Sequence stratigraphy and palaeogeography of the Middle Jurassic Brent and Vestland deltaic systems, Northern North Sea

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The regional development of the Middle Jurassic Brent Group (Northern North Sea) has been studied within a sequence stratigraphic framework, and four depositional sequences (Exxonian) have been recognized. The phases of lowstand, progradation, aggradation, retrogradation and drowning of the 'classical' Brent deltaic system and a renewed deltaic progradation (the 'Vestland deltaic system') are illustrated by cross-sections and regional palaeogeographic maps. The Bajocian Brent delta progradation and aggradation developed during a period of varying rate of relative sea-level rise, forming a continuous sheet-like package of delta front facies associations in front of heterogeneous delta plain deposits. The stacking pattern varies from strongly progradational near sequence boundaries at a minimum rate of sea-level rise to aggradational during periods of pronounced sea-level rise. No delta incision or lowstand deposition due to major relative sea-level falls is envisaged. The Early Bathonian delta retreat took place in retrogressive pulses, and was probably influenced by synsedimentary fault activity along the ancient Viking Graben structure, forming an estuary in the Southern Viking Graben and gradually drowning the deltaic system in the Northern Viking Graben. After the maximum flooding of the Brent deltaic system in the Early Bathonian a second, pronounced deltaic progradation (the 'Vestland deltaic system') took place from the Central Viking Graben to ca. 60°30'N. In the Middle Bathonian a tectonic phase initiated the retreat of the Vestland deltaic system and possible erosion of the Brent Group deposits on the crests of tilted fault blocks in the Northern Viking Graben. The deposition of the Brent and Vestland deltaic systems was terminated by a pronounced tectonic rifting phase in the latest Bathonian.

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Introduction

The Middle Jurassic Brent Group and its time-equivalents form a key reservoir interval in the studied area of the Northern North Sea (Figs. 1, 2a, b, 3). Most of Britain's and Norway's oil reserves are found within this reservoir interval. After twenty years of extensive studies, more than 200 papers have been published on aspects of Brent Group stratigraphy, structure, sedimentology and oil field geology (Richards 1992). The development of the Brent deltaic system has been interpreted in these papers using palynological, sedimentological and sequence stratigraphic approaches (Graue et al. 1987; Brown & Richards 1989; Cannon et al. 1992; Helland-Hansen et al. 1992; Mitchener et al. 1992; Whitaker et al. 1992; Rattey & Hayward 1993; Johannessen et al. 1995). The papers by Mitchener et al. (1992) and Rattey & Hayward (1993) encompass the entire Northern North Sea, the rest all have a local or semi-regional scope within either the UK or the Norwegian sector.

The Brent Group lithostratigraphy is essentially simple, consisting of five formations, which from the base upwards are Broom, Rannoch, Etive, Ness and Tarbert (Bowen 1975; Deegan & Scull 1977; Vollset & Doré 1984). In addition to the five formations of the Brent Group, the Oseberg Formation in the Norwegian sector is considered as a Broom Formation time equivalent (Graue et al. 1987; Cannon et al. 1992). The Broom and Oseberg Formations represent early lateral infill of the basin, whereas the remaining formations, which make up the main part of the Brent Group, comprise a major regressive/transgressive wedge (Graue et al. 1987; Helland-Hansen et al. 1992; Steel, 1993). The Brent deltaic system is interpreted to be mainly of a fluvial-wave interaction type (Johnson & Stewart 1985; Brown et al. 1987) although its inferred regime does vary considerably from place to place and through time (Steel 1993). The term 'Brent Group' has been restricted to areas north of about 60°N, whereas the time-equivalent deposits south of 60°N have been assigned to the Vestland Group (Vollset & Doré 1984). In the Vestland Group, the delta plain deposits of the Sleipner Formation and the marine sands of the Hugin Formation are equivalents of the Ness and Tarbert Formations, respectively. In the Bruce Embayment (Fig. 2a), the Middle Jurassic fluvio-deltaic deposits are subdivided into the A, B and C sands (e.g. Richards 1991). The relationship between these sands and the Brent and Vestland Group sediments is discussed later.

Our approach in creating a regional synthesis of the Brent and Vestland Group successions from 59°N to

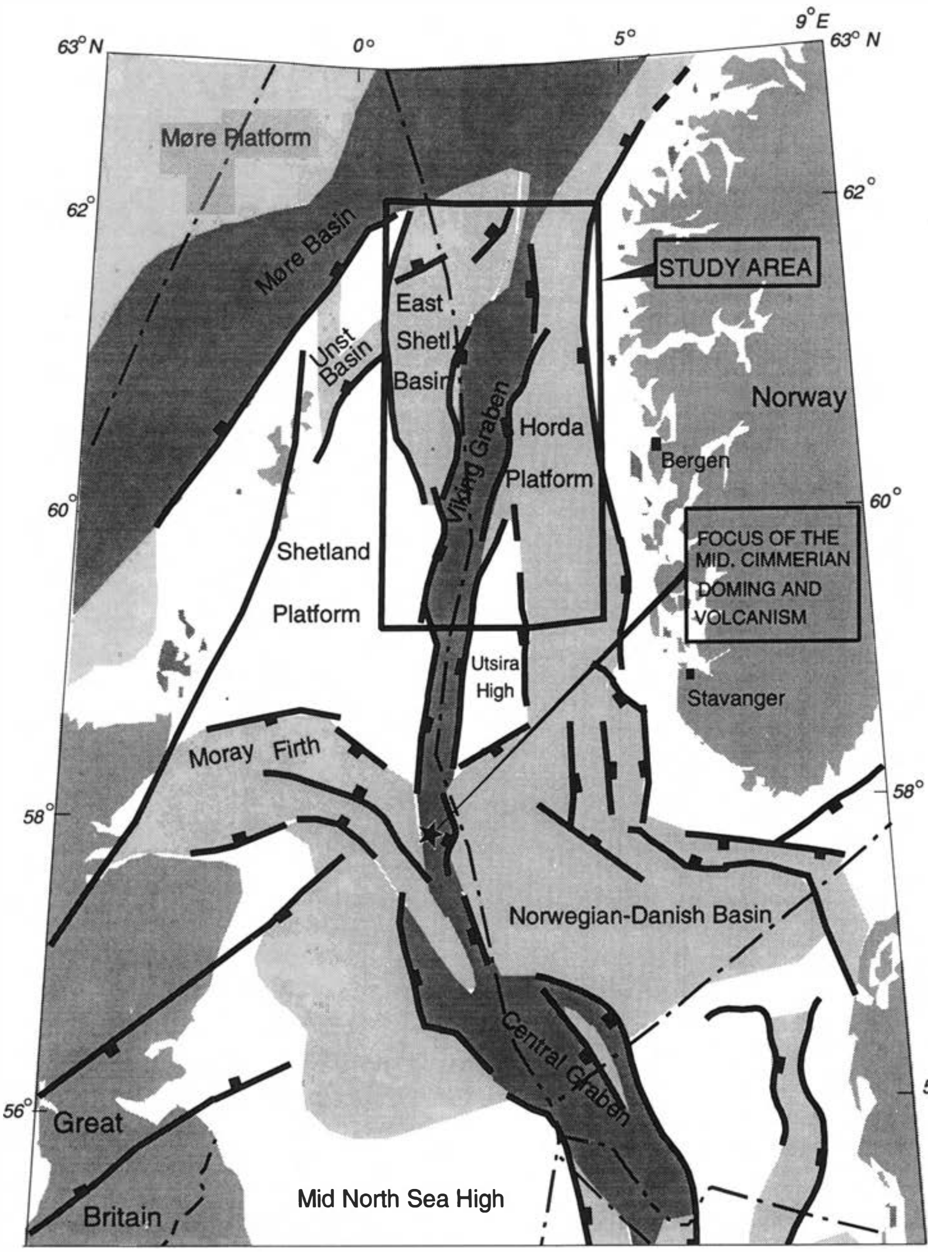

Fig. 1. The North Sea area with location map of the study area. Inserted area shown in Fig. 4.

62°N has been to integrate data from palynology, sedimentology and structural geology into a sequence stratigraphic framework. In this way several facies associations have been defined and used for recognition of key sequence stratigraphic surfaces (flooding surfaces and sequence boundaries) and to identify system tracts and depositional sequences. Furthermore, the facies associations form the basis of a series of palaeogeographic maps for each sequence which are described in turn.

During the discussions, we will focus on key issues from a petroleum production perspective, including the significance of the sharp contact between the Rannoch and Etive Formations and its relation to a seaward displacement of the Brent deltaic system, the tectonic influence on advance and retreat of the deltaic system and, finally, the significance of local sediment supply.

Stratigraphic and structural setting

Brent and Vestland group sediments are recorded in the East Shetland Basin, the North Viking Graben and over parts of the Horda Platform (i.e. from 59°N to 61°30′N) (Figs. 1, 2a, b). Their original distribution on the East Shetland Platform is not clear, although the depositional thinning from the basin centre towards the East Shetland Platform may indicate temporary emergent conditions in the western part of the basin. Moreover, Middle Jurassic deposits are found in the Unst Basin (Fig. 1) (Johns & Andrews, 1985), indicating a wider deltaic front than is seen today.

The Middle Jurassic succession of the North Sea was laid down in a shallow ramp-type basin without a pronounced shelf/slope break and likely with very gentle

