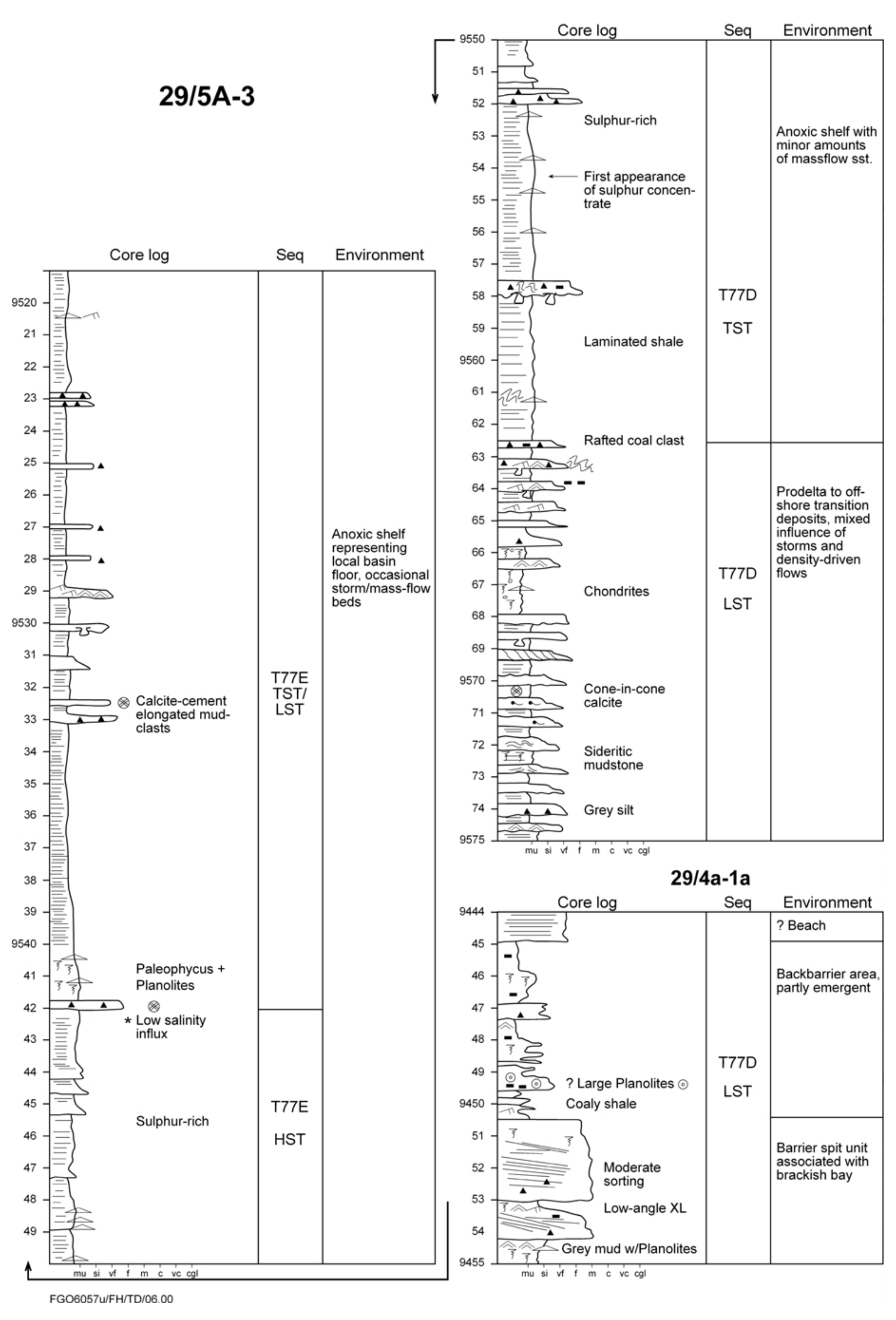


Fig. 14. Core log from wells 29/5A-3 and 29/4A-1a, showing interpreted sedimentary environments, sequences and systems tracts. This core log is primarily representative of facies association 2.

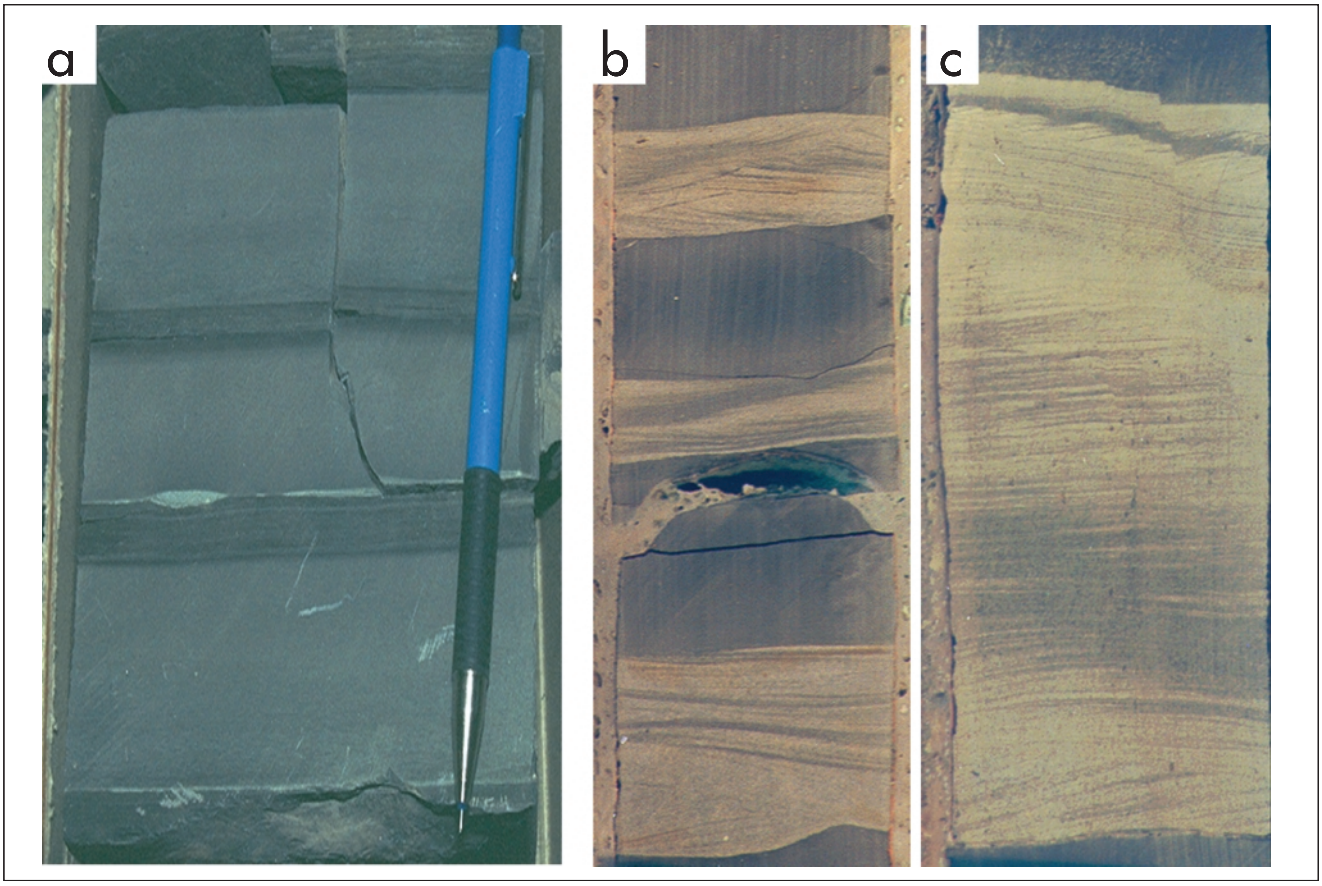


Fig. 15. Core photos from facies association 2. A) 30/14-1, T80 cycle: Laminated mudstone consisting of normal-graded low-density turbidites. Note basal sandlenses, 9458 ft. B) 30/14-1, T80 cycle: ripple-laminated sandbeds in muddy shelfal succession, 9468 ft. Wave-related currents are believed to have influenced the genesis of at least the upper rippled bed. C) 30/14-1, T77 cycle: strongly aggraded ripple lamination in sandbed, 9559 ft. The convex-upwards lamina may have formed as an effect of oscillatory currents. See text for discussion.

juxtaposing coarse sandstone and the overlying finer-grained interbeds of FA 3. Such surfaces may be associated with a granule lag, and the sediments overlying it display low-angle cross-stratification, wave- and current ripples, and occasionally double mud-drapes (Fig. 18b). The coarse sandstone beds are usually 0.1-1.2 m thick, but 'megabeds' up to 7 m in thickness have been observed (Fig. 17). Dish and pillar structures (water-escape features) are common (Fig. 18a), otherwise the coarser part of the sandstone beds is structureless or displays parallel lamination and in rare cases crossbedding. Injection of clean sandstones into 'dirtier' (more fine-grained) parts or into overlying finer-grained units is often seen in conjunction with contorted bedding. In cases where the seismic control is good, deposits of the T77 cycle in areas dominated by FA 3 is seen to be situated in the foreset parts of low-angle clinoform units.

Facies association 3 is interpreted as slope mass-flows (mainly high-density turbidites) formed in a slope setting. The mass-flow interpretation is uncontroversial, since it conforms to the published accounts of the Forties Formation mentioned earlier in this section, but the notion of a slope setting needs to be discussed. Our arguments for this are based on the differences between the mass-flows of FA 3 and FA 1. The former occur in thicker units present within seismically defined clinoform packages, are less well sorted and usually coarser-grained than their FA 1 counterparts, lack trace fossils characteristic of a deepwater setting (i.e. the *Zoophycus* of FA1), are associated with wave ripples, double drapes and cross-stratification, and have a greater abundance of slump-related features. In sum, these differences suggest that FA 3 was formed in a more shallow setting than FA 1, such as a graded slope subjected to wave reworking and instability. We envisage this slope to be located downdip of a shallow-marine platform (see below), and that it further downdip translates into a moderate water-depth distal shelf to basin floor area in which FA 1 and 2 accumulated.

Facies association 4: Laminated and cross-bedded sandstones

Irregular coarsening upwards units, 5-10 m in thickness and involving beds of FA 3 and FA 4, are common in the T77 cycle (Figs. 10 and 11). The finer-grained lower part of these units starts with a succession of FA 3 beds that show an increasing degree of sandstone amalgamation upwards. Above these mass-flows, the generally coarser

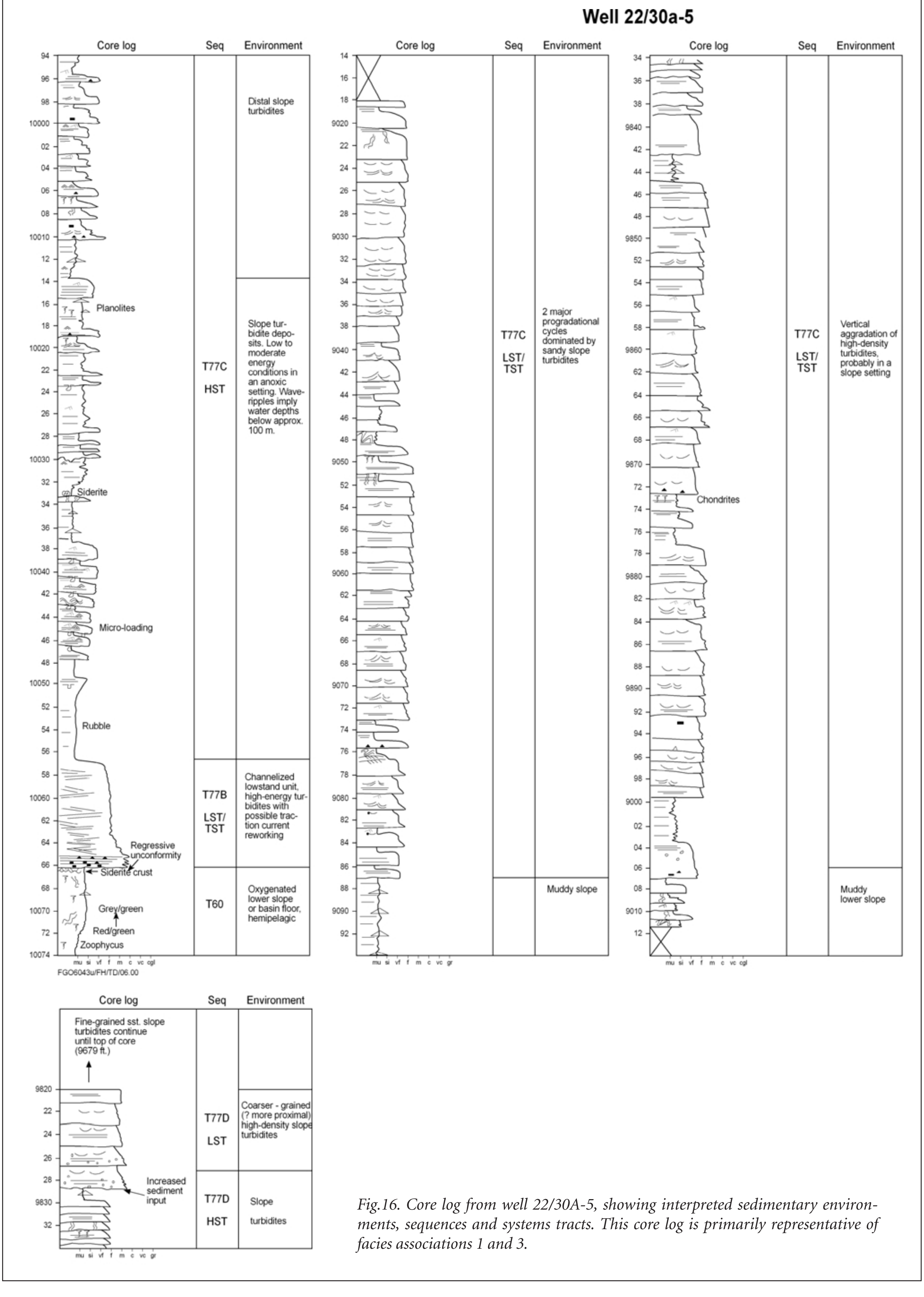


Fig.16. Core log from well 22/30A-5, showing interpreted sedimentary environments, sequences and systems tracts. This core log is primarily representative of facies associations 1 and 3.

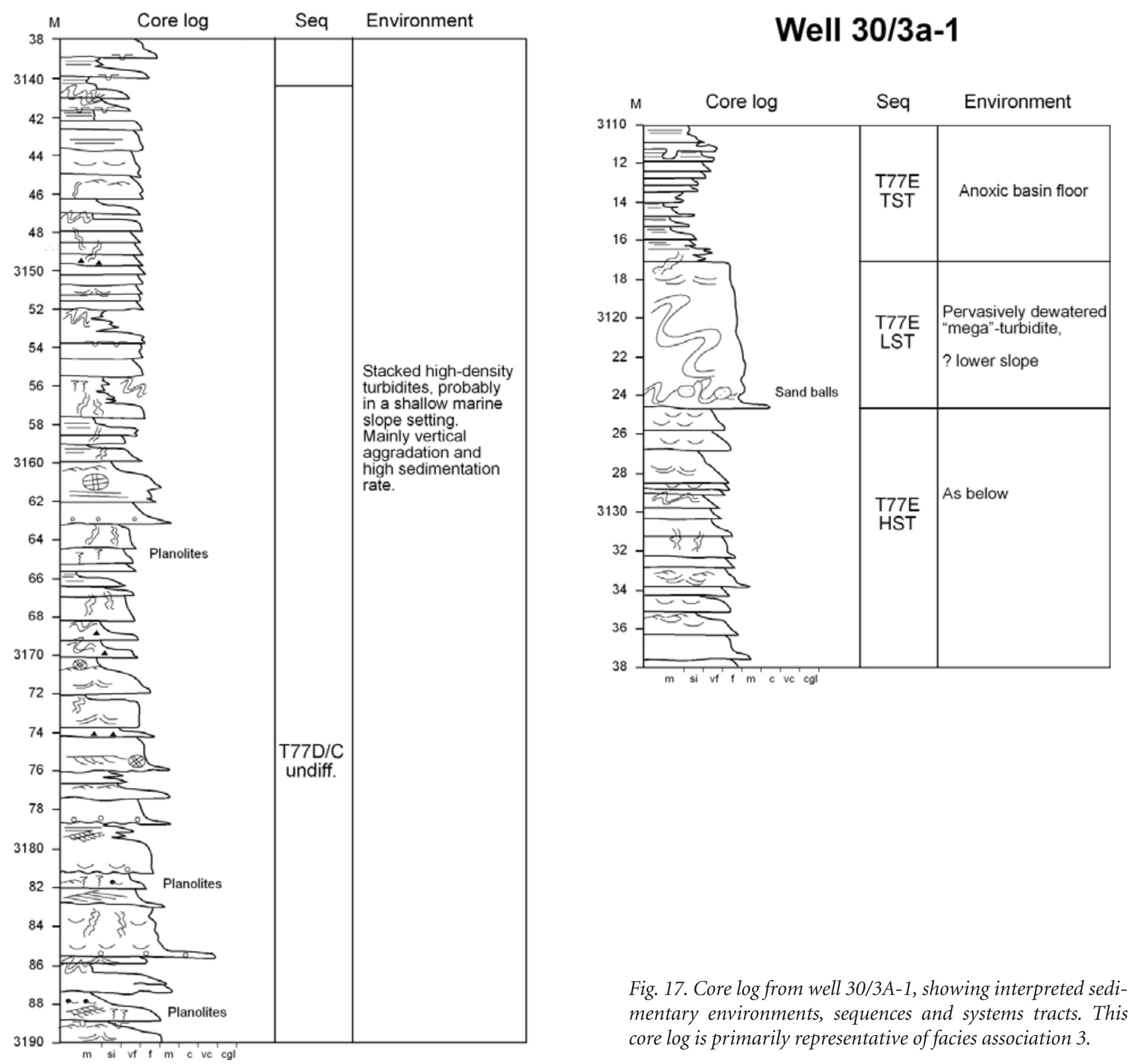


Fig. 17. Core log from well 30/3A-1, showing interpreted sedimentary environments, sequences and systems tracts. This core log is primarily representative of facies association 3.

upper parts of the CU units are composed of beds belonging to FA 4. These display alternations between well-sorted, medium- to coarse-grained sandstones with plane parallel stratification and crossbedding (Fig. 19a, c) and finer-grained sandstones containing possible wave-knit lamination (Fig. 19b), current ripples, parallel-lamination, pinch-and-swell lamination reminiscent of HCS, and trace fossils such as *Chondrites, Planolites, Teichichnus, Skolithos, Palaeophycus*, and *Diplocraterion.* FA 4 also occur as 2-20 m thick units that show no apparent grain-size trends except for occasional upwards fining tendencies at the top. Examples of such units are seen in Fig. 14 (29/4A-1 well) and Fig. 20 (T77 cycle in well 23/27-9). Sandbeds in these units are often dm-thick, medium- to coarse-grained, ungraded to normal-graded with sharp bases and tops, and contain large amounts of grey mudclasts and coal debris (twigs up to several cm in thickness have been observed). In other cases, bedsets are thicker (up to 7 m) and commonly display low-angle crossbedding with subordinate amounts of trough crossbedding and moderate- to high angle small-scale planar crossbedding, sometimes with mud-drapes (Fig. 19c). Finer-grained sandbeds similar to those of coarsening upwards units mentioned above are present as interbeds. Siderite crusts on bedding planes and siderite cement are common, particularly in association with sand-silt alternations. FA 4 is restricted in occurrence to those parts of the study area that is associated with structurally elevated areas, and is common in wells on the Josephine High (T65 sequence only), the eastern flank of the Forties-Montrose High, the western margin of the Cod Terrace, and above some of the major salt diapirs (Figs. 10 and 11).

Fig.18. Core photos from facies association 3. A) 30/3A-1, T77C cycle: slope high-density turbidites with dish structures and long vertical burrows, 3186-3188 m. Note coarse basal layer above base of mass-flow indicated by pencil. B) 22/18-5, T77E cycle at around 8683 ft.: possible shallow marine indicators (double mud drapes near base of photo, wave/combined ripples in central lower part of photo) in a fine-grained interval between deposits otherwise interpreted as slope turbidites. The base of the succeeding mass-flow bed can be seen overlying laminated siltstones near the top of the photo.

As outlined above, the Forties Sandstone Member has traditionally been interpreted as a deep-marine sedimentary system. The coarse-grained, normal-graded to ungraded 'event-beds' of FA4 may well have formed in such a setting, although the abundance of coaly debris including very large twigs, hints at the proximity to vegetated areas. However, the characteristics of the remainder of FA 4 suggest that sedimentary processes typically operating at shallower water depths may have been in operation. The presence of wave-ripples and possible HCS imply that storm/wave-generated currents occasionally reworked the sediments, and this is also indicated by the more well-sorted nature of the FA 4 sandstones compared to those of FA 3. The nature and diversity of the trace fossil suite is atypical for a deep marine setting, and the presence of high-angle crossbedding (sometimes with regularly-spaced mud-drapes) is also hard to explain without invoking traction currents operating on a temporal scale that is unlikely to occur even in sustained turbidity currents. Moreover, the absence of features such as dish-and-pillar structures and Bouma sequences implies that FA 4 was formed in an environment dominated by processes other than 'deep-water' mass-flows.

The superpositioning of FA 3 and FA 4, as seen in many of the irregular coarsening-upwards units in the Forties Sandstone Member, is indicative of a vertical transition from FA 3 mass-flows to the more shallow-water deposits of FA 4. Since these units tend to occur in association with the topsets of the seismically observed clinoforms associated with the Forties Sandstone Member, the coarsening upwards tendencies might indicate progradation of coastal lithosomes. The occurrence of FA 4 only in association with the clinoform topsets and on synsedimentary elevated areas also hints at a shallow-water environment. A discussion on the morphology of this coastal setting is provided in a later section.

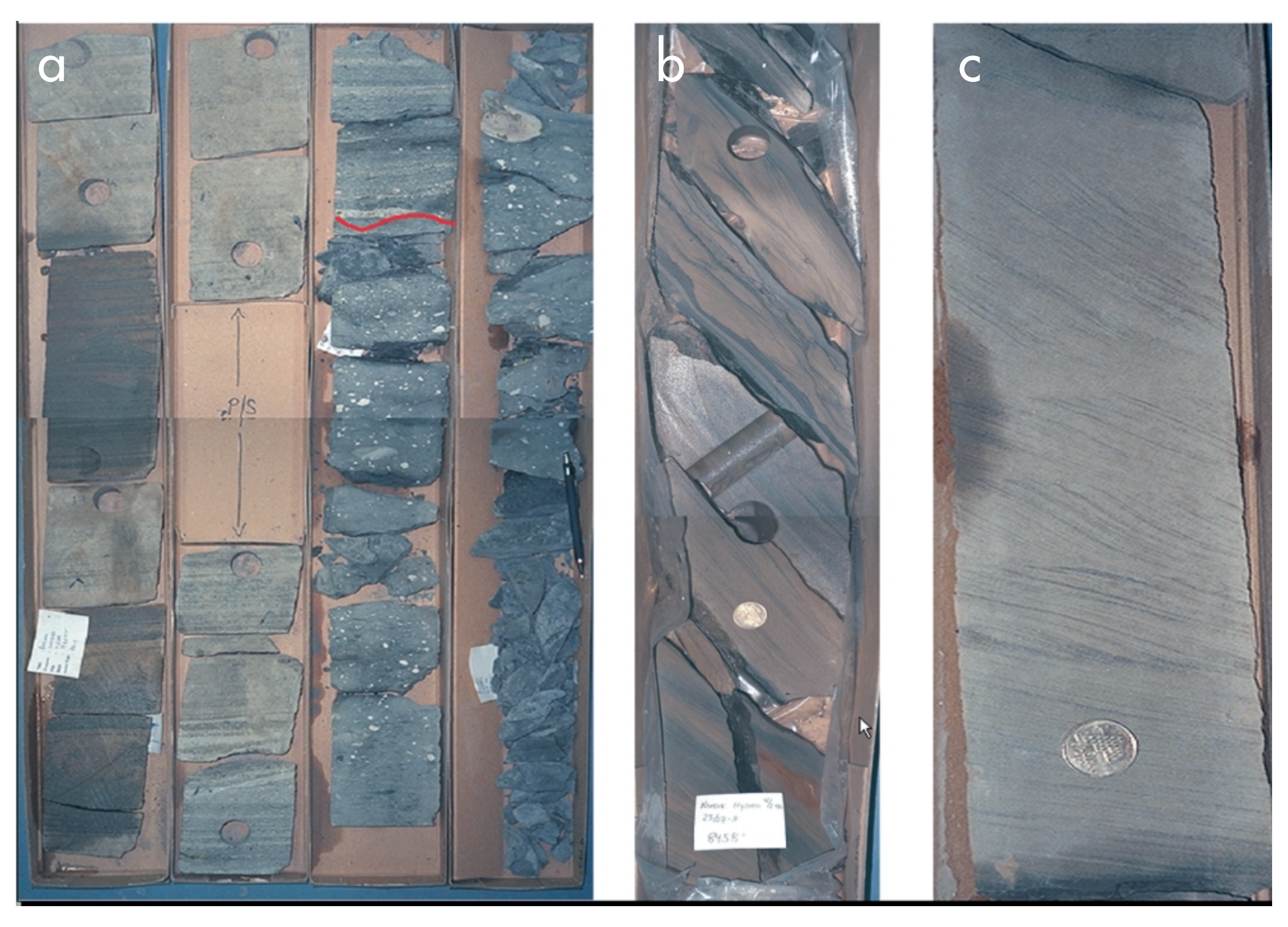


Fig. 19. Core photos from facies association 4. A) 30/7A-10, T65 cycle: FA 1 cohesive debris flows with chalk clasts erosively overlain (at red line) by FA 4 shoreline sandstone with plane parallel stratification, 9781-9793 ft. B) 23/27-8, T77C cycle: possible wave-knit lamination with carbonaceous to silty drapes, 8455-8458 ft. C) 23/22A-3, T77B cycle: sigmoidal to planar XB with abundant mud drapes, 2807 m, reflecting traction currents (spit/shoreface setting).

Facies association 5: Heterolithic deposits rich in plant material

FA 5 is only present in the T77 cycle (main part of Forties Sandstone Member), and constitutes about 5% of the studied deposits. The characteristics of FA 5 depart significantly from those usually associated with the Forties Sandstone Member, and it has therefore received much attention in this study. Like FA 4, this facies association has only been observed in wells situated on structural highs, as displayed by the green-coloured pattern on Fig. 10. It has been seen in the following cored wells:

- 7/11-A5, in the T77E lowstand unit
- 23/27-9 (T77B LST upper part, Fig. 20)
- 23/21-2 (T77 D and E LST, Fig. 20)
- 23/27-1 (T77A LST, upper part of T77B LST, and T77C LST, Fig. 21)
- 23/27-4 (most of T77 B and C cycles, Fig. 22)
- 29/4A-1A (upper part of T77D LST, Fig. 14)

Inferred occurrences in non-cored wells are based on correlation with the cored wells, taking into account structural position and seismic evidence for intra-T77 unconformities. By comparison with the palynofacies data below, it can be seen that the biostratigraphic samples taken from FA 5 fall into the non-marine to marginal-marine palynofacies categories.