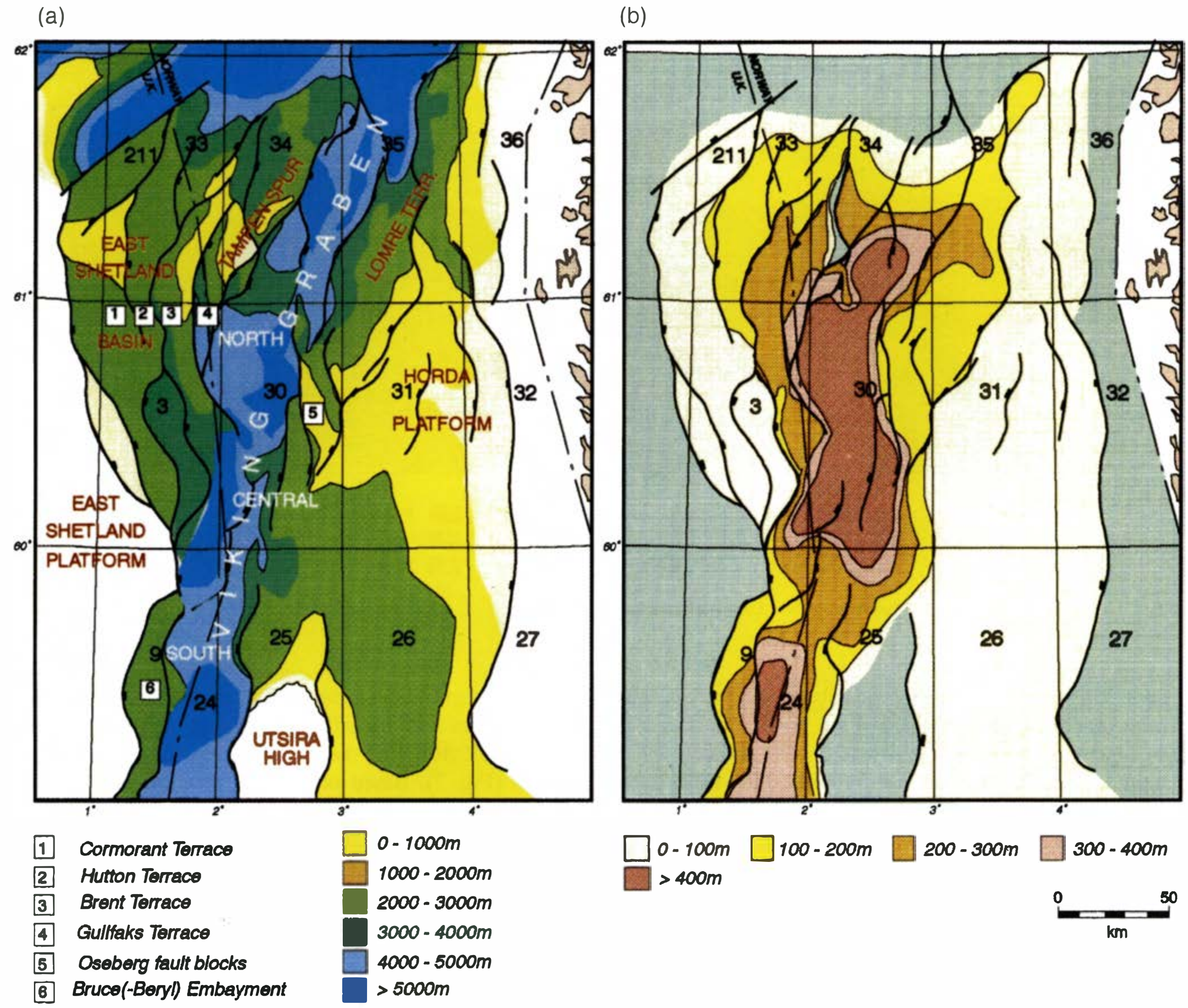

Fig. 2. The Northern North Sea area. (a) Main structural elements and depth structure map to base Brent/Vestland Groups or older. (b) Isopach map of the Brent and Vestland deltaic systems.

clinoform geometries (Mitchener et al. 1992; Olsen & Steel 1995). This makes identification of major sequence boundaries difficult, as shifts of facies belts are rarely dramatic (Mitchener et al. 1992).

The Brent Group was deposited in an extensional basin characterized by two main lineaments: NE–SW trends of predominantly Caledonian origin and N–S trends of Permian/Triassic origin (Eynon 1981; Threlfall 1981; Rattey & Hayward 1993). The major Permian and Early Triassic crustal thinning caused tilting of basement fault blocks (Badley et al. 1984; Gabrielsen et al. 1990; Steel & Ryseth 1990; Yielding et al. 1992; Roberts et al. 1993). By mid-Triassic times a post-rift thermally subsiding basin had been established (Steel 1993). The Early Jurassic Mid-Cimmerian tectonic phase caused a domal uplift in the southern region of the North Sea with a focus at the triple junction between the Moray Firth, Central Graben and Viking Graben as well as uplift on the eastern and western flanks of the basin, with an accompanying relative sea-level fall (Ziegler 1982; Underhill & Partington 1993) (Fig. 1). Subsequent erosion of the dome and the uplifted basin flanks provided an extensive sediment supply for the prograding lower Brent deltaic system (Rannoch, Etive and lower Ness Formations) into the thermally subsiding Viking Graben during Aalenian–Bajocian times. The transition from the lower Brent to the upper Brent deltaic succession (upper Ness and Tarbert Formations) is related to Late Bajocian–Early Bathonian transgressive events on the Norwegian shelf (Fält et al. 1989; Olaussen et al. 1992). The upper Brent deltaic system retreated southwards during the Early Bathonian (e.g. Olaussen et al. 1992).

There is a growing consensus for block-faulting and associated erosion in latest Bajocian and Early Bathonian prior to the main Late Jurassic rifting phase (Helland-Hansen et al. 1992; Johannessen et al. 1995). This minor tectonic phase is seen particularly to affect the upper part of the Ness and the Tarbert Formations in the form of synsedimentary fault activity along the pre-existing rift system lineaments, creating increased accom-

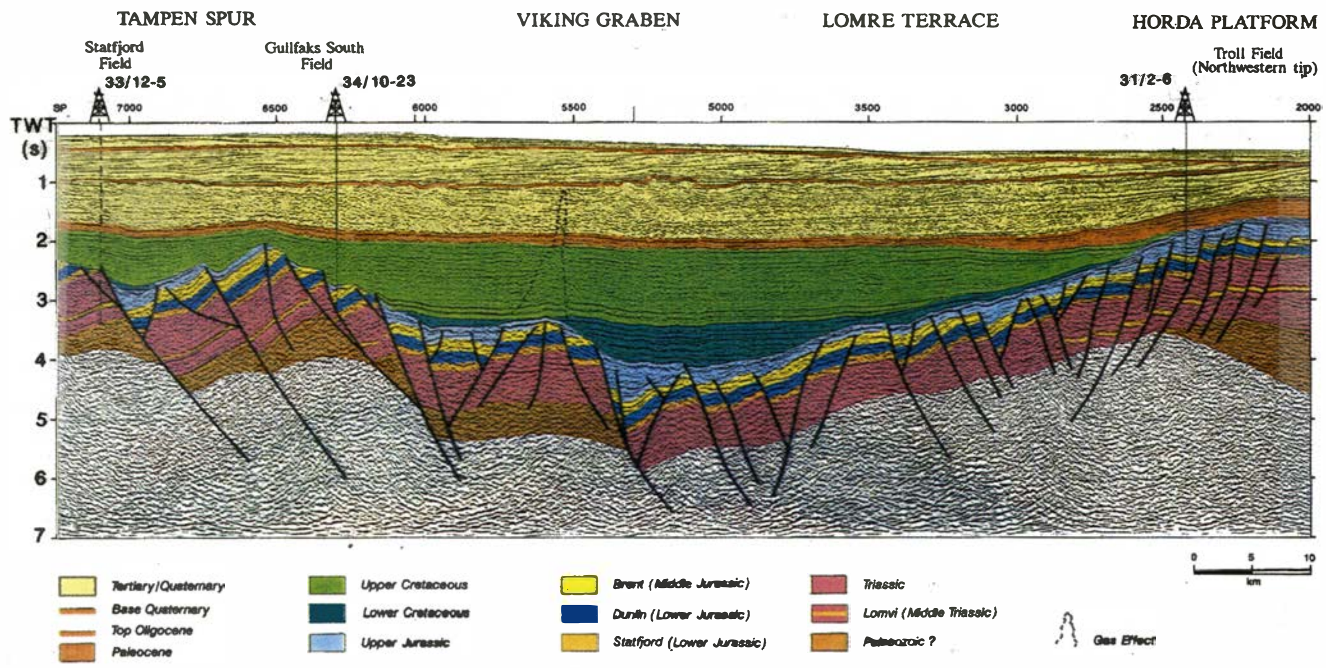

Fig. 3. Seismic section across the North Viking Graben. Location shown in Fig. 4.

modation space and causing the subsequent retreat of the Brent deltaic system. In Mid–Late Bathonian times the fault activity became more severe with erosion of the Brent Group deposits on the crests of tilted fault blocks (Helland-Hansen et al. 1992; Johannessen et al. 1995). This second period of extension of the Viking Graben peaked during the Late Jurassic (Yielding et al. 1992), creating a tilted fault block topography with accompanying crestal erosion and sediment infill (Fig. 3). Eventually, conditions of restricted marine circulation were established in the grabenal troughs, with anoxic deposition of Heather and Draupne Formation source rocks (Fjæran & Spencer 1991).

Methodology

Database

The sequence stratigraphic analysis presented here is based upon data from more than 150 wells covering an area of 200 × 300 km between 59°N and 62°N in both UK and Norwegian sectors of the Northern North Sea (Fig. 4). Detailed sedimentological descriptions of cores, TOTAL laboratory reports and published data form the basis for the interpretation of depositional environments and definition of facies associations on selected type wells (Figs. 5a–c, 6). The established facies associations can be recognized on wire-line logs, and geological cross-sections in north–south and east–west directions have been produced using representative key wells (Figs. 9–13). Regional seismic data have been used, both to determine the location of major faults and to define the basin outline and limits (e.g. Fig. 3).

Biostratigraphical data have been used for establishing key surfaces and a relative chronology to provide a time framework for our basin-wide sequence stratigraphic model (Fig. 7). Based on this model a series of palaeogeographic maps has been produced as 'photos' representing limited time intervals (Figs. 14a–16d). Together, the succession of maps provides a tentative impression of the changing depositional patterns of the Brent deltaic system through time and space.

Facies associations

A suite of facies associations has been defined for the five formations of the Brent Group on the basis of detailed core descriptions. Type wells are presented in Figs. 5a–c. Each facies association is characteristic of a particular sub-environment within the deltaic setting and can be recognized on wire-line logs in the studied area. Mapping of facies associations within the different sequences has formed the basis for recognition of major palaeogeographic elements (Fig. 6), which is necessary for developing an improved regional sequence stratigraphic understanding of the Brent deltaic system.

Even though facies associations developed during progradation and retrogradation are broadly similar, the stacking patterns are different. Therefore, the recognition of certain stacking patterns can be used to enhance understanding and prediction away from well data points (e.g. Mitchener et al. 1992).

Fan-delta sandstone association. – This facies association is largely composed of medium- to coarse-grained, subarkosic marine sandstones of the Broom and Oseberg

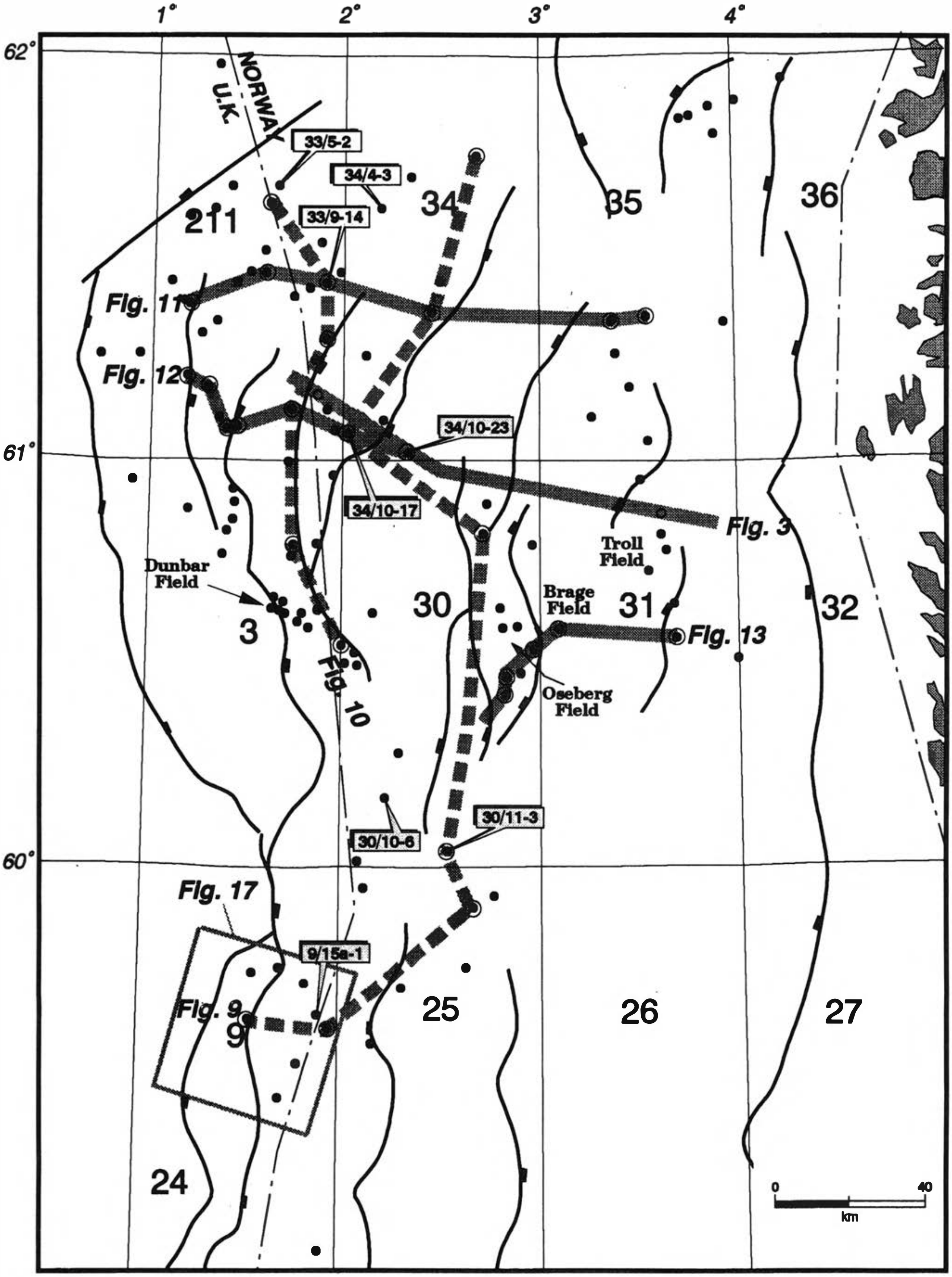

Fig. 4. The Northern North Sea study area with location map of studied wells (black dots; released wells only. Non-released wells used are not displayed.), seismic section (Fig. 3), geological cross-sections (Figs. 9–13) and Bruce Embayment palaeogeography (Fig. 17). See Fig. 1 for location of study area.

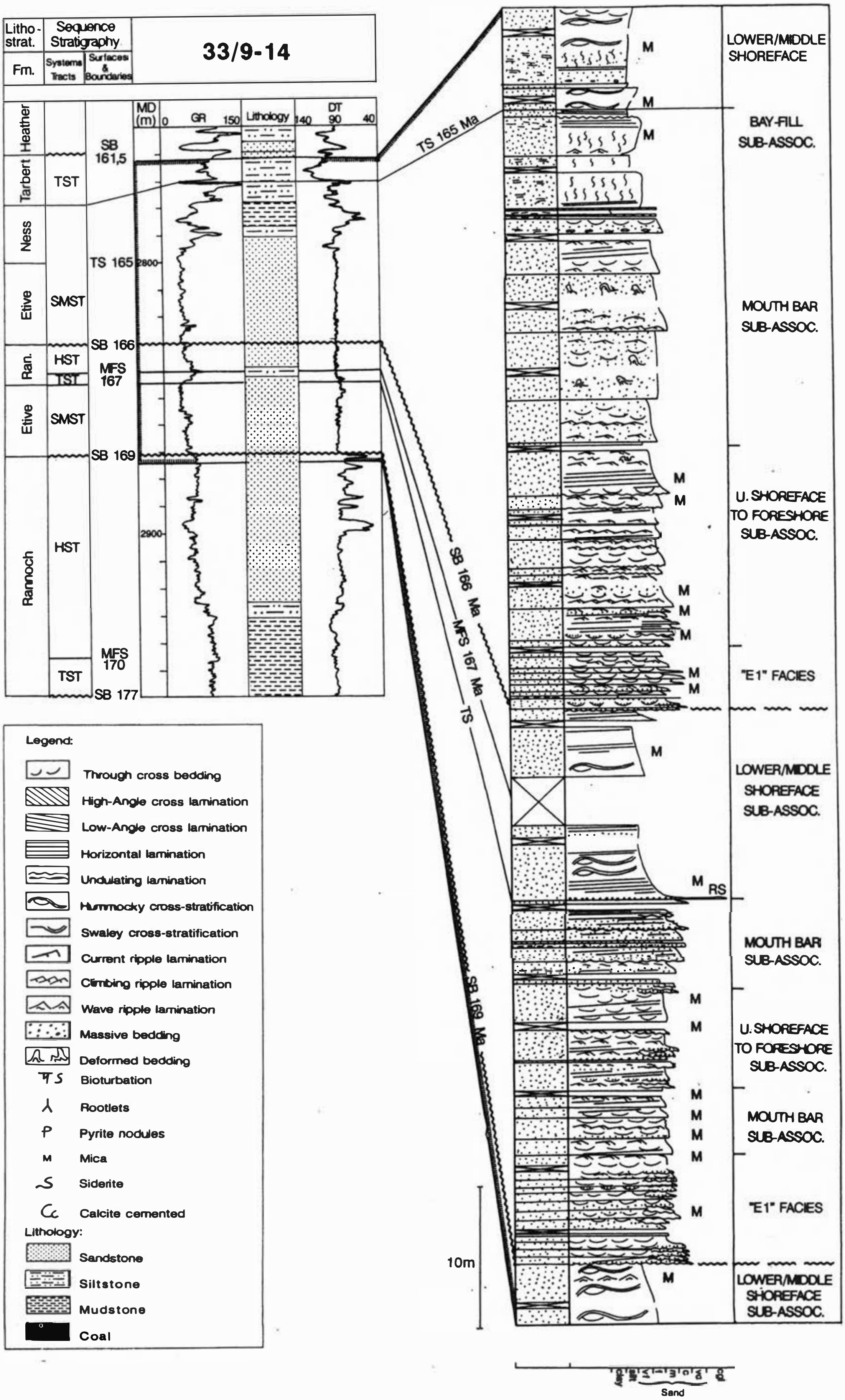

Fig. 5 (a).

Fig. 5. Sedimentary logs showing typical facies associations within the Brent and Vestland deltaic systems, represented by (a) well 33/9-14, (b) well 34/10-17, and (c) well 9/15a-1. Legend is shown in Fig. 5a. Wire-line logs are Gamma-ray (GR) and Sonic (DT) logs. Sequence stratigraphy abbreviations are listed in Fig. 9. Other abbreviations are given in the text.

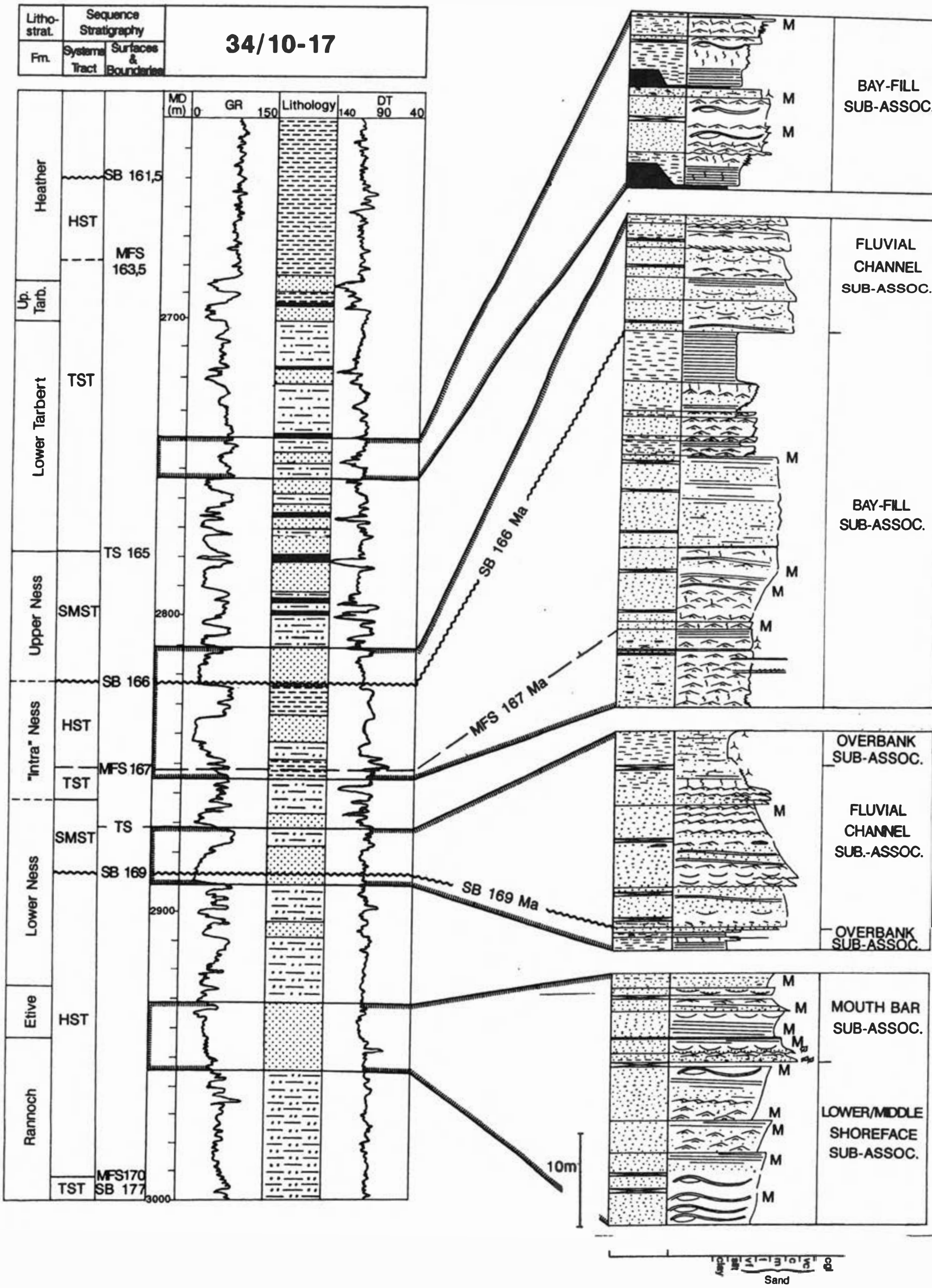

Fig. 5 (b).