FA 5 is dominated by fine-grained lithologies such as mudstone, sandy siltstone and coaly shale, but cm- to several meter thick sandstones, occasionally very coarse-grained, are also present. In addition to the clastics, a re-crystallized limestone unit, characterized by a vuggy karst-like fabric and meniscate burrows, is included in FA 5 in the T77C cycle of 23/27-1 (Fig. 21). All of the clastic deposits contain abundant organic material, especially plant fragments such as twigs, leaf particles, macerals, and root-traces (Fig. 23). The inferred presence of root-traces is obviously crucial to the interpretation of depositional environment, but convincing examples of downward-branching tube-like features associated with coal filaments and grey mud have only been found in a couple of cores (most notably in 23/27-1 and 23/21-2A). These are associated with siltstones displaying small burrows (*Diplocraterion, Polykladichnus*), dense wispy to contorted lamination,

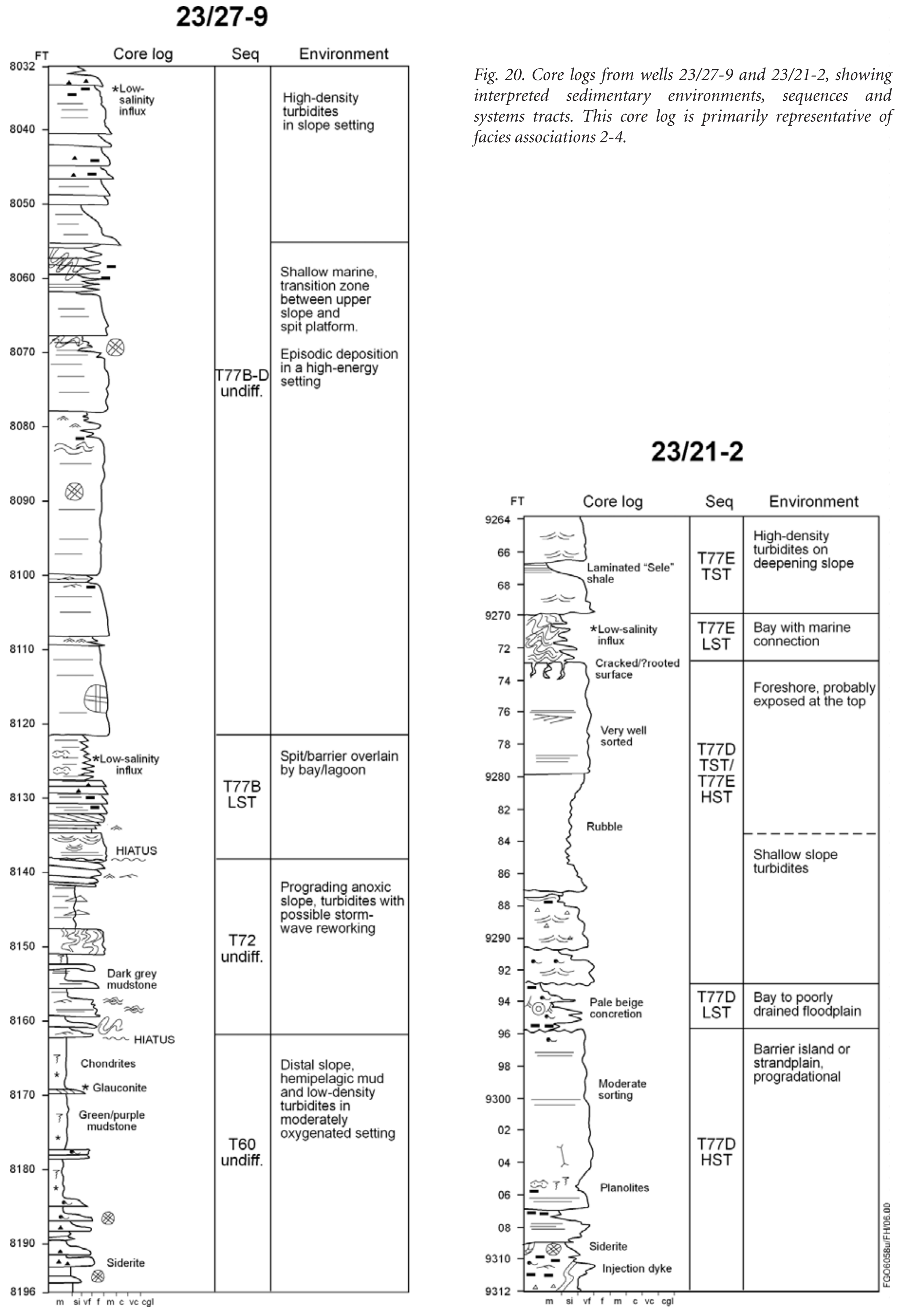


Fig. 20. Core logs from wells 23/27-9 and 23/21-2, showing interpreted sedimentary environments, sequences and systems tracts. This core log is primarily representative of facies associations 2-4.

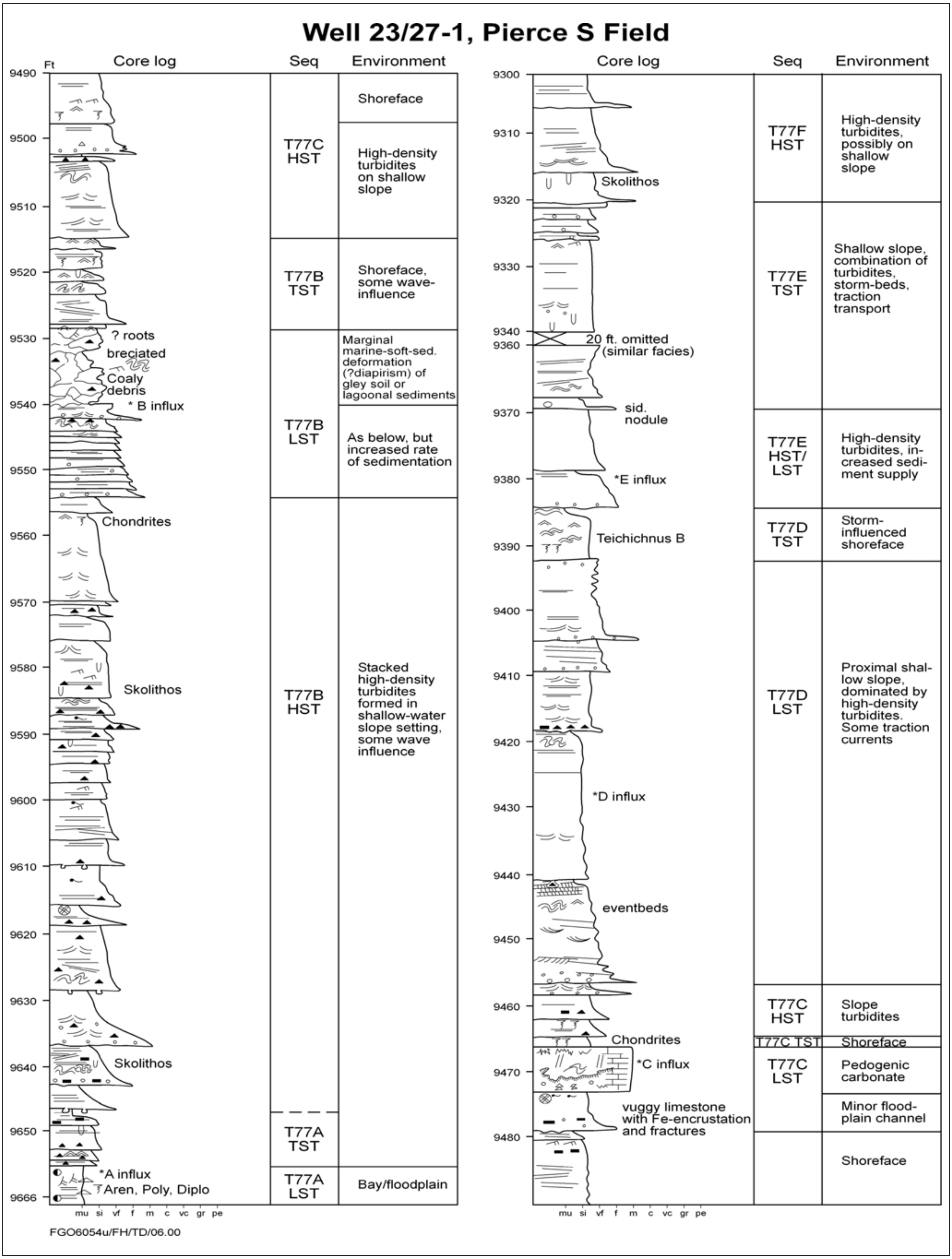


Fig. 21. Core log from wells 23/27-1, showing interpreted sedimentary environments, sequences and systems tracts. This core log is primarily representative of facies associations 3-5

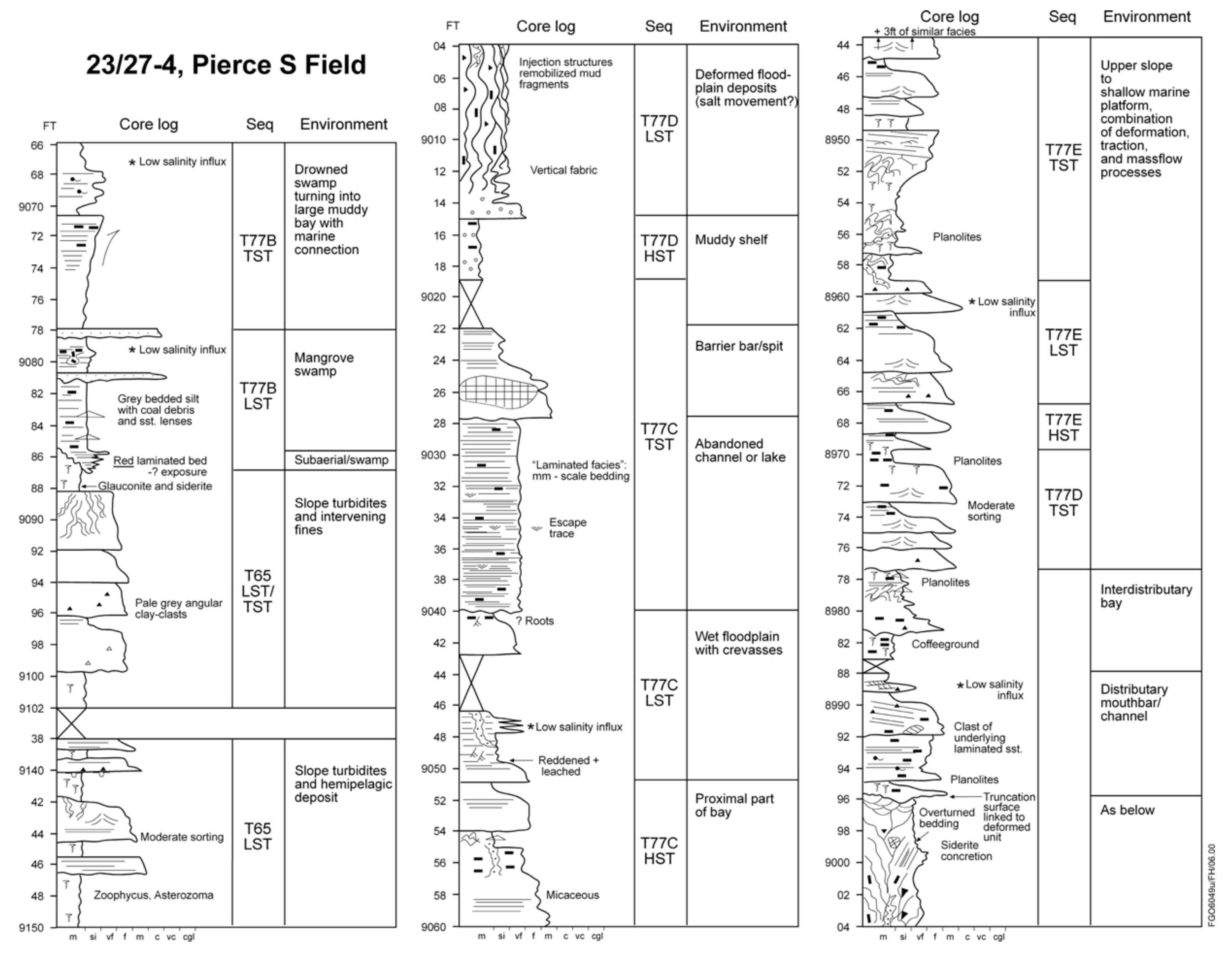


Fig. 22. Core log from wells 23/27-4, showing interpreted sedimentary environments, sequences and systems tracts. This core log is primarily representative of facies associations 3-5