Formations. The sandstones are developed either as bioturbated rather flat-lying units which alternate with micaceous siltstones/mudstones, or as rarely bioturbated, large-scale units of unidirectional foresets up to 25 m thick, which dip internally at 10–30° (Graue et al. 1987; Helland-Hansen et al. 1992). A fan delta origin is indicated by the internal geometries showing steeply inclined progradational surfaces and wedge-like foresets, and by the observation of these sandstones being attached to the basin margin. The overall organization of

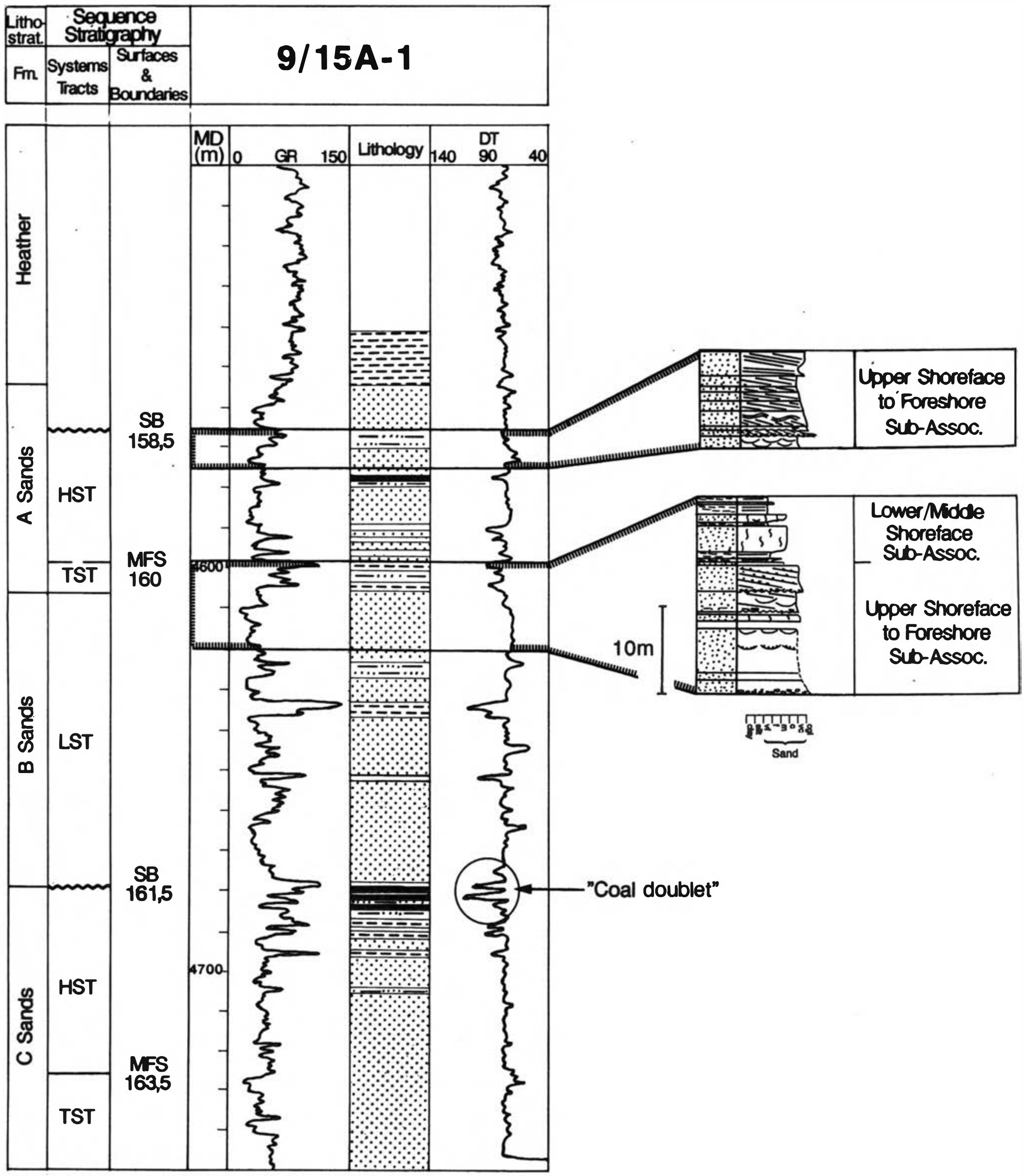

Fig. 5 (c).

the sandstone beds is suggestive of gravity flow processes (Graue et al. 1987; Cannon et al. 1992; Helland-Hansen et al. 1992).

Prodelta mudstone association. – In the northern part of the North Viking Graben (Fig. 2a), the lower part of the Rannoch Formation is marked by the presence of a dark grey, uniform and carbonaceous mudstone interval with well-developed parallel lamination, representing the most distal and fully marine sediments of this formation (Johannessen et al. 1995; Olsen & Steel 1995; Reynolds 1995). This facies may be indistinguishable from the underlying Dunlin Group if a Broom or Oseberg Formation package is not present (Cannon et al. 1992).

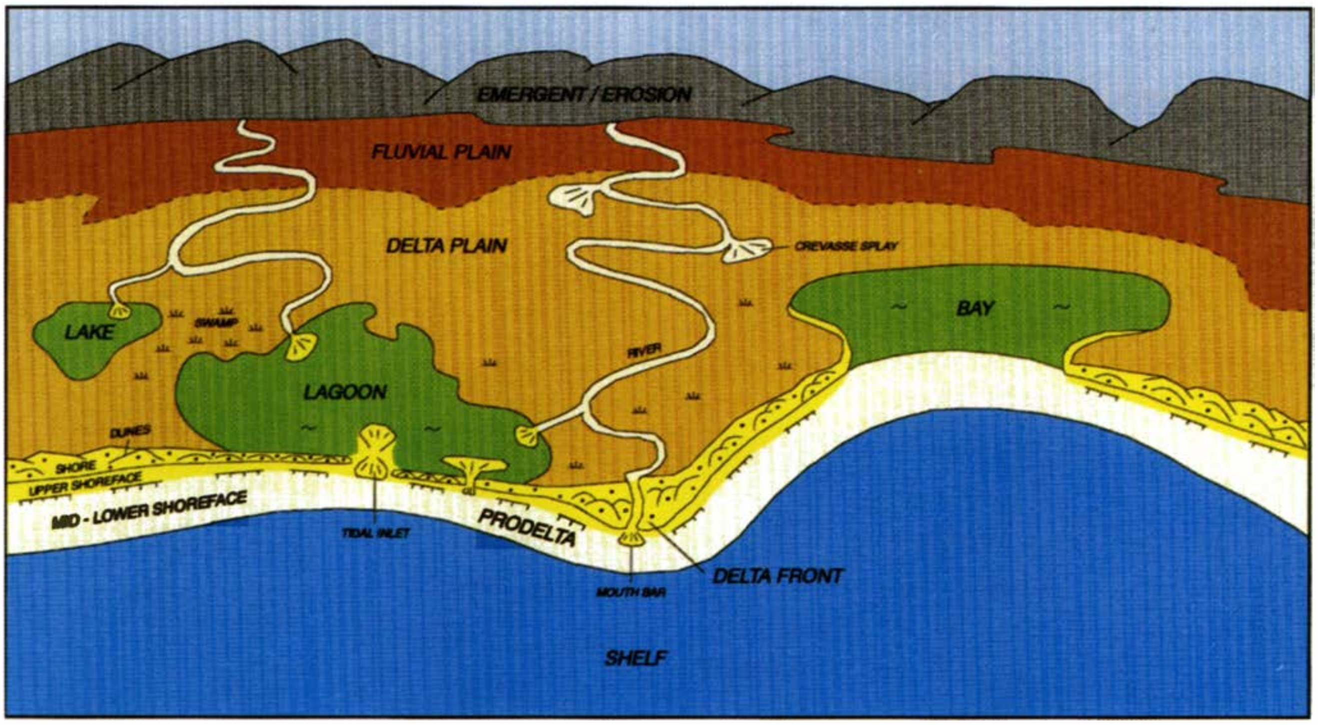

Fig. 6. Depositional environments encountered within the Brent Group. The colour code applies also for Figs. 8–16.

Offshore to lower/middle shoreface association. – This facies association shows a continuous upward transition from interbedded shales and siltstones to fine-grained micaceous and argillaceous sandstones.

The *offshore sub-association* is characterized by 'streaky' mudstones consisting of alternating laminae of mudstone and siltstone. These are moderately bioturbated. The 'streaky' mudstones grade upwards into more mica-rich siltstone and sandstone dominated units with characteristically alternating intervals of slightly undulating parallel lamination and intensely bioturbated, originally laminated sandstone. This sediment package probably represents an alternation of storm sands and fair-weather mud layers, deposited in an offshore environment (Livera & Caline 1990; Walker & Plint 1992; Olsen & Steel 1995).

The *lower to middle shoreface sub-association* consists of clean, micaceous, very fine- to fine-grained sandstone. The dominant sedimentary structures are low-angle cross-bedding (5–8°) and low-angle undulatory lamination (amalgamated hummocky and swaley cross stratification). This lamination is well developed due to alternations between quartz/feldspar-rich and clay/mica-rich laminae (Figs. 5a, b) (Cannon et al. 1992; Olaussen et al., 1992; Scott, 1992; Johannessen et al. 1995; Olsen & Steel 1995; Reynolds 1995). Hummocky stratification generally gives way to swaley cross-stratification upwards. This succession of structures is characteristic of prograding storm-dominated shoreface units (Leckie & Walker 1982).

Upper shoreface to foreshore and mouth bar association. – The upper shoreface to foreshore facies association characteristically overlies the lower/middle shoreface association. In the northernmost North Viking Graben area the boundary between the two is very distinct, marked by pronounced changes in grain size, degree of sorting and petrographic composition (Fig. 5a) (Olsen & Steel 1995). However, along the western and eastern basin margins and especially south of the Tampen Spur area this transition is more gradual (Fig. 5b).

The sandstones of this association are primarily medium-grained with minor intervals of fine and coarse-grained sand and thin pebble lags. They can be subdivided into two sub-associations; the upper shoreface to foreshore and the mouth-bar sub-associations.

The *upper shoreface to foreshore sub-association* contains fining-upward units of fine- to medium-grained, well-sorted sandstones with small-scale trough cross-strata, low-angle cross-strata (8–12°) and horizontal lamination. Current ripple lamination may commonly be seen as well as root-traces and disseminated carbonaceous matter (Figs. 5a, b). This interval is interpreted in terms of surf-zone processes succeeded by foreshore processes. The low-angle laminations and excellent sorting are consistent with swash zone, wave-wash-up and backwash in water depths of only a few metres (DeCelles & Cavazza 1992; Scott 1992; Johannessen et al. 1995; Olsen & Steel 1995). Alternatively, the same sedimentary structures and fining-upwards trends have been taken by some as evidence of fluvially influenced channels (e.g. Simpson & Whitley, 1981; Parry et al., 1981; Brown & Richards 1989; Reynolds 1995) and by others as tidal channel fill sandstones (e.g. Daws and Prosser 1992).

In the northernmost Tampen Spur area, Olsen & Steel (1995) described a sandstone facies (*'E1 Facies'*) within

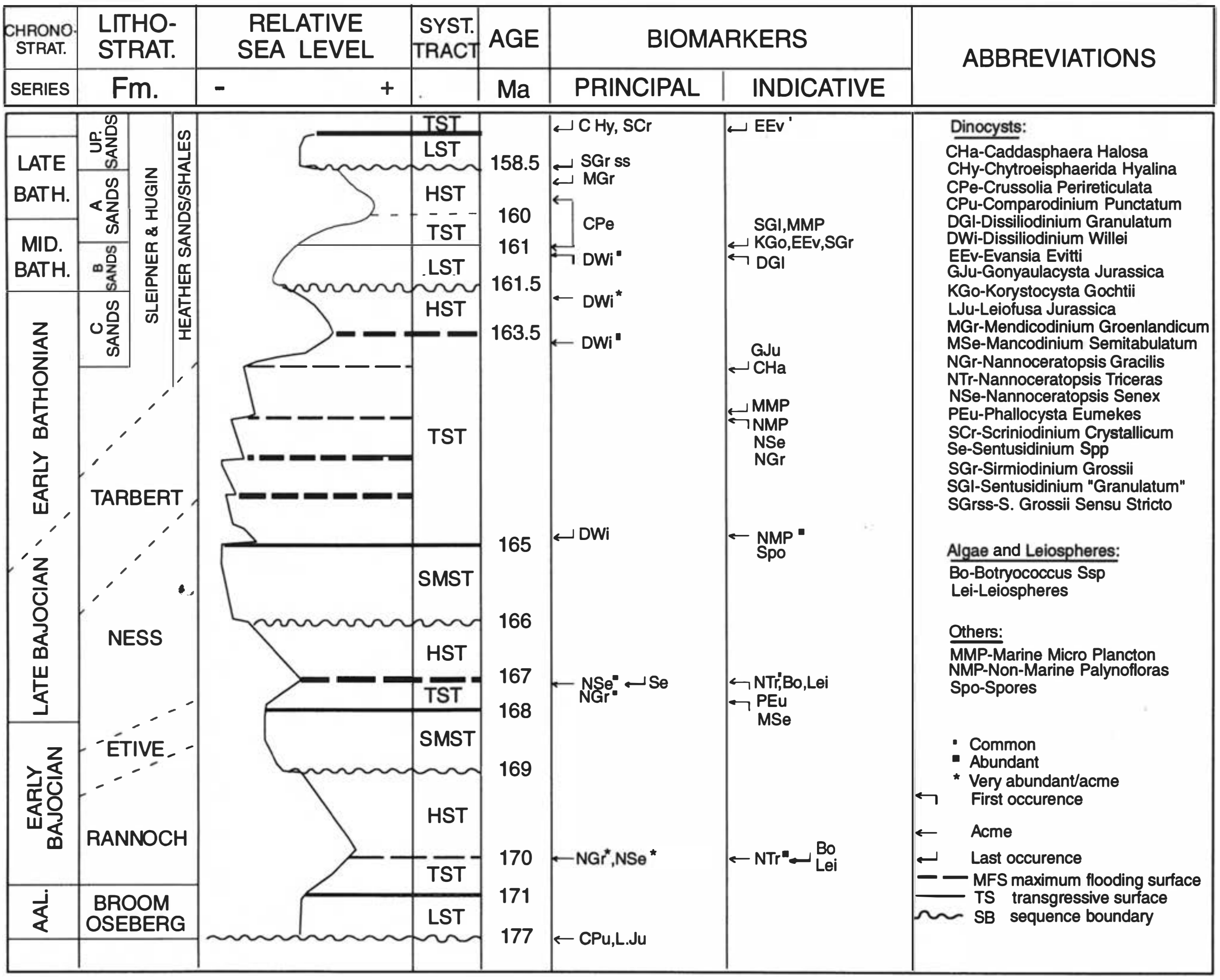

Fig. 7. Proposed biostratigraphy chart for the Brent Group.

the upper shoreface to foreshore sub-association related to minor base-level fall episodes. In what follows this particular sub-association will be referred to as the '*E1 facies*'. The *E1 facies* overlies the lower/middle shoreface sub-association and is characterized by a pronounced repetition of thin sandy and pebbly fining-upwards units, with markedly erosive bases (Fig. 5a). The grain size varies from coarse to very coarse in the bottom of each unit to fine-grained sand towards the top. The grain-size trend is accompanied by a transition from massive to trough cross-strata or low-angle cross-bedding to climbing ripple lamination. The upward-fining motif is characteristically terminated by a zone of mica-rich laminae 1–3 cm thick, associated with mudstone- and organic-rich material. This facies is probably linked to minor apparently multiple, erosional episodes, which are related to downwards and outwards shifts of deposition on the delta front (Olsen & Steel 1995). Note, however, that the sharp-based nature of some of the fining-upward units has been taken by some as proof of the importance of erosion by longshore troughs, bars and rip channels on a normally prograding shoreface (e.g. Jennette & Riley in press; Olsen & Steel, in press) but by others as evidence of a major basinward shift of the shoreface (e.g. Van Wagoner et al. 1993). The sequence stratigraphic interpretation of the Rannoch/Etive boundary is strongly dependent upon the interpretation of these sedimentary environments of the lowermost part of the Etive Formation, which will be discussed in more detail later.

The *mouth-bar sub-association* mainly consists of medium- to coarse-grained, non-micaceous, poorly sorted sandstones characterized by deformed and massive bedding. High-angle (20–30°) cross-stratification, trough cross-bedding and current ripple lamination are seen locally (Figs. 5a, b). These sandstones may have been deposited on the subaqueous slopes of delta mouth-bars, where intervals of instability and mass flow processes would alternate with wave-driven oscillatory currents on the upper part of the deltaic front (Johannessen et al. 1995; *E2 facies* of Olsen & Steel 1995).

Delta plain association. – The delta plain association forms a heterolithic suite of coal beds, palaeosols, mudrocks and ribbon- and relatively thin sheet-like sandstones. These mixed lithologies reflect fluvial channel, overbank, stagnant swamp, interdistributary bay, mouthbar and lagoonal sub-environments of the delta plain (Fig. 5b) (Graue et al. 1987; Livera 1989; Ryseth 1989; Helland-Hansen et al. 1992).

The *fluvial channel sub-association* consists of coarse-to fine-grained trough cross-bedded, massive, planar cross-stratified and current ripple-laminated, poorly sorted sandstones, with rare mud clasts and organic debris. The sandstones are sharp-based, usually commencing with thin intra-formational pebble lags. Individual sandstone units are either simple fining-upward units or composite, multi-storey units (Fig. 5b). The sharp bases, vertical fining and assemblage of sedimentary structures strongly suggest a fluvial origin (Livera 1989; Ryseth 1989; Johannessen et al. 1995).

The *overbank sub-association* is dominated by mudrocks and palaeosols. The mudstones are pale to medium grey, 'massive' with slickensides, 'paper'-lamination or soft-sediment deformation. Less abundant roots, early diagenetic sphaero-siderite and desiccation cracks are also seen. Interbedded mudrocks and silt- or sandstones (5–10 cm thick layers) are other typical facies. Both fining-upward and coarsening-upward grain-size trends may be seen within the sandstone layers. The palaeosols are characterized by carbonaceous root casts, and include both muddy and sandy lithologies (Fig. 5b). Within each palaeosol a gradual upward development is seen from fully preserved sedimentary structures to finer grained material with no relict structures. The mudstones are considered to have been deposited in standing water, such as shallow lakes. The laminated character of the heterolithic facies reflects energy fluctuations during deposition and a crevasse environment is therefore inferred (Livera 1989; Ryseth 1989).

The coal beds and carbonaceous mudstones constitute the *stagnant swamp sub-association*. The coals are very variable in thickness and form both continuous and discontinuous units. The coals usually have a dull lustre, but in thicker beds brittle vitrain lenses can be seen. Well-developed roots are often recorded at the base (Livera 1989; Ryseth 1989). According to Ryseth (1989), the coals and carbonaceous mudstones were deposited in shallow lacustrine conditions on the delta plain.

The sandstones of the *bay-fill sub-association* show coarsening-upwards grain-size trends from silty very fine-to fine-grained sand (Figs. 5a, b). Wave-generated ripple laminations, mud-drapes and synaeresis cracks are common. Bioturbation is common in the lower part of each coarsening-upward unit. Rootlets often penetrate the top of stacked units, which terminate with a few centimetres of coal or carbonaceous mudstone. Trace fossils of *Teichichnus* sp., *Planolites* sp. and *Diplocraterion* sp. have been identified. The presence of *Diplocraterion polyupsilon*, typical of muddy lagoonal environments (Pollard, pers. comm.) and synaeresis cracks is interpreted in terms of a brackish water environment (e.g. Pemberton & Wightman 1992). The coarsening-upward sandstones were probably deposited from distributary channels entering a bay or lagoon (bay-head deltas), whereas peat, mudstones and siltstones accumulated in swamps, bays or lagoons (Johannessen et al. 1995; Reynolds 1995). The characteristic stacking pattern of this sub-association may reflect deposition controlled by autocyclic processes (Reynolds 1995).

Biostratigraphy

Many different biostratigraphic charts exist for the Middle Jurassic section and several authors have tried to find the optimal age resolution for the Brent Group (e.g. Haq et al. 1987; Graue et al. 1987; Fält et al. 1989; Mitchener et al. 1992; Helland-Hansen et al. 1992; Partington et al. 1993; Johannessen et al. 1995). The charts are, however, not directly comparable as the various authors develop their charts using different species, ages, zonations and geographical locations for the events.

Biostratigraphic well reports were used in combination with published data in order to develop a biostratigraphical scheme to support the recognition of key surfaces and sequences of the proposed Brent deltaic model. Quantitative biostratigraphy studies by Simon Petroleum Technology proved particularly useful, both for the recognition of flooding surfaces, as indicated by acmes reflecting marine/brackish incursions, and for the location of maximum regression intervals (barren of dinocysts). Only dinocysts were found reliable as principal biomarkers, whereas the presence of algae, leiospheres, spores and other non-marine palynofloras together with non-age diagnostic dinocysts were used for local correlation events. The key events are summarized in Fig. 7 and are used during the description of the Brent depositional sequences.

Sequence stratigraphic framework

The sequence stratigraphic definitions used for the Brent depositional model are adapted from the 'Exxon model' as presented in Vail et al. (1977), Posamentier et al. (1988), Posamentier & Vail (1988) and Van Wagoner et al. (1990).