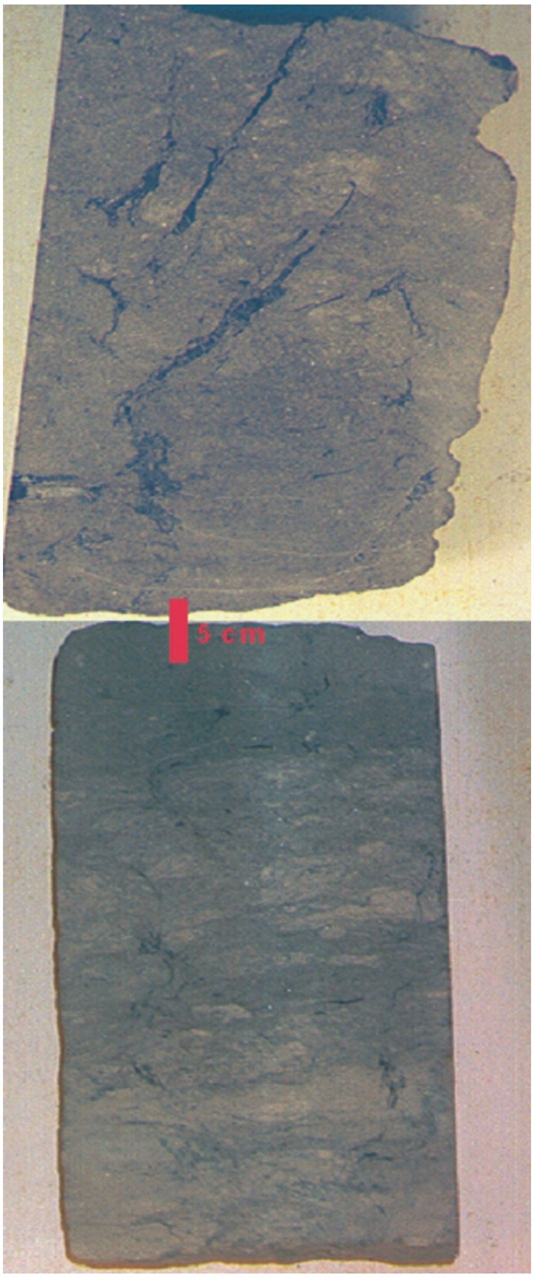


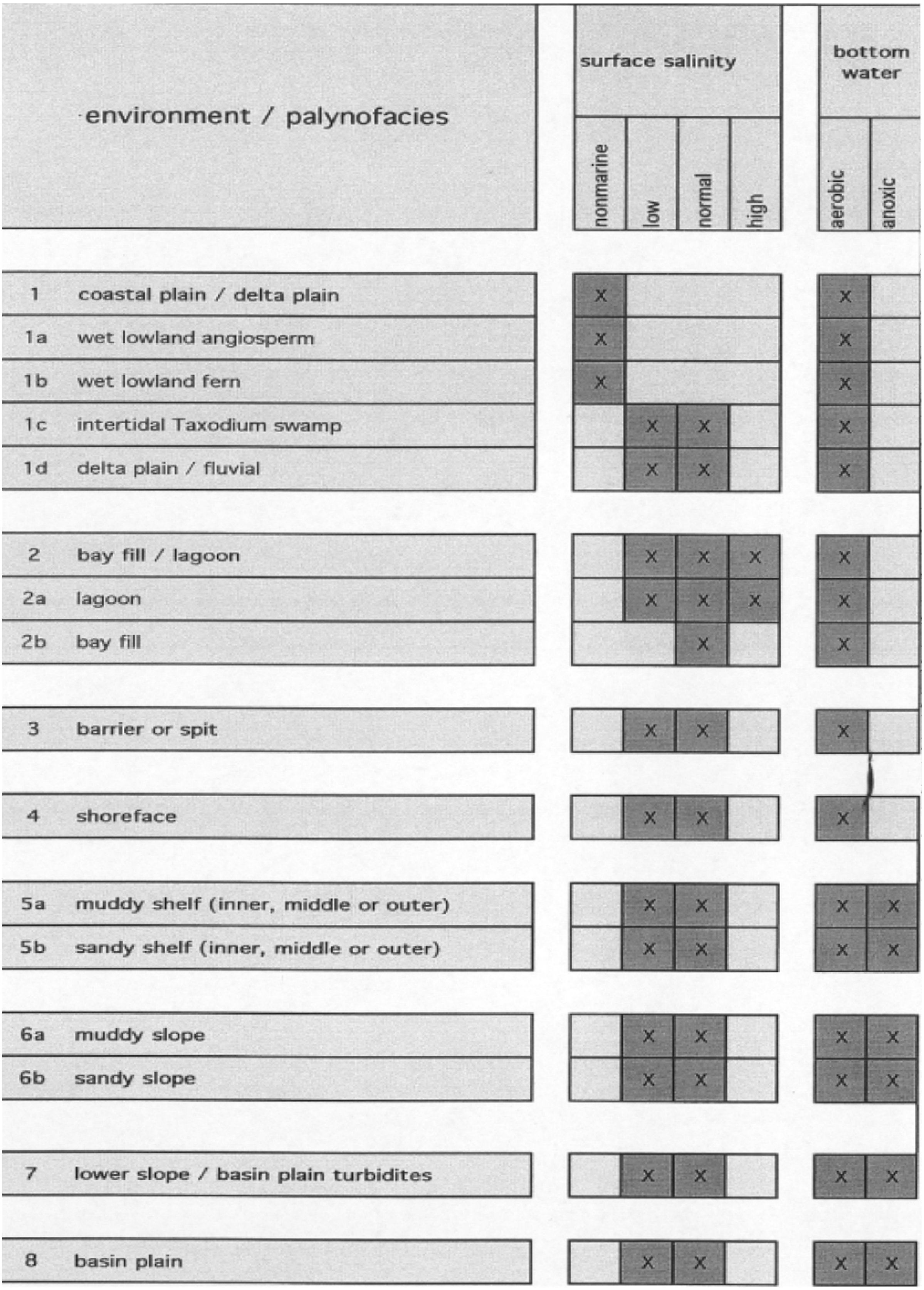
Fig. 23. Example from 23/27-1 (T77A cycle, around 9660 ft.) of probable pedoturbated intervals with root-traces.

and angular fragments of coal and claystone in an otherwise massive fabric (Fig. 23).

Otherwise, the mudstones of FA 5 are grey with mm-scale lamination, lenticular bedding and occasional *Planolites* burrows and escape traces. Reddened horizons have been seen in a few cases, most notably associated with the possible base T77 unconformity in 23/27-4 (Fig. 22). Vertically, the mudstone intervals tend to show gradual contacts to the more abundant heterolithic intervals. These are up to 10 m thick, and are characterized by cm-scale interbedding of fine-grained sandstone and grey burrowed (*Planolites*) to weakly laminated mudstone. Current and wave ripples are seen, bedding planes are extremely rich in plant fragments, and the units may in places have a distorted appearance, as witnessed by microfaulting, contorted bedding (sometimes folded into a vertical position), and large irregular mud- and sandclasts. These distorted units superficially resemble the soft-sediment deformed portions of the slope deposits in FA 2, however, the lack of water-escape structures, graded beds and the woody and burrowed nature of the FA 5 heterolithics make differentiation possible. It should also be noted that these distorted units are present in wells overlying salt domes. The thicker sandstone beds (1-5 m) in FA 5 are upwards fining, erosively-based beds with clay clast lags, and consist of plane parallel stratified to crossbedded sandstones similar to those seen in FA 4. The grain-size varies from fine to coarse, and wave ripples, climbing current ripples and coaly debris commonly occur.

Facies association 5 is interpreted as marginal marine to coastal wetland deposits. Apart from the palynological evidence (below), this interpretation is based on the presence of root-traces, the occasional reddening, and the trace fossil suite. Other lines of evidence supporting a marginal marine depositional setting are the wave ripples and the possible pedogenic features, such as the karstic limestone unit and the wispy ped-like appearance of some of the siltstones. The 1-5 m thick upwards-fining sandstone beds are thought to represent small channels that may have transported sediment from the exposed highs into the surrounding depocentres.

Due to their limited areal extent (occurring only in association with structural highs), it is envisaged that the deposits of FA5 formed on subaerial to partly submerged parts of shoals and islands rather than in association with a major deltaic coastal plain. It is difficult to assign the heterolithic deposits of FA 5 to a specific sedimentary environment. However, based on the descriptions given above, a bay/lagoon and marsh setting characterized by alternating quiescent and more agitated periods (mud/sand alternations) is envisaged. This bay/lagoon and marsh environment may be the landward part of a shoreline to marsh system similar to that described by Schwimmer & Pizzutto (2000). The superficial resemblance to the slope heterolithics of FA 2 was mentioned above, and adds a degree of uncertainty to the facies interpretation. However, the microfaulted and contorted character of some of the FA 5 heterolithic units does not imply mass-wasting processes, but might instead be indicative of early post-depositional deformation. In this context, the presence of these units above salt diapirs that underwent growth during the Paleocene (Davison et al. 2000 a, b) is interesting. Perhaps the incremental



environment / palynofacies		surface salinity				bottom water	
		nonmarine	low	normal	high	aerobic	anoxic
1	coastal plain / delta plain	X				X	
1a	wet lowland angiosperm	X				X	
1b	wet lowland fern	X				X	
1c	intertidal Taxodium swamp		X	X		X	
1d	delta plain / fluvial		X	X		X	
2	bay fill / lagoon		X	X	X	X	
2a	lagoon		X	X	X	X	
2b	bay fill			X		X	
3	barrier or spit		X	X		X	
4	shoreface		X	X		X	
5a	muddy shelf (inner, middle or outer)		X	X		X	X
5b	sandy shelf (inner, middle or outer)		X	X		X	X
6a	muddy slope		X	X		X	X
6b	sandy slope		X	X		X	X
7	lower slope / basin plain turbidites		X	X		X	X
8	basin plain		X	X		X	X

Fig. 24. Palynofacies classification scheme applied in the present study.

growth of the salt diapirs promoted emergence of small islands in the North Sea Paleocene basin, and also lead to deformation of the deposits that were able to drape the diapirs during pauses in their growth.

Palynofacies analysis

In conjunction with the sedimentary facies analysis, palynofacies studies were undertaken to interpret the environmental conditions prevailing during deposition of the Forties Sandstone Member. As discussed above, these conditions were significantly influenced by the biotic crisis that took place during deposition of the Forties Sandstone Member, causing reduced water circulation and the progressive elimination of most benthos in deeper water due to dysaerobia or anoxia.

The depth of the base of aerobic water varied at different times and in different parts of the basin due to a variety of factors such as water turbidity/movement, water temperature, the amount of water runoff and clastic input. It is therefore not possible to define a specific water depth for the aerobic/dysaerobic or dysaerobic/anoxic interface, but the presence of common to abundant sapropelic amorphous kerogen can be used to infer dysaerobic to anoxic conditions. This material mostly represents the remains of photosynthetic Coscinodiscid diatoms and both photosynthetic and phagotrophic (carnivorous) dinoflagellates cells, both of which repeatedly bloomed in the largely enclosed North Sea Basin during the Paleocene–Eocene transition.

The presence of discrete intervals containing abundant populations of the dinocyst *Subtilisphaera* within the Sele Formation also indicates that surface waters in some areas of the North Sea Basin were periodically invaded by lower salinity water. In these intervals, *Subtilisphaera* cysts occur in varying abundance with normal marine dinocyst assemblages due to the complex relationship of water masses of different salinity, both laterally and vertically, plus variations in runoff and the geography and topography of the coastline and shelf. Despite this complexity, five pulses of *Subtilisphaera* abundance can be delineated in the lower Sele/Forties interval, corresponding to pluvial events A to E discussed above. One model that could explain the repeated occurrences of these freshwater pulses is that they represent pluvial phases associated with relatively increased air and water temperature (including ‘extreme’ high temperatures within the WP3 warming event). Higher temperatures would increase the evaporation/precipitation cycle and hence result in pluvial phases and increased runoff. An alternative model is that the periods of increased runoff resulted from tectonic uplift along the basin margin, and hence at the same time as enhanced sand deposition in parts of the basin. It should be taken into account that the North Sea Basin at this time was quite stratified, so that freshwater plumes might flow quite some distance seawards above the low salinity basinal waters. Hence, the pluvial phases themselves may not be indicative of shallowing.

The palynofacies classification used in the present study utilises schemes previously published in which palynofacies methodology has been applied to a variety of sedimentary basins (Whitaker 1984; Habib & Miller 1989; Van der Zwan 1990). In the North Sea Paleocene section, Boulter & Riddick (1986) studied the Forties Field, distinguishing between 36 palynodebris types which were assessed using semi-quantitative and statistical techniques in order to distinguish sedimentological features within the depositional system. Schröder (1992) also studied the Paleocene to lowermost Eocene of the North Sea as part of a biostratigraphic project that included the Sele and Balder formations. Except for the work of Boulter & Riddick (1986) and Schröder (1992), none of the above studies are directly applicable to the unusual conditions that characterised deposition in the North Sea Basin during the Paleocene - Eocene transition.

The scheme used in the present study combines elements of published schemes with the unique conditions characterising the North Sea the Paleocene – Eocene. In this respect, it is also relevant that there is no modern analogue for the latest Paleocene North Sea. The closest example of a restricted and stratified anoxic basin is the Black Sea, but temperature and rainfall were significantly higher, fringing vegetation much more prolific, and nutrient input possibly an order of magnitude greater in the North Sea Basin.

Figure 24 shows the eight major environmental categories that were distinguished during the study. These are broadly arranged numerically from non-marine, through paralic/nearshore marine, to distal marine. Coastal plain, bay fill/lagoon and barrier/spit palynofacies are mostly aerobic and are subdivided on the basis of their local facies. Exceptions are some locally developed stagnant, anoxic water bodies that can be distinguished by the presence of pyritized sapropelic kerogen. In contrast, most marine environments vary with respect to both the surface water salinity (within the photic zone) and the degree of bottom-water oxygenation. Four sub-environments can therefore be designated for most marine environments based on a combination of salinity and oxygenation:
'B' (low-salinity, brackish' surface water)
'M' (normal salinity, 'marine' surface water)
'O' (aerobic, 'oxygenated' surface water)
'A' ('anoxic' surface water)

Palynofacies classes

The following section documents the eight environments and sub-environments (Fig. 24) based on the constituent palynomorphs and kerogen. These represent both autochthonous elements associated with habitats close to the depositional site and allochthonous elements transported to the depositional site. The latter become increasingly common in offshore marine environments and close to fluvial and deltaic outflow.

1. Coastal plain / delta plain

Consists of subgroups 1a - wet lowland angiosperm community, 1b - wet lowland fern community, 1c - intertidal *Taxodium* swamp, and 1d - delta plain/fluvial.

Preservation is good to excellent. Palynological assemblages reflect the local plant communities and are typically dominated by wet lowland angiosperm pollen and/or fern spores in wet lowland settings, and *Inaperturopollenites (Taxodiaceaepollenites)* in intertidal swamp habitats. Bisaccate pollen occurs as a background element but may be locally abundant in habitats close to gymnosperm plant communities. Fungal hyphae and fruiting bodies are common to locally abundant. Abundant woody and herbaceous material is derived from the local plant communities, and is poorly sorted and mostly comprises medium to large particles. Sapropel is typically absent, but may be common in some stratified lake and bogs. Resinous material is occasionally common in intertidal swamp environments.

In wet lowland environments, marine dinocysts and brackish water algae and dinocysts are only present due to storm deposits or as reworked elements. The freshwater alga *Pediastrum* is locally common to abundant. In intertidal swamps, brackish water algae and dinocysts may be common to abundant, but marine dinocysts are typically absent to rare. Delta plain to fluvial assemblages away from the immediate vicinity of a single plant community comprise a mixture of pollen and spores which have good to excellent preservation. Fungi and freshwater algae such as *Pediastrum* with excellent preservation may be locally common. Rare marine dinocysts may occur due to reworking or as a result of storm deposits.

2. Bay-fill or lagoon (depending on development of barrier)

Consists of subgroups 2a - lagoon (may be brackish, normal salinity, hypersaline) and 2b - bay fill: normal marine salinity.

Preservation is good to excellent, particularly in lagoons due to the low-energy regime and minimal transportation. Miospore assemblages reflect the local plant communities and are typically dominated by angiosperm pollen and/or fern spores close to wet lowland settings, and *Inaperturopollenites (Taxodiaceaepollenites)* in intertidal swamp habitats. Bisaccate pollen such as pine (*Pinus*) and spruce (*Picea*) can occur commonly as they can be transported long distances by wind. Fungal hyphae and fruiting bodies are common to locally abundant.

Aquatic palynomorphs vary according to the salinity regime. Brackish lagoons contain distinctive low-diversity, high-dominance assemblages including *Cyclopsiella* and *Paralecaniella*. Some *Leiosphaeridia*, the prasinophycean alga *Pterospermella* and certain dinocysts of the *Subtilisphaera* plexus may also inhabit low-salinity lagoons. Aquatic assemblages inhabiting high-salinity lagoons are less well documented, but probably include some undescribed small spinose dinocysts. These forms possibly have a wide salinity tolerance extending into normal or even low-salinity habitats. In addition to brackish and high-salinity assemblages, marine populations occur in bays and some lagoons due to continuous or intermittent marine connection. These populations contain marine dinocyst taxa such as *Apectodinium, Areoligera, Cerodinium, Cordosphaeridium, Glaphyrocysta, Hystrichosphaeridium* and *Spiniferites*. The relative abundance of these taxa depends on a variety of factors including the nature of the adjacent marine habitats.