A complete depositional sequence is subdivided into lowstand/shelf margin, transgressive and highstand systems tracts, dependent upon the change in relative sea level (RSL) that takes place at the shoreline position (e.g. Posamentier & Vail 1988; Posamentier et al. 1988, 1992). The lowstand system tract (LST) is deposited during relative sea level (RSL) fall (forced regression) or when the RSL slowly starts to rise again after a minimum, but before the onset of the next transgression. Alternatively, a shelf margin systems tract (SMST) develops after minimum RSL, but only if no RSL *fall* proceeds its deposition (see below). When the rate of RSL rise outpaces the rate of sediment supply, the transgressive systems tract (TST) is initiated. The TST is terminated when the relative sea-level rise is at its maximum, defined by the maximum flooding surface (MFS). When the rate of RSL rise slows down and becomes outpaced by the rate of sediment supply, an overall regression occurs, known as the highstand systems tract (HST) (Posamentier & Vail 1988).

A depositional sequence is bounded at its top and base by sequence boundaries. A sequence boundary can be of type 1 or 2, dependent upon the relation between eustacy and subsidence at the shoreline position (Posamentier & Vail 1988). A type 1 sequence boundary occurs if the rate of eustatic sea-level fall *exceeds* the rate of basin subsidence at the depositional shoreline break. This will cause subaerial exposure and erosion associated with stream rejuvenation (incision). The resultant deposits belong to the lowstand systems tract of the sequence above. A type 2 sequence boundary occurs if the rate of eustatic sea-level fall is *less* than the rate of subsidence, i.e. the relative sea level continues to rise but at a *decreasing* rate. In this case there will be subaerial exposure and a downward shift in coastal onlap patterns landward of the depositional shoreline break. Seaward of the shoreline break there will be no evidence of incision, but a basinward shift of facies can be recorded (Posamentier & Vail 1988; Van Wagoner et al. 1988). A type 2 boundary is also characterized by a change in stacking pattern, from highly progradational to slightly progradational/aggradational. The prograding/aggrading clinoforms above the boundary are referred to as the shelf-margin systems tract (SMST) (Posamentier & Vail 1988; Van Wagoner et al. 1990).

The sequence and sequence boundary definitions above are focused on the eustatic sea-level control on depositional processes, whereas little attention has been given to identify tectonic controls on deposition and how they may overprint the eustatic signature (e.g. Rattey & Hayward 1993; Posamentier & Allen 1993). Considering that the Brent deltaic system accumulated in a thermally subsiding rift basin and was subjected to periodic synsedimentary tectonism, the following modifications to the 'Exxonian' sequence stratigraphic scheme were made before the Brent depositional sequences were defined:

1. A sequence boundary (type 1) can be defined if a significant relative sea-level fall is caused by regional uplift exceeding the eustatic sea-level variations (Underhill & Partington 1993; Rattey & Hayward 1993).
2. A sequence boundary (type 1) can be defined if significant erosion on uplifted basin margins and on tilted fault blocks takes place, with corresponding flooding events and thick deposits occurring on the down faulted side (Rattey & Hayward 1993).
3. A maximum flooding surface can be defined if a flooding event is recorded on a regional scale, even if the event originates from tectonic subsidence or reduced sediment supply rather than from eustatic sea-level rise (Rattey & Hayward 1993). It requires, however, that the flooding event is not related to a sequence boundary as described in option 2 above.

In this study a sequence boundary of type 2 is defined where the best candidate for a minimum RSL rise is found. This occurs theoretically between each maximum flooding surface in the sedimentary package (Fig. 8) (Vail et al. 1977; Posamentier et al. 1988). However, although empirical data suggest good candidates for type 2 sequence boundaries, a precise correlation of these observations within a scattered data set is not possible: during a progradational phase of a deltaic system, decreased rates of RSL rise can occur several times. In addition, a *distinct* phase of minimum RSL rise may not occur at all, passing from regressive to transgressive conditions. Therefore, type 2 boundaries may in practise not be uniquely defined or may even be invisible in the sedimentary record (W. Helland-Hansen, pers. comm. 1995). However, the best candidates for type 2 sequence boundaries have been indicated because the correlation of these observations highlights the important question of whether they are the results of major sea-level falls causing severe erosion and lowstand deposition (SB type 1), or the results of subtle sea-level variations during more or less continuous sedimentation (SB type 2).

The sequence boundaries and surfaces were related to absolute ages using the cycle chart of Haq et al. (1987). A complete match was not obtained, and, therefore, in some cases, the observed surfaces were simply assigned ages according to the proposed Brent model. It should, however, be stressed that the absolute ages are only advisory, and are primarily used as a convenient way to name the different surfaces in a chronological order.

Brent depositional sequences and their palaeogeographic development

Four depositional sequences of Middle Jurassic age have been identified within the Brent and Vestland Groups north of 59°N (Fig. 8). The sequences illustrate the geological development of the Brent deltaic system through the main phases of lowstand and progradation (Sequence 1), aggradation (Sequence 2), retrogradation and drowning (Sequence 3 – SMST and TST). Thereafter, a new phase of progradation occurred in the south (Sequence 3 – HST). Finally, a tectonic phase of fault block erosion occurred in the north associated with a complete retreat of deltaic deposition in the south (Sequence 4).

The base of the Brent deltaic system is defined at the Aalenian unconformity (SB at 177 Ma), which was induced by Late Toarcian uplift in the triple junction between the Central Graben, Viking Graben and Moray Firth (Ziegler 1982; Underhill & Partington 1993). The end of the Brent delta deposition is considered to be represented by the unconformity in the latest Bathonian (SB at 158.5 Ma), which was initiated by major phases of fault block tilting and erosion and flooding of the deltaic areas north of 59°N.

The major flooding event recognized within Sequence 3 (MFS 163.5 Ma) caused the drowning and the termina-

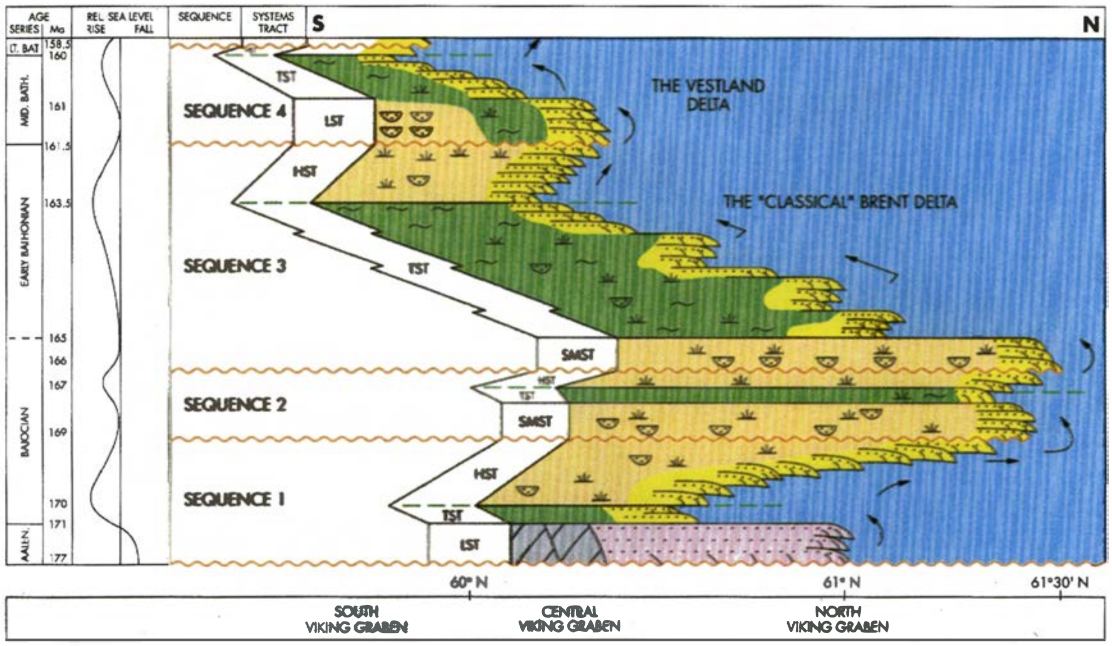

Fig. 8. Sequence stratigraphic model showing the four depositional sequences proposed for the Middle Jurassic Brent and Vestland deltaic systems.

tion of the 'classical' Brent deltaic deposition in the Northern Viking Graben and introduced estuarine deposition far south into the Southern Viking Graben (Richards 1991). A new regressive–transgressive phase has been recognized *above* the flooding surface south of approximately 60°30′N. The recognition of this younger, distinct phase has led to the introduction of a new term 'the Vestland deltaic system' for the deltaic cycle deposited after MFS 163.5 Ma (Fig. 8). The term 'Vestland' refers to the Vestland Group (Vollset & Doré 1984), which contains most of the sediments of this phase.

The Brent lowstand (Sequence 1 – LST and TST)

The Mid-Cimmerian doming in the triple junction between the Viking Graben, Central Graben and Moray Firth Graben in Late Toarcian times resulted in a dramatic sea-level fall in the North Sea area (Ziegler 1982; Underhill & Partington 1993), associated with uplift and erosion of the eastern and western basin margins of the Viking Graben. The base of the Brent Group is defined at the regional erosional unconformity created by this uplift (Mitchener et al. 1992).

The lowstand systems tract (Seq. 1). – The Brent lowstand systems tract is bounded by a type 1 sequence boundary (SB 177 Ma) at the base and a flooding surface at the top (FS 171 Ma) (Figs. 8, 9). During the Aalenian a fluvial system crossed the Horda Platform bringing coarse-grained, immature sediments from the emerged basin flanks to the shallow sea in the Northern Viking Graben (Fig. 14b). The sediments of the lowstand systems tract were deposited rapidly as sediment gravity flows on steeply inclined, progradational, shallow water fan delta lobes (Graue et al. 1987; Helland-Hansen et al. 1992). Several fans are superimposed, as seen in the more distal areas, where the fans typically add to a total thickness of 60 m. In a more proximal position the fans are amalgamated and less easy to distinguish. In the East Shetland Basin similar, but thinner (typically 10–15 m), coarse-grained sandstones were deposited (Brown et al. 1987; Cannon et al. 1992).

The Aalenian basin fill deposits are called the Oseberg Formation in the east (Norwegian sector) and the Broom Formation in the west (UK sector) (Graue et al. 1987; Cannon et al. 1992). They are interpreted as a lowstand system tract (LST) of the Brent mega-cycle, deposited along the basin margins during the period of relative sea-level fall and subsequent slow sea-level rise, resulting from Toarcian uplift and the following thermal subsidence (cf. Helland-Hansen et al. 1992 and Eschard et al. 1993).

Equivalents of the lowstand deposits are not observed in wells flanking the basin to the south in quadrant 30 (Figs. 4, 9, 14b), although one would expect major lowstand systems fronting the uplifted triple junction in the south (W. Helland-Hansen, pers. comm. 1995). No good explanation for this apparent contradiction has been found from the proposed model. An alternative interpretation is, however, that some of the lowermost fluvial/delta plain deposits that are thickly developed in the Central Viking Graben (Fig. 9) are time equivalent to the Broom and Oseberg deposits, with submarine fans deposited in front of these in the undrilled basinal areas. However, the current interpretation (Fig. 14b) is preferred due to an observed increase in dinocysts, and thereby an interpretation of the MFS 170 Ma near the *base* of the Brent Group in wells at this location. Thus no deposits correlatable to the Oseberg Fm are observed here.

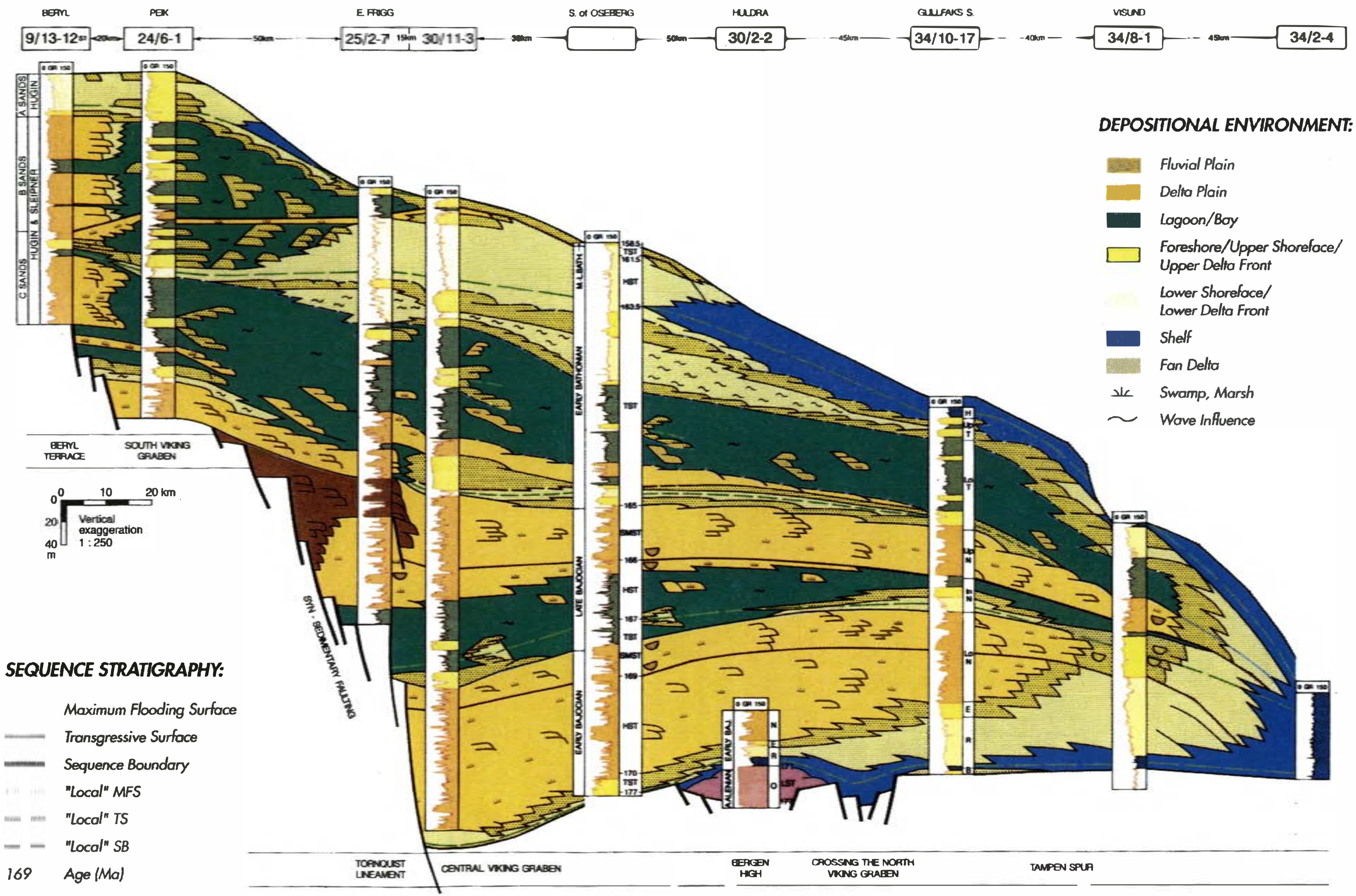

Fig. 9. S–N cross-section of the Brent and Vestland deltaic systems. See Figs. 2a and 4 for location and geographical names. Abbreviations: HST – Highstand Systems Tract, TST – Transgressive Systems Tract, SMST – Shelf-Margin Systems Tract, LST – Lowstand Systems Tract. Formation names: H – Heather, T – Tarbert, N – Ness, E – Etive, R – Rannoch, B – Broom, O – Oseberg.

The transgressive systems tract (Seq. 1). – In Early Bajocian the lowstand deposits were flooded, establishing more marine conditions in the East Shetland Basin and the Northern Viking Graben, and lagoonal environments on the Horda Platform (Fig. 14c). However, the sea did not transgress south of 60°N since coastal plain deposits are present here, as indicated by Mitchener et al. (1992). The transgressive systems tract is bounded by a flooding surface at the base and a maximum flooding surface (MFS 170 Ma) at the top. Acmes of the dinocysts *Nannoceratopsis gracilis*, *N. senex* and occasionally *N. triceras* are characteristic of this regional flooding event (Fig. 7), giving an earliest Bajocian age.

Marine shales of the uppermost levels of the Oseberg and Broom Formations and the prodelta mudstone association in the basal part of the Rannoch Formation constitute the transgressive system tract (TST) of the first Brent depositional cycle (cf. Eschard et al. 1993).

The Brent progradation (Sequence 1 – HST)

Following the regional flooding event at 170 Ma the Brent deltaic system prograded rapidly northwards from approximately 60°N to 61°30′N during the Early Bajocian, forming a highstand systems tract (Figs. 9, 14d). The Rannoch, Etive and lower part of the Ness Formations form an overall regressive phase deposited during a period of slow sea-level rise where accommodation was outpaced by high sedimentation rates (e.g. Eschard et al. 1993). This caused a rapid progradation, which is evident from a seaward stepping stacking pattern of the facies associations.

The highstand systems tract (Seq. 1). – This highstand systems tract is bounded by a maximum flooding surface (MFS 170 Ma) at the base and a type 2 sequence boundary at the top (SB 169 Ma) (Fig. 8). The deposits of the highstand systems tract comprise a complete, vertical succession representing the transition from offshore to delta plain sedimentary environments (e.g. well 34/10–17 on the southern Tampen Spur, Fig. 5b). Prodelta mudstones at the base grade upwards into lower–middle shoreface deposits (Rannoch Formation), which in turn are overlain by deposits of the upper shoreface to foreshore association (Etive Formation). Finally, sediments of the delta plain association (Ness Formation) complete the highstand succession. The *lateral* development is characterized by prograding clinoforms, such that each facies association forms a more or less continuous, seaward prograding sheet (Figs. 8, 9). The top of the highstand systems tract is defined at the base of a stacked channel interval on the delta plain, which is considered as the best candidate for a type 2 sequence boundary (SB 169 Ma) before the onset of the overlying transgression (MFS 167 Ma) (Fig. 5b).

On the northern part of the Brent delta (north of approximately 61°15′N) the sharp contact between the Rannoch and Etive Formations as observed on the southern Tampen Spur (Fig. 5b) becomes even more pronounced, marked by an abrupt change in grain size, degree of sorting and petrographic composition of the sands (Olsen & Steel 1995). In addition, the depositional character of the lowermost Etive Formation changes significantly compared to that further south, as illustrated by well 33/9-14 on the northern Tampen Spur (Fig. 5a). The sharp Rannoch–Etive boundary to the north has been proposed as a candidate for the sequence boundary to the depositional sequence above (SB 169 Ma), and terminates sequence 1 in the north. The boundary corresponds to the stacked channel interval in the south (Fig. 5b), implying that the delta plain and shoreface facies associations are time equivalent and pass laterally into one another (Fig. 9). There exists, however, considerable controversy on whether the Rannoch–Etive boundary should be interpreted as a sequence boundary in the north (Olsen & Steel 1995; Olsen & Steel, in press). Our reasons for interpreting the boundary as a type 2 sequence boundary are discussed in detail below.

The well correlations suggest that the lower part of the Brent deltaic system is characterized by a strongly progradational stacking pattern of the sediments during highstand (Fig. 9). However, this pattern is in places interrupted by more aggradational episodes, where the accommodation space balanced the sediment supply. The fluctuations between strongly progradational and aggradational stacking patterns is believed to be caused by changes in the relationship between subsidence, eustatic sea-level rise, synsedimentary faulting and the amount of sediments supplied to the system. However, the stacking pattern may also be controlled by autocyclic processes (i.e. channel switching).

The significance of the Rannoch/Etive transition in the north (SB 169 Ma and SB 166 Ma)

In the northern part of the Brent deltaic system (north of 61°15′N) a sharp and erosional boundary surface separates the Rannoch and Etive Formations, and a significant change in grain size and sedimentary structures is observed into the overlying sandstone package (e.g. Fig. 5a). These observations have caused considerable debate on its stratigraphic significance. Divergent opinions are mainly due to different interpretations concerning the amount of wave, tidal and fluvial influence detected in the strata of the lowermost Etive Formation (e.g. Olsen & Steel, in press). Thus, the Etive Formation has been considered as upper shoreface, foreshore, barrier and strand-plain deposits (e.g. Cannon et al., 1992; Mitchener et al., 1992; Olsen & Steel 1995; Jennette & Riley, in press), as distributary mouth-bar deposits (e.g. Simpson & Whitley 1981; Johannessen et al. 1995; Olsen & Steel 1995), as tidal channel and inlet deposits (e.g. Daws & Prosser 1992; Scott 1992) and as braided fluvial channel deposits (e.g. Parry et al. 1981; Brown & Richards 1989;

Van Wagoner et al. 1993; Reynolds 1995). Dependent upon the inferred depositional environment, the Etive succession has been interpreted in terms of deposition during normal regression on the shoreface (Cannon et al. 1992; Helland-Hansen et al. 1992; Mitchener et al. 1992; Olsen & Steel, in press), as an incised valley fill (e.g. Van Wagoner et al. 1993; Reynolds 1995; Jennette & Riley, in press) or as linked to minor erosional episodes on the shoreface (e.g. Olsen & Steel 1995; Olsen & Steel, in press). The first interpretation signifies that there is a shale-out and thereby no exploration potential north of the Brent deltaic system, whereas the second allows the possibility of lowstand deposits and thus of new prospects further north. The third option may give a seaward displacement of the deltaic system, with the deposition of a shelf-margin systems tract. No major lowstand deposits in front of the delta are envisaged.