3. Barrier or spit

Kerogen recovery is generally low, with grains having poor preservation due to high energy and frequent oxidation. The kerogen is typically dominated by rounded inertinite and sometimes abundant wood fragments. Palynomorphs are rare, poorly preserved and mostly comprise thick walled forms that are more resistant to oxidation and abrasion.

4. Shoreface

Kerogen is similar to that in barrier and mouth bar facies, but includes a higher number of nearshore marine and non-marine palynomorphs. The preservation of some palynomorphs is fair, but most have poor preservation due to abrasion and oxidation.

5. Muddy shelf and sandy shelf

Consists of subgroups 5M - marine surface water, 5B - brackish due to freshwater surface plume, 5O - oxygenated (aerobic) bottom water, and 5A - anoxic bottom water. In the muddy shelf category, marine dinocysts are relatively abundant and well-preserved. Although modern marine dinocyst populations vary on different parts of the shelf, transportation and mixing of populations generally makes precise differentiation of palaeo-shelf environments difficult except in nearshore regimes. Fossil species from nearshore environments probably include *Hystrichosphaeridium*, with *Apectodinium, Areoligera, Cerodinium, Cordosphaeridium, Glaphyrocysta, Hystrichosphaeridium* and

Spiniferites characterizing various mid to outer shelf habitats.

Miospore populations broadly reflect the adjacent plant communities, but this relationship becomes less well developed offshore and in areas affected by longshore currents. Heavier spores are less well represented offshore, with wind-blown bisaccate pollen becoming more abundant. Preservation is fair to good. Woody and herbaceous material derived from the plant communities is poorly sorted in nearshore environments and become better sorted offshore. Brackish water dinocysts such as *Subtilisphaera* are abundant in areas of high runoff and surface fresh-brackish water plumes. The amount of pyritized sapropelic kerogen reflects the degree of bottom water oxygenation, increasing with bottom water anoxia.

In the sandy shelf category, assemblages characterising muddy shelf deposition occur plus less well preserved material potentially transported from more proximal marine, paralic and nonmarine environments discussed above. Sandy shelf environments may therefore be characterised by a variety of allochthonous material and are often difficult to distinguish from sandy slope environments based solely on palynofacies analyses.

6. Muddy slope and sandy slope

Consists of subgroups 6M - marine surface water, 6B - brackish due to freshwater surface plume, 6O - oxygenated (aerobic) bottom water, and 6A - anoxic bottom water

In the muddy slope category, dinocysts are well-preserved, common to abundant, and mostly represent taxa dispersed by surface water currents from more proximal shelf habitats prior to sinking. Some specimens may also be transported from shelf areas due to sediment transportation. The dinocyst populations are relatively diverse and include the genera *Apectodinium, Areoligera, Cerodinium, Cordosphaeridium, Glaphyrocysta, Hystrichosphaeridium* and *Spiniferites* which characterise various mid to outer shelf habitats. Miospore populations are similar to those in adjacent middle to outer shelf areas, and generally have the same relative abundance to marine dinocyst populations, so that it can be difficult to distinguish outer shelf from slope environments based on miospore populations. However, heavier spores are less well represented than in shelf environments and wind-blown bisaccate pollen may be more abundant. Brackish water dinocysts such as *Subtilisphaera* are abundant in areas of high runoff and surface fresh-brackish water plumes. The amount of pyritized sapropelic kerogen reflects the degree of bottom water oxygenation, increasing with bottom water anoxia. Preservation is fair to good.

In the sandy slope category, assemblages characterising muddy slope deposition occur plus less well-preserved material potentially transported from more proximal marine environments discussed above. Sandy slope environments may therefore be characterised by a variety of allochthonous material and are often difficult to distinguish from sandy shelf environments based solely on palynofacies analyses.

7. Lower slope / basin plain turbidites

Consists of subgroups 7M - marine surface water, 7B - brackish due to freshwater surface plume, 7O - oxygenated (aerobic) bottom water, 7A - anoxic bottom water. Subgroup 7B is more commonly developed than in other facies; 7A is less commonly developed than in muddy shelf and slope facies due to vertical mixing of water masses.

Kerogen is poorly sorted and comprises abundant transported woody debris and rare to common herbaceous plant debris. Preservation is typically poor due to the high-energy environment. Sapropelic kerogen is variably present, reflecting bottom-water conditions and varies from absent in oxygenated bottom waters to abundant in anoxic bottom waters. Dinocysts, spores and pollen are rare due to dilution by woody debris and high sedimentation rates. Fungal hyphae are locally common due to transportation from delta top environments. The ratio of brackish to marine dinocysts is generally high due to brackish/freshwater plumes associated with fluvial discharge.

8. Basin plain quiescent

Consists of subgroups 8M - marine surface water, 8B - brackish due to freshwater surface plume, 8O - oxygenated (aerobic) bottom water, 8A - anoxic bottom water.

Kerogen and palynomorph assemblages are broadly similar to those in muddy shelf and slope environments, but with a higher proportion of wind-transported bisaccate pollen and *Inaperturopollenites* (= *Taxodiaceaepollenites*) that are transported relatively long distances by water. Heavier spores are less well represented than in shelf and slope environments. Dinocysts are well preserved, generally common, and mostly represent taxa dispersed by surface water currents from more proximal shelf habitats prior to sinking. The dinocyst populations are relatively diverse and include the genera *Apectodinium, Areoligera, Cerodinium, Cordosphaeridium, Glaphyrocysta, Hystrichosphaeridium* and *Spiniferites* which characterise various mid to outer shelf habitats.

Brackish water dinocysts such as *Subtilisphaera* are common in areas of high runoff and surface fresh-brackish water plumes, but overall tend to be less abundant in shelf and slope environments. The amount of pyritized sapropelic kerogen reflects the degree of bottom water oxygenation, increasing with bottom water anoxia. These conditions prevail in basin plains environments. Preservation is generally good to excellent. Woody and herbaceous material derived from the plant communities is rare.

Results of the palynofacies analyses

The above classification implies that a large range of palaeo-environments was present during deposition of the Forties Sandstone Member. A graphical contrast between some of these palynofacies can be seen on Fig. 25. Interpretations based on palynofacies analysis generally have a higher level of confidence in nearshore marine and non-marine locations than in offshore environments due to increased transportation and mixing of material in the latter. This is particularly important in the present study because independent palynofacies, sedimentological and seismic interpretations indicate that some of the Forties sections were deposited in non-marine to nearshore environments, with the recognition of these non-marine and shallow marine palynofacies being crucial to the model presented in this study.

The most common palynofacies classes in the studied succession are palynofacies 6, 7 and 8, indicating deposition in slope to basin plain settings with anoxic bottom conditions. In these locations, amorphous sapropelic kerogen is abundant and probably mostly represents the remains of unicellular microplankton (diatoms and dinoflagellates). This material can only be incorporated into the sediments in significant quantities when no benthos is present to ingest and re-circulate the sinking organic material. Slope and basin plain environments were interpreted in the following 29 cored wells:
22/18-5: 8603,5-8719,2ft
22/20-2: 8953,0-9232,5ft
22/24b: 9625,5-9675,0ft
22/25b-5: 9542,2-9973,6ft
22/30a-5: 9900,5-10082,0ft
23/21-2: 9269,0ft
23/21-4: 12730,4-12993,0ft
23/22-1A: 9316,3-9416,0ft
23/22a-2Z: 8952,0-9195,1ft
23/22a-3: 8911,6-9300,1ft
23/26a-17: 8547,8-8601,6ft
23/27-1: 9310,4-9368,0ft
23/27-1: 9567,1-9660,0ft
23/27-2: 10247,3-10347,8ft
23/27-4: 9087,0-9148,3ft
23/27-5: 9120,0ft (2779,8m)
23/27-7: 10190,2-10360,8ft
23/27-8: 8257,5-8443,5ft
23/27-9: 8035,5-8195,0ft
30/2-1: 10039,4-10058,0ft
30/2a-2: 10329,6-10378,5ft
30/3a-1: 10210,8-10453,9ft
N1/2-1: 10217,5-10383,5ft
N1/3-6: 9584,5-9605,5ft
N1/3-7: 10421,5-10638,7ft
N7/11-1X: 9590,0-9701,0ft
N7/22-3X: 10086-10111ft
N7/11-A5: 9626,0ft; 9557,0ft
N16/1-4: 1705,9ft (520,0m)

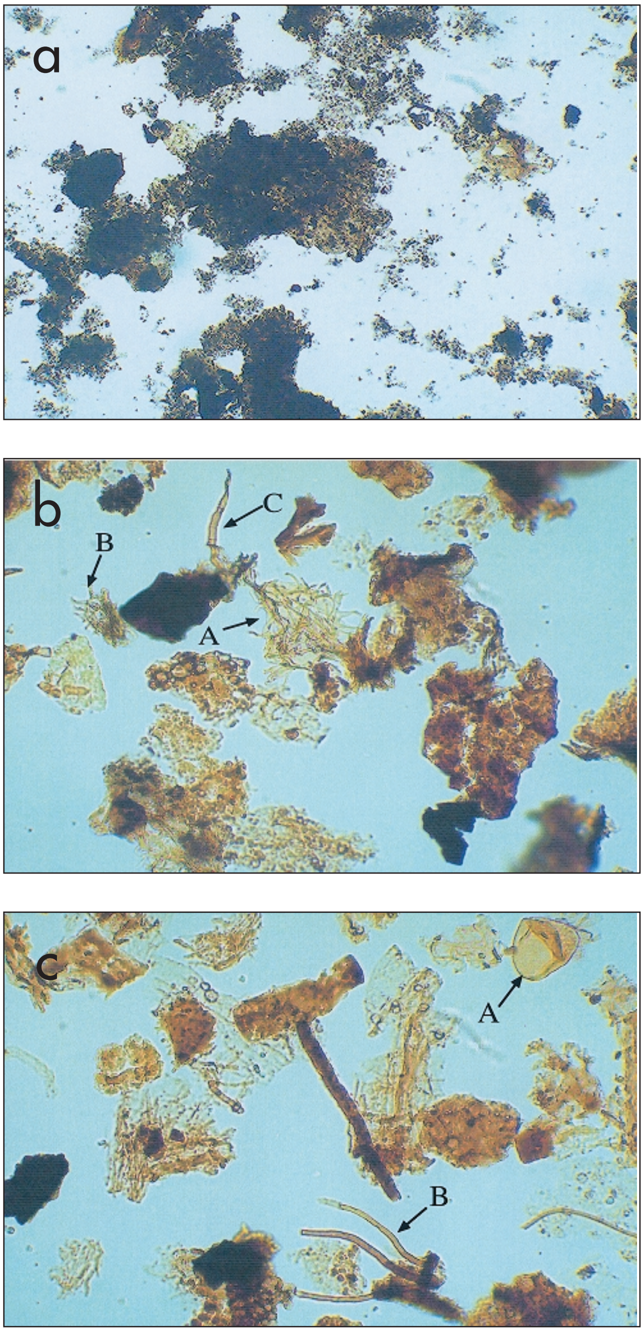


Fig. 25. Photographs of contrasting palynofacies. A) Basin plain category - amorphous sapropel, B) Nearshore category - neritic dinocysts mixed with broken (high-energy) spores and fungi, C) Coastal plain category - non-marine assemblage dominated by well-preserved spores and fungi.

The second most common palynofacies class is the shelfal deposits of palynofacies 5. Anoxic bottom water conditions become progressively more rare in shallower shelf environments, and are typically not developed in inner neritic environments due to wave action. Shelf environments were interpreted in 12 of the cored wells:
22/30a-5: 10038,2-10065,2ft
23/21-2: 9270,5-9283,5ft
23/22a-3: 9242,3ft
23/27-4: 9067,8-9071,7ft
23/27-5: 9038,6-9066,8ft
23/27-6: 9631,1-9841,2ft
29/3a-2: 8833,0-8842,5ft
29/5a-3: 9541,0-9574,2ft
30/14-1: 9489,1-9720,0ft
30/7a-10: 9759,5-9816,0ft
30/7a-11Z: 9586,3-9637,3ft
N7/11-3X: 10147,0-10429,0ft

Nearshore marine and paralic palynofacies belonging to classes 2, 3 and 4 are less common. Anoxic bottom water conditions are typically not developed in these environments due to wave action. Shoreface environments were interpreted in the following eight cored wells:
22/24b-ST1: 9654,3ft
23/27-8: 8448,0ft
30/7a-10: 9783,3ft
30/7a-11Z: 9654,8ft
N1/2-1: 10377,5ft
N7/11-1X: 9608,8ft
N7/11-3X: 10376,0-10388,0ft
N7/11-A5: 9565,0-9583,0ft

Barrier or spit environments were interpreted in the following six cored wells:
23/27-1: 9368,0-9455,7ft
23/27-4: 9017,0ft
23/27-5: 9172,0-9250,6ft
23/27-9: 8035,5-8125,4ft
29/4a-1A: 9445,0-9454,5ft
30/1-1A: 10188,10-10260,1ft

Bay fill or lagoon environments were interpreted in the following five cored intervals:
23/21-2: 9294,5-9310,0ft
23/27-1: 9466,0-9534,0ft
23/27-4: 8960,0-8989,0ft
23/27-4: 9079,2-9084,0ft
N7/11-A5: 9593,0ft

Non-marine palynofacies of class 1 (discussed above) are subdivided into delta plain/fluvial and coastal plain, with wet lowland habitats containing fern and angiosperm plants communities being distinguished (palynofacies 1). Intertidal swamps characterized by abundant *Taxodiaceaepollenites* are included in this category. Anoxic bottom water conditions are typically not developed in these environments except in stagnant lakes and probably to a minor extent locally in swamp environments. Non-marine environments were interpreted in five cored intervals:
23/27-1: 9466,7ft
23/27-4: 8960,0-8989,0ft
23/27-4: 9048,0ft
23/27-4: 9079,2-9084,0ft
N7/11-3X: 10156,0ft

By comparison of the above data with the structural map of Fig. 2, it is clear that nearshore to non-marine palynofacies occurrences are found in wells located on structural highs or salt domes. This and other aspects of the palynofacies interpretations will be discussed when reviewing all of the different data types in the next section.

Discussion: paleogeography and local shallow-water deposition

General indicators of shallow-water conditions

Although most of the Forties Formation formed in relatively deep-water conditions, the data presented above imply that shallow-marine conditions prevailed locally within the study area (associated with structural highs, see below). Since this conclusion has important implications for prospectivity in terms of presence and nature of reservoir rocks, an integrated discussion of the shallow- to marginal marine aspects of the depositional model will be given in the following section.

In the North Sea as a whole, the concept of local shallow-water conditions during latest Paleocene to earliest Eocene times is well established (i.e. 'Dornoch delta' and related units discussed in Mudge & Copestake 1992 and Dixon & Pearce 1995). However, these shallow marine deposits have so far only been documented for westerly regions of the basin, such as in the Outer Moray Firth and on the East Shetland Platform, and our suggestion that shallow-water conditions also existed in parts of the South Central Graben is therefore quite radical. The presence of shallow-marine sediments to the east has been related to maximum Paleocene coastal progradation caused by large sediment influx from the tilted and uplifted East Shetland Platform (e.g. Jones & Milton 1994; Dixon & Pearce 1995; Neal 1996). This concept is well documented on regional seismic lines from areas to the north of the presently studied region, where large-scale deltaic clinoforms are seen to prograde westwards during this period. Progradation occurred during conditions of overall relative sea-level rise causing aggradation of the coastal system in a relatively narrow zone near the eastern edge of the East Shetland Platform. This trapping of sand proximally meant that the rate of relative sea-level rise locally overwhelmed the rate of sediment supply in basinal areas, thus causing net retrogradation of submarine fans in some distal areas (Galloway 1998).

As illustrated in the seismic section, clinoform-like seismic features that might reflect shallow-marine conditions occur in the stratigraphic interval between the top Lista and top Forties reflectors. These offlapping reflectors have dips between 0.5-2 degrees and heights of 30-90, and their progradational geometry with a flat topset portion, a well-developed breakpoint or rollover and a gently sloping to tangential foreset to bottomset morphology (Fig. 7) makes them comparable to shelf-slope clinoforms described in the literature (i.e. Mitchum et al. 1977; Helland-Hansen 1992; Fulthorpe & Austin 1998; Dreyer et al. 1999; Driscoll & Karner 1999). The front of the larger of these clinoform sets is readily mappable on seismic data, since a marked thinning of the Forties succession is associated with lines corresponding to the breakpoints of this unit. This thinning, which takes place over the 2.5-5.5 km wide zone comprising the foreset part of the clinoform, involves a reduction in T70 thickness from 120-170 m in the sandy breakpoint area to 10-60 m in the muddy bottomset area. The clinoform fronts show a general NW-SE orientation, extending across the Norwegian sector in blocks 1/3, 7/12 and 7/11 (northern breakpoints), and from block 1/6 into the southwestern corner of block 1/2 (southern breakpoints) (dotted line of Fig. 5). In the UK sector, there is a tendency for the northern breakpoint line to curve around to attain an E-W orientation in the vicinity of the Lomond Field. Offlapping patterns are also known from deep-marine submarine fan settings, particularly at distal reaches of such areas where the overall fan system thins and the lobes prograde across sediment-starved basin plains. This might explain some of the smaller and less continuous clinoform patterns seen in the study area, but seems at odds with the main, continuous offlap-front outlined above. It is therefore suggested that this main offlap-front represents the depositional shoreline break or shelf break of a shallow-marine system. If this is the case, shallow-marine depositional elements were present west to southwest of the dotted line on Fig. 5 during the T77 cycle, with slope and basin plain areas east and northeast of this line. Local deep-water conditions within this 'Forties shallow-marine province' certainly seem to have prevailed, for instance in structural lows between salt ridges. At the present stage of investigation, however, the study area is not completely covered by 3D seismic data, so a more detailed scrutiny of the seismic geomorphology should be made at a later stage.

Both the sedimentary facies and the palynofacies schemes comprise elements that are indicative of shallow-water sedimentation. The two independent facies interpretations can be compared by using their common geographical database (each palynofacies sample has a unique well number and core-depth for which a sedimentary facies interpretation is also available). This database (parts of it listed in above sections) together with the information contained within the isopach- and structural maps, reveal two important factors:

1) There is a strong tendency for samples belonging to the shallow- to marginal marine palynofacies categories to be derived from core intervals that are interpreted to contain shallow- to marginal marine deposits.
2) Virtually all of the palyno/sedimentary facies thought to reflect shallow- to marginal marine conditions are found in wells located on structural highs where a relatively thin Forties succession is present. This implies that the structural highs were positive-relief features during T70 deposition, and that the depositional and oceanographic conditions associated with these elevated areas promoted coeval development of atypical palynological and sedimentary facies assemblages. These assemblages are characterized by wave-related structures, heterolithic deposits with few massive sands, a high input of terrestrial material (proximity to vegetated areas), moderate amounts of bioturbation despite the mostly anoxic conditions in the basin, and a scarcity of fully marine dinocysts. The watermasses above the structural highs are believed to have been more agitated and nutrient-rich than those of the surrounding areas, promoting both the increased amount of *Apectodinium* and *Subtilisphaera* ('pluvials') and the shallower-water facies types.

In sum, the widespread seismic clinoform front, the palynofacies with non- to marginal marine affinity, and the sedimentary facies indicative of nearshore to subaerial depositional conditions on structural highs, imply that shallow-water conditions may have existed locally during the Late Paleocene within the study area.

Paleogeography at the Lista-Forties transition

Based on the above datasets, a series of paleogeographical maps was constructed, highlighting the manner in which the depositional setting and in particular the coastal morphology changed throughout Late Paleocene times (Figs. 26 and 27).

In the **T72 cycle**, most of the study area was in a mud-prone slope to basin floor setting (Fig. 26a). However, structural uplift may have been initiated at the transition from the Lista to the Forties/Sele Formations along the Josephine High and probably also on the Forties-Montrose High, as seen by the thin Late

Paleocene succession in these areas. Sheet-like 5-10 m thick FA 4 sandstone units interpreted as shoreline deposits are present in cores from Josephine High wells (not shown in this paper). These sandstones unconformably overlie slope mudstones and debris flows of FA 2 (Fig. 19a), and similar debris flows rich in chalk clasts tend to reappear in the finer-grained section above the FA 4 sheet sandstone. Log patterns and occasional core data from time-equivalent downdip deposits imply that a muddy succession with some chalk-rich debris flows are present as lateral equivalents to the shoreline sheet-sands. The entire succession has been interpreted as mass-flow deposits belonging to the Andrew Formation (T40 in this study) by Pauley (1995) and Holmes (1999). However, our biostratigraphic data show that the sandstones contain vast amounts of reworked material from the Andrew and Maureen Formations mixed with what is believed to be in-situ biostratigraphic markers characteristic of the transition between the T60 and T70 cycles. Moreover, the presence of shelf/shoreface palynofacies types and the dominance of low-angle crossbedding, subhorizontal lamination and presence of trace fossils such as *Skolithos* and *Palaeophycus* are indicative of a shallow high-energy environment rather than a submarine fan system. The presence of this sheet-like sandstone only in wells on structural highs strengthens this argument. It is envisaged that the shoreline sandstones formed by reworking of older (sandy) deposits as the highs were uplifted into the zone of wave reworking. The preceding mass-flows indicate mass-wasting processes during initial phases of uplift, whereas the younger mass-flows may reflect renewed slope sedimentation as the highs once again became submerged in the ensuing transgressive phase. The observation that the older (T65) sandstone unit seems to be present on the crest of the Josephine High (crosshatched area on Fig. 26a) while the younger (T72) sandstone unit appears to be present only on the eastern flank indicate slow rise and eastward tilt of the high, thus pushing the shoreline downdip as elevation increased. Note that an unconformity surface corresponding to the T70 IRS is inferred from wireline log data in the crestal wells on the Josephine High. This surface is thought to have formed during continued uplift of the high during the T70 cycle, and erosion or non-deposition associated with T70 IRS was responsible for the thin development of this cycle in the area.

In the basinal areas east of the highs, both the well correlations and seismic data imply the presence of local fan-shaped thickness anomalies associated with the T60 - T72 cycles. The few cores through these units are exclusively composed of the more heterolithic version of FA 3, usually with 75% sandstone and 25% mudstone. They are interpreted as submarine fans in a lower slope to basin floor position that were fed by slope channels receiving eroded material from the nearby highs. Subsequent differential compaction and the pinchout of these fans into FA 2 mudstones imply that they may form traps with a combined structural and stratigraphic closure.

Lower Forties Sandstone Member paleogeography

As is suggested by the large erosion/bypass areas in Fig. 26b, tectonic uplift of basement highs peaked at the stratigraphic interval corresponding to the base of the main Forties sandstone unit, probably in relation to the Thulean volcanic phase and the opening of the Atlantic ocean (Nadin & Kusznir 1995; Dore & Jensen 1996). Biostratigraphic evidence coupled with seismic data and log correlation suggest that the lower part of the T70 cycle is missing or very thin both in the western and northeastern parts of the study area, effectively creating a NNW-SSE oriented elongated depositional centre corresponding mostly to the East Central Graben and the Breiflabb Basin (Fig. 2). Within this depocentre, several actively growing salt diapirs and footwall highs existed, as is evidenced by the absent to condensed T70 deposits on top of these structural elements. Seismic sections and isopach maps (Figs. 6 and 7) illustrate these changes from thin T77 deposits on the highs to rapidly expanding T77 successions in the surrounding elongated sub-basins. The area of thickness expansion is often associated with clinoforms dipping away from the highs.

The complex basin physiography is reflected by the lateral variation in facies types. In 23/27-1, the lower to middle portions of the Forties Sandstone Member contain deposits of FA 5 displaying root-traces (Fig. 23) and non-marine palynomorphs (Fig. 25). These marginal marine heterolithics (grey on Fig. 26b) occur locally on the Pierce South and other salt domes and on parts of the Forties-Montrose High. In association with the latter example, elongated and channel-like seismic thickness anomalies crossing the southwestern part of the study area might represent remnants of distributaries supplying sediment to the central parts of the study area.

Deposits belonging to FA 4 (yellow and green on Fig. 26b) are thought to have occurred adjacent to the FA 5 units at a slightly lower topographic level on the structurally elevated areas. T77 A-C cycle shallow-marine sediments have been inferred in a number of cored wells, including 7/11-1X, 7/11-3X, 23/27-9 (Fig. 20), 23/22A-3, 23/27-1, -2 and -8 (Fig. 21), and 30/1-1. Log correlations suggest that these shallow-marine lithosomes formed irregular, elongated rims around the highs, with a preferred direction of elongation to the south and southeast. Further downdip, in wells located in the flanks and sub-basins between the highs, these shoreline-shoreface deposits are transitional to thick successions of FA 3 sandy slope deposits (orange on

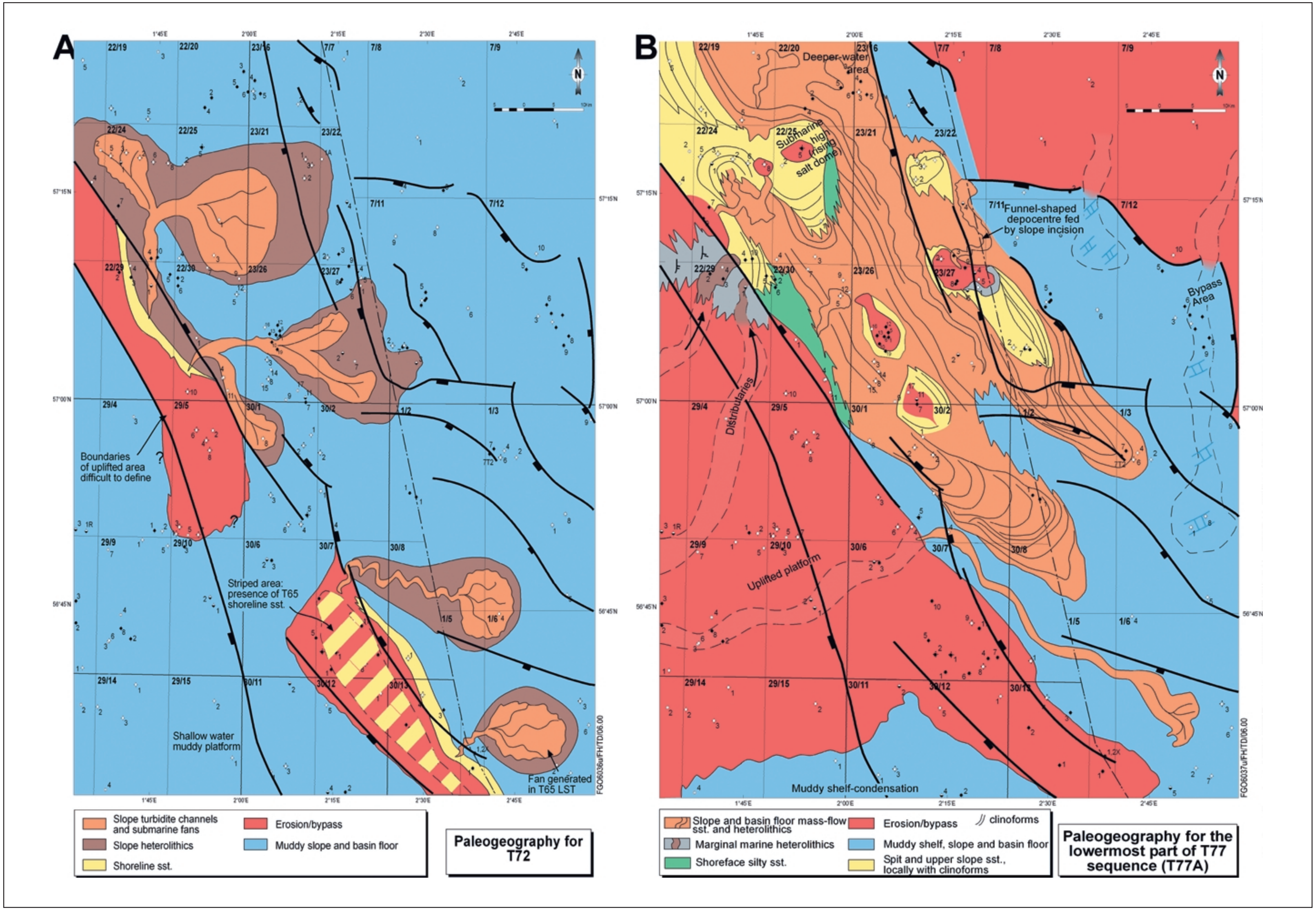


Fig. 26. Paleogeographic reconstructions of the study area. A) Lista-Forties formations transition, note suggested emergence of reactivated Mesozoic high and the effects of this on the sedimentation patterns. B) Basal part of the Forties Sandstone Member, with major depocentre in the East Central Graben and high areas flanking this trough. Note emergent salt domes and associated shallow-marine systems (i.e. spits) within the East Central Graben.

Fig. 26b) that in turn interfinger with fine-grained slope and basin floor deposits of FA 1 and 2 (Figs. 10 and 11). The water depth in this setting appears to have varied from 0-150 m according to the facies distribution and the height of clinoforms seen on seismic sections crossing the 'basin-and-high' province (i.e. Fig. 7). Core and seismic data imply that the greatest water depths were developed in block 22/20 and in the western to central parts of block 23/16. This is the only area where one consistently finds the 'massive' sandy turbidites of FA 1, although log and isopach data imply that conditions suitable for forming such deposits also may have existed in downdip parts of blocks 23/21 and 23/22 (i.e. the blocky T77 well-logs in 23/22A-4). Consequently, this depocentre area, which has been given a stippled orange pattern on Fig. 26b, probably represented a sand-prone basin floor region located between diapirs and on the downfaulted side of the Cod Terrace. To the northeast, deposits of the T77A cycle appear to be missing, possibly due to the existence of an uplifted shelfal area located in a position of the present-day Jæren High (Fig. 26b). The absence of the lower parts of the T77 cycle to the west leads us to speculate that this area may have experienced sediment bypass or even undergone erosion at this time (incision surfaces are seen locally on seismic data). Further discussion of this somewhat unusual coastal morphology will be given below.

Upper Forties Sandstone Member paleogeography

The uppermost part of the Forties Sandstone Member (T77 D and E cycles) is stratigraphically located near the top of the *Apectodinium*-bearing interval (pluvial phase E, see above). Comparison of Figs. 26b and 27a implies that significant retrogradation of the Forties depositional system took place between the T77C and T77E cycles. The local highs associated with salt diapirs appear to have become partly submerged, and some of these (i.e. Pierce-Lomond area) seems to have become sites of major offshore sand ridges, similar to modern-day salt related shoals such as the Ship Shoal offshore Louisiana and those surrounding the Helgoland 'salt-pillow island' in the German Bight (see discussion below). The proposed shoal deposits are cored in 7/11-3X, 7/11-A5, 23/27-1and 23/27-4 (Figs. 21 and 22). The western coastline is still believed to have been associated with the Forties-Montrose High, while the Josephine High appears to have become submerged and is now part of a large embayed muddy shelf area with limited sediment input. Sandy slopes characterized by turbidite deposition still remained in the Cod-Pierce area (cored in 1/2-1, 23/21-4, 23/27-4, 23/27-7, 30/2-1, 30/3A-1; Figs. 17 and 22) and in a narrow zone on the western flank of the Forties-Montrose High (cored in 22/18-5 and 23/26A-12Z). A muddy slope/shelf area probably separated these slope segments, but this cannot be verified due to lack of well control and poor seismic resolution (cross-hatched pattern on Fig. 27a). The proposed shallow-marine area along this western flank has a flat-lying semi-transparent seismic character without any clinoforms, and the heterolithic to upwards-fining development indicates a deepening shoreface setting.

In the NE part of the study area, our correlations indicate that the T77E cycle is composed of Sele Formation mudstones that may have accumulated in a deep shelf to basin plain setting. As shown in Fig. 27a, drowning of this area (including the Jæren High) was initiated during the T77C cycle. The thicker development of the upper part of the Forties Formation in this area can be attributed to increased rates of subsidence on the downthrown side of the Cod Terrace. As will be shown below, this trend towards increased subsidence to the NE accelerated to such an extent in the T80 cycle that western parts of the previously elevated Jæren High now became a depocentre.

Upper Sele Formation paleogeography

The transgressive trend documented for the later part of the T77 cycle culminated in a large-scale flooding of the entire study area in the early part of the T80 cycle (Fig. 27b). No major sand development is envisaged in the Norwegian part of the study area, where shelf to basin plain mudstones of the Sele Formation occur interbedded with a few thin turbidites and storm sand beds. The presence of storm beds and wave ripples suggests that only moderate water depths (? 50-150 m) were created by the regional flooding. Seismic interpretation and well data from block 1/3 imply that large volumes of resedimented chalk accumulated in this distal eastern part of the study area. Mapping of this chalk shows that it was derived from the east.

In the British sector, a few 5-20 m thick sandstone units of probable channelized slope to basin plain turbidite origin is present in the T80 cycle (cored in 22/24B-4ST1). These can only be correlated locally, and thus seem to represent small submarine fans probably sourced from the east or northeast. The T80 cycle is otherwise muddy and relatively thin in most of the British part of the study area, and is missing due to non-deposition on the major salt diapirs (Machar, Erskine, Pierce South). Its laminated non-burrowed character and high content of sapropelic material imply anoxic bottom conditions.

Coastal morphology and transition to deeper-water areas

The lateral change from shallow-water areas to deeper-water slopes and troughs dominated by turbidite deposition is a striking feature on the paleogeographic

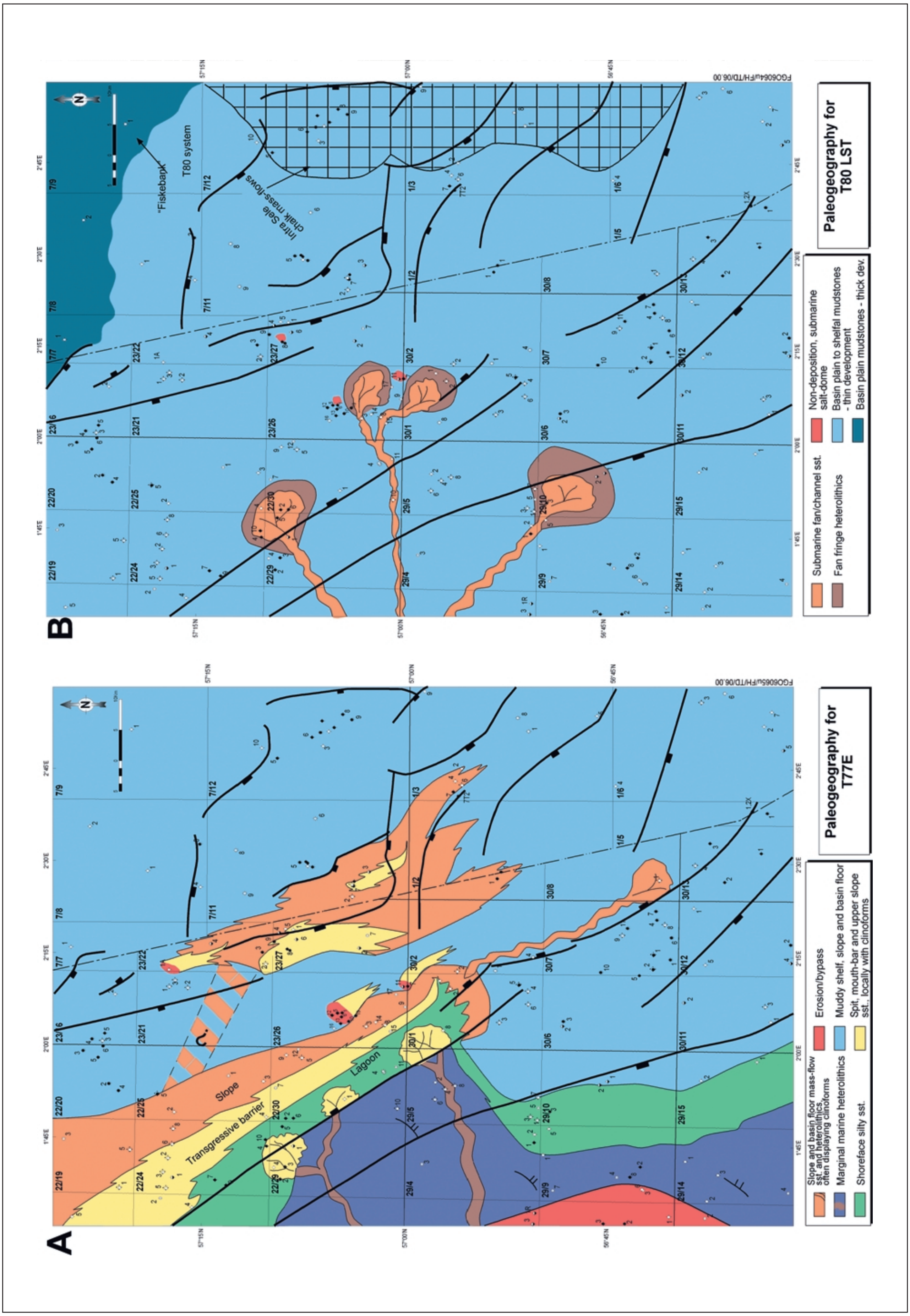


Fig. 27. Paleogeographic reconstructions of the study area. A) Upper part of the Forties Sandstone Member. Note significant base-level rise compared to situation on Fig. 26a, and the transgressive coastal lithosomes that are thought to occur locally within the study area. B) Upper part of Sele Formation subsequent to drowning of the Forties Sandstone Member. Shelfal to deep-water conditions are assumed to dominate across the entire study area.

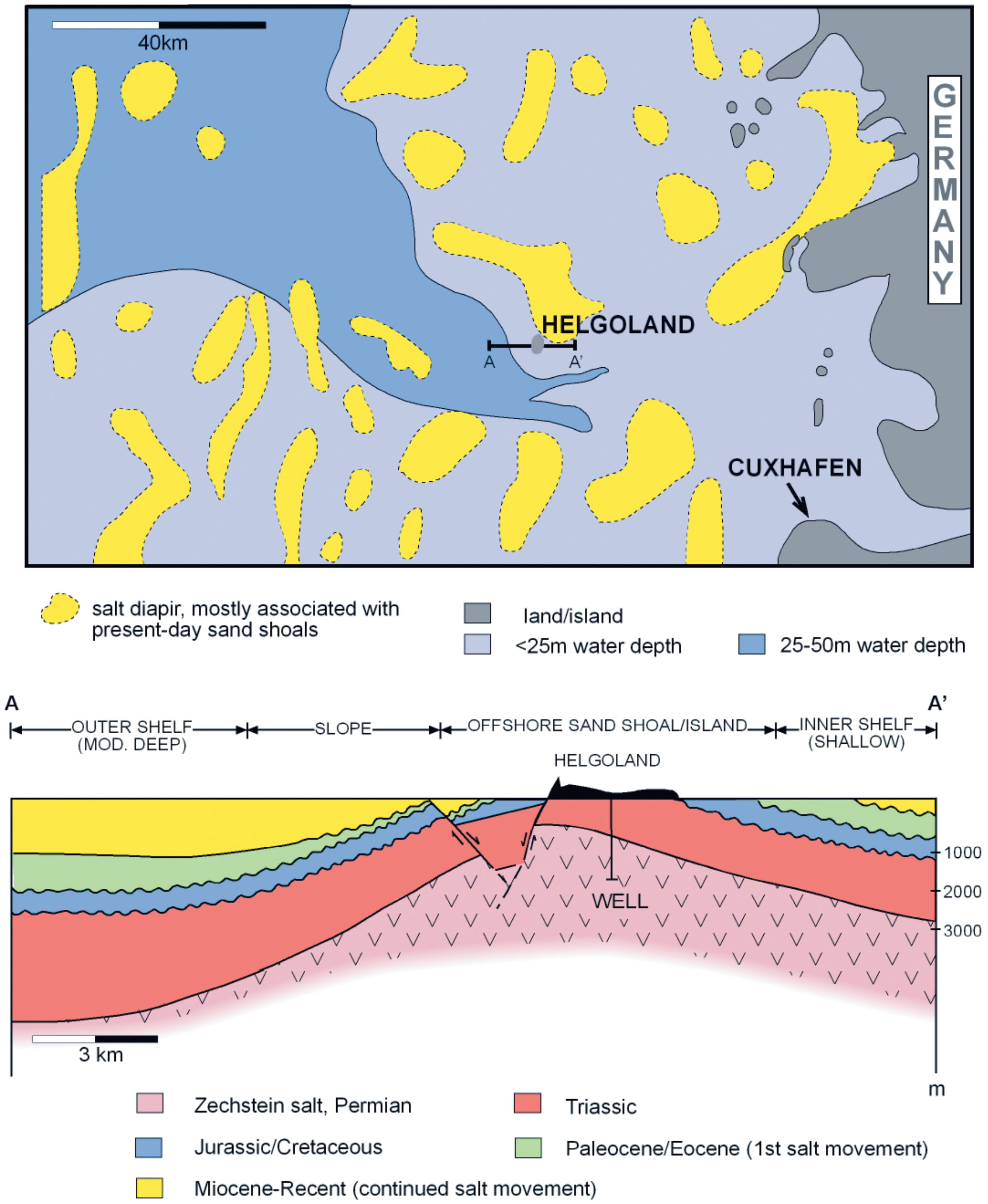


Figure 28. Map and cross-section of the Tertiary to Quaternary deposits of the German Bight. Note the association between saltdomes such as that beneath the Helgoland Island and development of shallow-marine sandbanks. See text for discussion.

reconstructions (Figs. 26 and 27, yellow-to-orange transitions). In this section, the coastal morphology of this system and the nature of the transition from shallow to deeper water will be addressed.

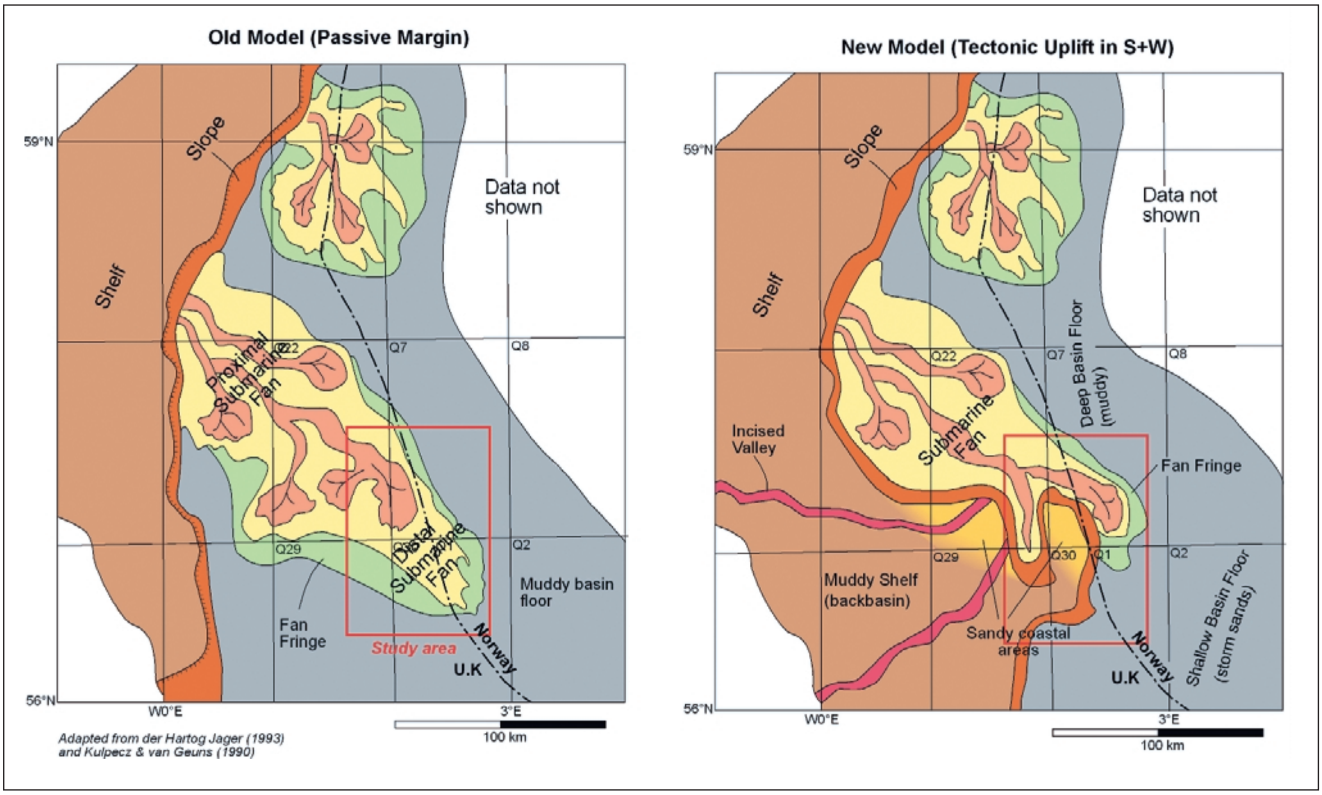
Based on the paleogeographic reconstructions, the coastal morphology was described above in general terms as a system of islands rimmed by shallow-marine sand accumulations. The island component consists exclusively of heterolithic bay and marsh shoreline deposits belonging to FA 5, and its occurrence on top of diapirs and footwall highs implies that the islands represented marginal marine wetland areas formed due to Late Paleocene tectonic uplift. The most prominent of these wetland areas seems to have developed on the Pierce structure, where the degree of structural elevation was optimal for preservation of marginal marine deposits. On the other related structures at the western edge of the Cod Terrace, the degree of uplift was either higher, causing mainly erosion (Lomond structure), or lower, resulting in lack of emergence and aggradation of shoal and slope deposits instead of marginal marine sediments. Present day analogs for this kind of setting are found in association with the Ship Shoal offshore Louisiana (linked to the Mahogany salt body, i.e. Rowan et al. 2000) and the Helgoland island in the German part of the North Sea (Fig. 28). This small island is located 70 km offshore and is underlain by a large pillow of Triassic salt formed during the Paleocene (Binot 1988). It contains salt marshes and cliffs of Triassic sandstone that represents a local sand source, and is surrounded by a reflective shoreline system with major sand shoals rimming the island (Schmidt-Thome 1987). It is evident from Fig. 28 that growth of this broad salt structure was initiated in the Paleocene, and that it has remained a bathymetric high ever since. Largest rate of growth is inferred to have taken place in the Paleogene both for the German Bight salt stocks and the Central Graben salt diapirs (Binot 1988; Davison et al. 2000a, b), and by comparison with present-day salt-related bathymetric highs in the Gulf of Mexico (Prather et al. 1998; Weimer et al. 1998; Rowan et al. 2000), these may have protruded tens to several hundred meters above the sea-floor. Hence, the salt-related structures and the fault block crests in the study area can be envisaged to have formed local shallow-water shoals and -ridges in an otherwise deeper-water setting. The westernmost of these may have had sand supplied from the hinterland, but the majority of the positive-relief structures were islands and shoals isolated from such a sand source. Hence, the sheet-like and rather thin coastal sands associated with these islands and shoals must have been supplied by local erosion of older sand-bearing strata as the salt stocks and fault crests slowly became emergent. Like for the Helgoland island, sand-bearing strata of Triassic age, deposited shortly after the salt accumulations, appear to be prime candidates for such a local sand source. Several fields in the study area, especially on the Josephine High (Figs. 1 and 2), are producing from well-developed Triassic reservoir sections

No sign of tidal activity has been seen in FA 5, and with the possible exception of the 'bundled' crossbedded set shown in Fig. 19c the same is true for FA 4. Further, the scattered occurrence of the wetland facies and the lack of any well-defined distributary system indicate that no major deltaic system existed in the study area. The characteristics of FA 4 instead suggest that wave-related processes were instrumental in forming the rim-sands surrounding the wetland-covered highs. Taking into consideration the elongated shape of these sand accumulations and their tendency to be located on the leeside of the emergent areas, the morphological elements of the coastal zone might correspond to capes, shoals, or spit-platform complexes (Nielsen et al. 1988; McNinch & Wells 1999; Novak & Pedersen 1999; Hiroki & Masuda 2000; Nielsen & Johannessen 2001). These form where waves approach sandy coasts at an angle, setting up longshore currents that enable the wave-dominated shoreline-shoreface facies belts to continue for tens of kilometers along the direction of littoral drift. The elongated and bathymetrically complex nature of the North Sea Basin during the Late Paleocene (Figs. 26 and 27) may have been conducive to setting up longshore currents.

The longshore-oriented coastal facies types of FA 4 contain wave ripples, subhorizontal lamination and low-angle crossbedding, whereas large-scale crossbedding is absent and medium-scale, high-angle crossbedding and HCS rarely occur. This favours deposition in a non-barred reflective coastal environment, since both dissipative barred coasts and spit-platform complexes are characterized by high- to moderate angle, large- to medium-scale compound crossbedding in the upper shoreface and HCS in the lower shoreface (Clifton et al. 1971; Hunter et al. 1979; Frey & Howard 1988; Roep et al. 1998; Nielsen & Johannessen 2001). Reflective coasts form in settings dominated by low-amplitude waves and are characterized by moderate to steep shoreface slopes without bars. As a result, the wave energy is concentrated in a bathymetrically relatively narrow zone that tends to be composed of coarser sand grades with abundant wedge-shaped sets of low-angle to sub-horizontal lamination (Komar 1976; Roep et al. 1998). Due to the dominance of low-amplitude waves, indicators of high-energy storm activity (HCS, gutter casts etc.) in the shoreface and inner shelf portions of reflective coasts are rare, whereas lower flow-regime structures such as ripples are abundant in these distal environments. These observations fit well with the features seen in FA 4, explaining the scarcity of HCS and high-to moderate angle crossbedding in these wave-influenced deposits. In summary, the shallow marine parts of the study area was, in Late Paleocene times, characterized by:

- low- to moderate wave energy conditions with wave fronts approaching the coast at an angle
- longshore currents operating along and between the land areas
- relatively steep slopes associated with rising diapirs and basement highs
- reflective shorelines forming elongated sand shoals and capes around the emergent areas.

With increasing water depth, reflective coastal successions normally show a gradual transition from coarser-grained



Adapted from der Hartog Jager (1993) and Kulpecz & van Geuns (1990)

Figure 29. Super-regional paleogeographies for the Forties Sandstone Member in the southern and central parts of the North Sea. Existing model to the left and the model proposed in this study to the right. Note especially the suggested shift of the palaeo-coastline more than 100 km to the east locally in the new model.

nearshore deposits to finer-grained shelf sediments (Short & Wright 1983; Frey & Howard 1988; Roep et al. 1998). In the present study, however, interfingering between sandstone-dominated shoreline sediments of FA 4 and equally sandy slope deposits of FA 3 is inferred. Only a few examples of this kind of lateral transition have been described in the literature (i.e. Surlyk 1987; Dalrymple et al. 2000), mostly from tectonically active settings where shoreline and slope environments coexist along relatively steep, tectonically enhanced gradients associated with tilted fault blocks. If this is the case for the studied succession, a continuation of the relatively steep reflective beach gradient into downdip parts of the basin is required. In this context, it seems plausible that the emergent salt diapirs and footwall highs may have created sufficiently steep gradients for the above-mentioned lateral transitions to occur. In this scenario, the depositional shoreline break represents a change from a sandy shallow marine 'platform' to an areally extensive slope environment where tectonic instability caused frequent deposition of sandy mass-flows. Only towards the bottomset portion of the 'Forties clinoforms' did a change towards muddy, deep shelf to basin floor sediments (FA 1 and 2) take place. It is also inherent in this model that only a small fraction of the volumetrically large Forties Formation submarine fan system was sourced from local areas associated with shallow- to marginal marine deposition. As discussed above, the majority of the deep-water deposits were derived from the East Shetland Platform as part of an extensive submarine fan system with an axial (NW-SE) transport direction. In this context, the growing salt structures and the series of rotated fault blocks just acted as obstacles hindering the advance of the submarine fan system. Turbidite channels were forced to deflect away from the positive relief features, and apart from a minor degree of sediment interfingering along the slope segments of the local highs, the shallow- and deep-water portions of the Forties Formation do not appear to have been genetically linked.

Implications for prospectivity

The contrasts between the old and the new depositional model for the Forties Sandstone Member in the greater study area are shown in Fig. 29. The introduction of a tectonically influenced, shallow- to marginal marine component to the depositional model is believed to enhance the prospectivity in the study area in several ways.

Moving the (local) coastline several tens of km to the east (Fig. 29) clearly changes the perception of the Late Paleocene sand distribution. Long transport distances to the distal part of a submarine fan are no longer needed to supply sand-sized material to the study area. In the new scenario, even short turbidite runout distances from the more easterly located shoreline would be sufficient to bring sand to blocks well into the Norwegian sector.

It is a common exploration concept in the Tertiary of the North Sea to look upon positive seismic thickness anomalies as good indicators of the presence of reservoir rocks. While this concept certainly is valid in deep-marine settings, it is not a pre-requisite for prediction of reservoir sand in shallow-water regions such as those that have been documented in the present study. As mentioned in the correlation section, all of the highs in the study area have a relatively thin Paleocene isopach but are still associated with heterolithic to clean sand of the T60 and more commonly the T70 cycle. These coastal rim-sands include well-developed beach deposits with a high reservoir potential.

The introduction of a substantial slope component in the study area introduces more possibilities of stratigraphic trap development in the form of intra-slope sandstone pinchouts, offlapping shallow-marine lithosomes, and submarine fans ponding against actively growing salt diapirs.

Conclusions

- Our data suggests that the Upper Paleocene depositional patterns were influenced by synsedimentary tectonism, related to fault displacements and halokinesis. The isopach map of the Forties Sandstone Member shows marked thinning (locally to zero) over structural highs and diapirs, and seismic sections and attribute maps show features like onlap onto highs, offlapping clinoforms on the flanks of highs, and lobate- to channel-like patterns reminiscent of submarine- and slope fans in the deeper troughs.

- A high-resolution stratigraphic framework, incorporating the T20-T90 cycles and numerous smaller-scale sequence stratigraphic units, has been erected for the study area. This provides us with 20-30 reliable timelines for well correlation and calibration of seismic reflectors.

- Published accounts of the Forties Sandstone Member in the southern North Sea describe this sand-rich unit as consisting of turbiditic mass-flow deposits belonging to a major submarine fan system. Results of the present study suggest significant modifications should be made to this model. By integrating sedimentological, palynological and seismically derived geomorphologic data, it is implied that the studied succession formed in a setting with highly variable bathymetry. On structural highs, thin marginal- to shallow-marine (wave-influenced) deposits tend to be present, while thick sandy mass-flow deposits (axial and transverse systems), heterolithic sediments (with some wave-influence) and laminated mudstones accumulated in the slope, deep shelf and basin floor areas between the highs. In this context, it is suggested that the Forties Sandstone Member sandstones partly are sourced from the local highs and from uplifted areas immediately west of the current study area. This contrasts with previous accounts in which long-distance transport of sand from the NW is favoured.

- A seismically mappable clinoform front is thought to reflect the transition from shallow- to deeper-water deposition in the study area. Such a transition is also supported by sedimentological and palynological data from cored wells traversing the clinoform front. This front is located well into the Norwegian sector in blocks 7/11 and 1/2, thus increasing the likelihood of finding sandstone with good reservoir quality in these areas. Moreover, basin floor areas to the east and south of the clinoform front may also be more sand-prone than previously thought, since in the new model they are located in a relatively proximal position with regard to the 'coastline', and not hundreds of kilometers away from a shallow marine sand source on the East Shetland Platform.

- A series of paleogeographical maps have been constructed, highlighting the distribution of reservoir rock throughout the Upper Paleocene succession. Relatively deep-water conditions with local shallowing across the Josephine and Forties-Montrose High is predicted for the top of the T60 cycle and the T72 cycle, whereas a major regressive maximum related to tectonic uplift, basin restriction and a warming event took place in the lower to middle part of the T77 cycle. This event led to the establishment of reflective shoreline systems and sand shoals in structurally elevated parts of the study area, while turbidite deposits continued to form in the intervening troughs. Aggradation and slight backstepping of the Forties shoreline-slope system occurred in the upper part of the T77 cycle, culminating in a regional flooding event creating deep shelfal to basin floor conditions in the lower part of the T80 cycle.

- Based on the new model, the prospectivity of the study area has increased due to the improved chance of reservoir rock being developed.

Acknowledgements: Norsk Hydro is thanked for the permission to publish these results. We would also like to extend our thanks to Eirik Larsen for help with the description and correlation of the Norwegian cores, to George Farrow for discussions in the early phase of this work, and to Paul Connell for his efforts to look at the micropaleontology of a few of the biostratigraphic samples. Constructive criticism from journal referees I. Price, L. M. Fält and J.E. Neal is also appreciated.

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