Towards a sequence stratigraphic interpretation of the Rannoch/Etive boundary. – Essentially, the sequence stratigraphic interpretation of the Rannoch/Etive boundary depends upon the interpretation of the depositional environment of the lowermost Etive sandstones. If the succession is attributed a braided fluvial origin, a type 1 sequence boundary is implied. However, if upper shoreface to foreshore, distributary mouth-bar, tidal inlet or tidal channel deposits are inferred, the boundary should be interpreted as either a type 2 sequence boundary or none at all (i.e. normal regression). The distinction is dependent on whether related sedimentary environments are interpreted as being partly or completely absent from the vertical succession. Therefore, the sedimentary structures and grain-size motifs of the uppermost Rannoch Formation and lowermost Etive Formation have been critically examined.

In the southern Tampen Spur area, the upper part of the Rannoch Formation is characterized by coarsening-upward units dominated by hummocky- and swaley cross-stratification with minor planar low-angle cross-stratification. These units are interpreted to reflect deposition in a lower to middle shoreface environment (Fig. 5b). The lowermost Etive Formation is characterized by stacked fining-upward units with low-angle cross-strata, plane parallel lamination, small-scale trough cross-strata, or predominantly massive or deformed bedding. These structures are similar to those described from high-energy barred coastline systems by Davidson-Arnott & Greenwood (1976) and Hunter et al. (1979), and therefore the lowermost Etive Formation is attributed to an upper shoreface (with longshore bars) to foreshore depositional environment. Hence, although a sharp boundary for the Rannoch/Etive transition is observed, a gradual shift in depositional environment from middle shoreface to upper shoreface and foreshore is observed (see also Johannessen et al. 1995; Olsen & Steel 1995). Thus, the Rannoch/Etive boundary is not interpreted as a sequence boundary in the southern areas.

In the northern Tampen Spur area (blocks 33/9, 34/7 and 34/8) the vertical grain-size trend of the Rannoch Formation is more complex. The uppermost metres of the Rannoch Formation are characterized by stacked fining-upward units of fine-grained sandstone, separated by several or multiple erosional surfaces. This uppermost interval is slightly more coarse-grained than the Rannoch sandstones below, and is characterized by alternating units of hummocky cross-stratification and wave-ripple lamination with minor massive intervals. The formation is also interpreted here to represent a lower/middle shoreface environment (Olsen & Steel 1995). The sedimentary structures of the lowermost Etive Formation in the north (blocks 34/8 and northern parts of 34/7 and 33/9) are predominantly trough and tabular cross-bedding with minor current ripple laminated intervals. The grain-size at the base of the units is coarse- to very coarse-grained, fining upward to fine-grained at the top. Thus a strongly fining-upward trend is seen. The fining upward motif is characteristically terminated by a zone of mica-rich laminae 1–3 cm thick, associated with mudstone-rich and organic-rich material (Fig. 5a; *E1 facies* of Olsen & Steel 1995).

Based on the described sedimentary structures for the lowermost Etive Formation, no convincing evidence for a braided fluvial origin has been found. Accordingly, the Rannoch/Etive boundary is not a candidate for a type 1 sequence boundary. The sedimentary descriptions do, however, suggest two possible interpretations: progradation of longshore troughs, bars and rip channels in a barred coastline environment could have produced the observed features (see also Hunter et al. 1979; McCubbin 1982; Olsen & Steel, in press). Alternatively, the sharp Rannoch/Etive boundary could be the result of reduced accommodation space, bringing coarser-grained, more proximal sediments (lowermost Etive Formation) onto more distal marine sediments (Rannoch Formation) (e.g. Olsen & Steel 1995; Olsen & Steel, in press).

Observations from the wells penetrating the most distal parts of the Brent deltaic sequence support the interpretations indicated above: (1) The northernmost wells drilled on the Brent delta (e.g. 33/5-2 and 34/4-3, Fig. 4) show a complete shoreface-foreshore succession correlatable as distal facies to a normally prograding to aggrading delta plain (Fig. 10). (2) A characteristic bell-shaped gamma-ray profile of the lower to middle shoreface deposits in the upper Rannoch Formation is preserved across the entire basin from east to west (Fig. 11). (3) For the Etive Formation, similar facies associations as those observed in well 33/9-14 (*facies 'E1'*) are recognized in several wells laterally along the delta front, presumably forming a continuous, sheet-like sandstone interval (Fig. 11). (4) The continuation of the Rannoch/Etive boundary surface may be correlated landward as a basal surface underlying an interval of stacked channel sandstones in the Ness Formation and basinward as a conformable surface within the Rannoch sandstones.

The observations described above favour an interpretation of a constant relative sea level and sedimentary

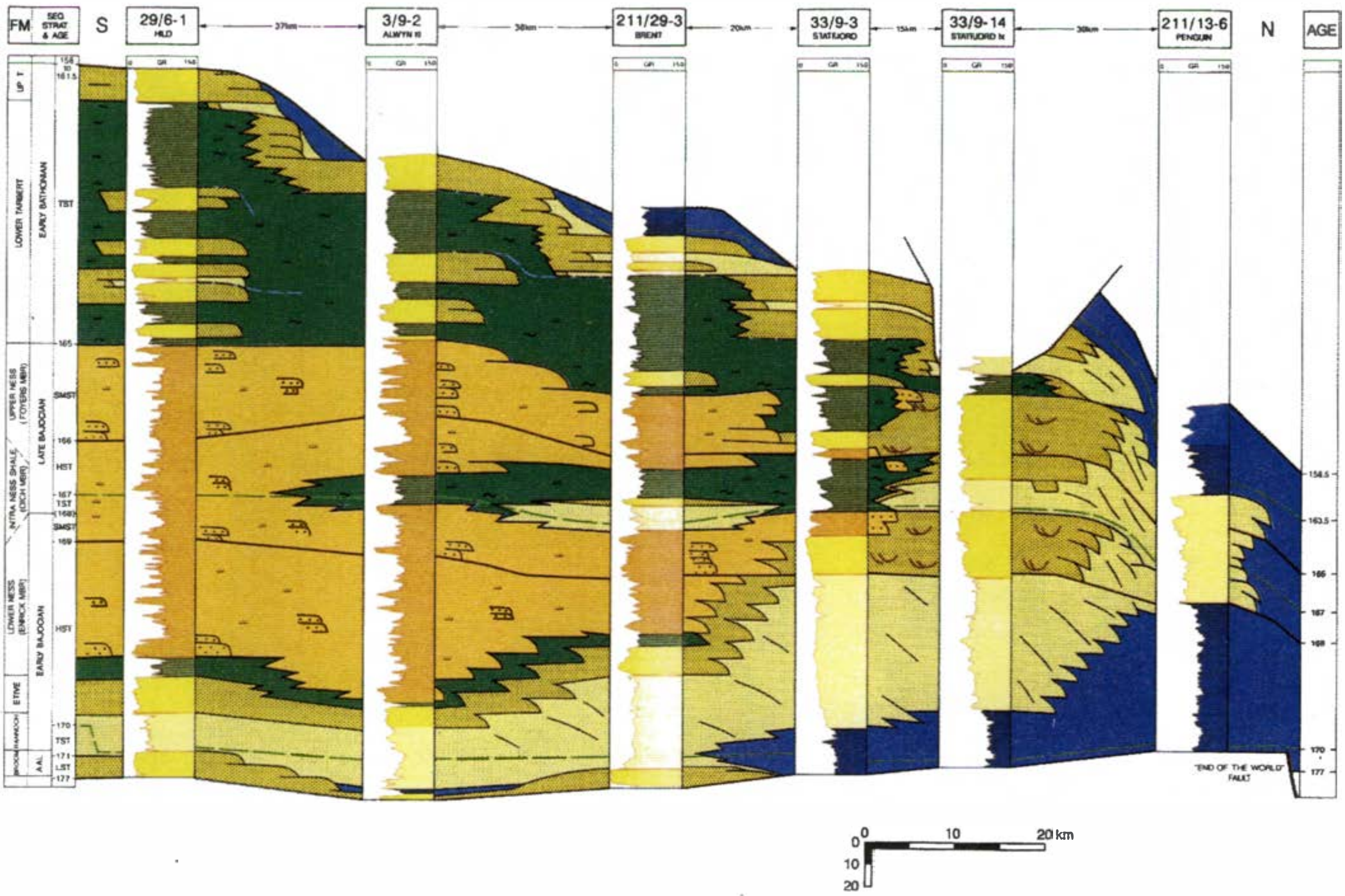

Fig. 10. S–N cross-section of the northern extension and pinch-out area of the Brent deltaic system. Legend as in Fig. 9. Location and geographical names shown in Figs. 2a and 4.

bypass as a cause for the Rannoch–Etive boundary as opposed to an interpretation of a major sea-level fall with corresponding erosion and incision of the Brent delta. However, it is likely that the lowermost Etive Formation was deposited as a result of oscillations around sea-level still-stand. During this overall still-stand, small relative sea-level falls created the multiple erosional surfaces of the '*E1 facies*', whereas the thin, amalgamated, accumulations formed during subsequent small relative sea-level rises.

The Rannoch/Etive boundary at the base of the '*E1 facies*' is interpreted as a regressive surface of minor erosion, marking the most pronounced basinward shift of facies on the delta front, and therefore as a type 2 sequence boundary (sensu Posamentier et al. 1988). The sequence boundary separates sequences 1 and 2 of the proposed depositional model, and is attributed the age of 169 Ma by comparison with the cycle chart of Haq et al. (1987).

A younger but similar boundary is recognized as a repetitive succession of the Rannoch and Etive Formations north of 61°15′N (Fig. 5a). This second, equivalent contact is related to the sequence boundary at 166 Ma separating sequences 2 and 3. This will be discussed later.

Brent aggradation (Sequence 2 – SMST, TST and HST and Sequence 3 – SMST)

Following the earliest Bajocian advance of the Brent delta, a period of aggradation or restricted progradation occurred in Early–Late Bajocian times, forming a relatively straight east–west delta front/shoreline at approximately 61°30′N. The aggradational part of the Brent delta is found between a type 2 sequence boundary (SB 169 Ma) and a flooding surface (FS 165 Ma). The aggradational package consists of shelf-margin, transgressive and highstand systems tracts of sequence 2 and a shelf-margin systems tract of sequence 3 (Fig. 8). During the period of aggradation, the delta was affected by a pronounced, regional flooding event (MFS 167 Ma) with a resulting landward displacement of facies. This was followed by a new rapid delta progradation, reaching latitudes close to its previous maximum northward extent. A type 2 sequence boundary (SB 166 Ma) separates the highstand of this rapid progradational phase from the aggrading shelf-margin systems tract above (Figs. 8–10, 14d, 15a, b).

Shelf-margin systems tract (Seq. 2). – The lowermost shelf-margin systems tract is bounded by a type 2 se-

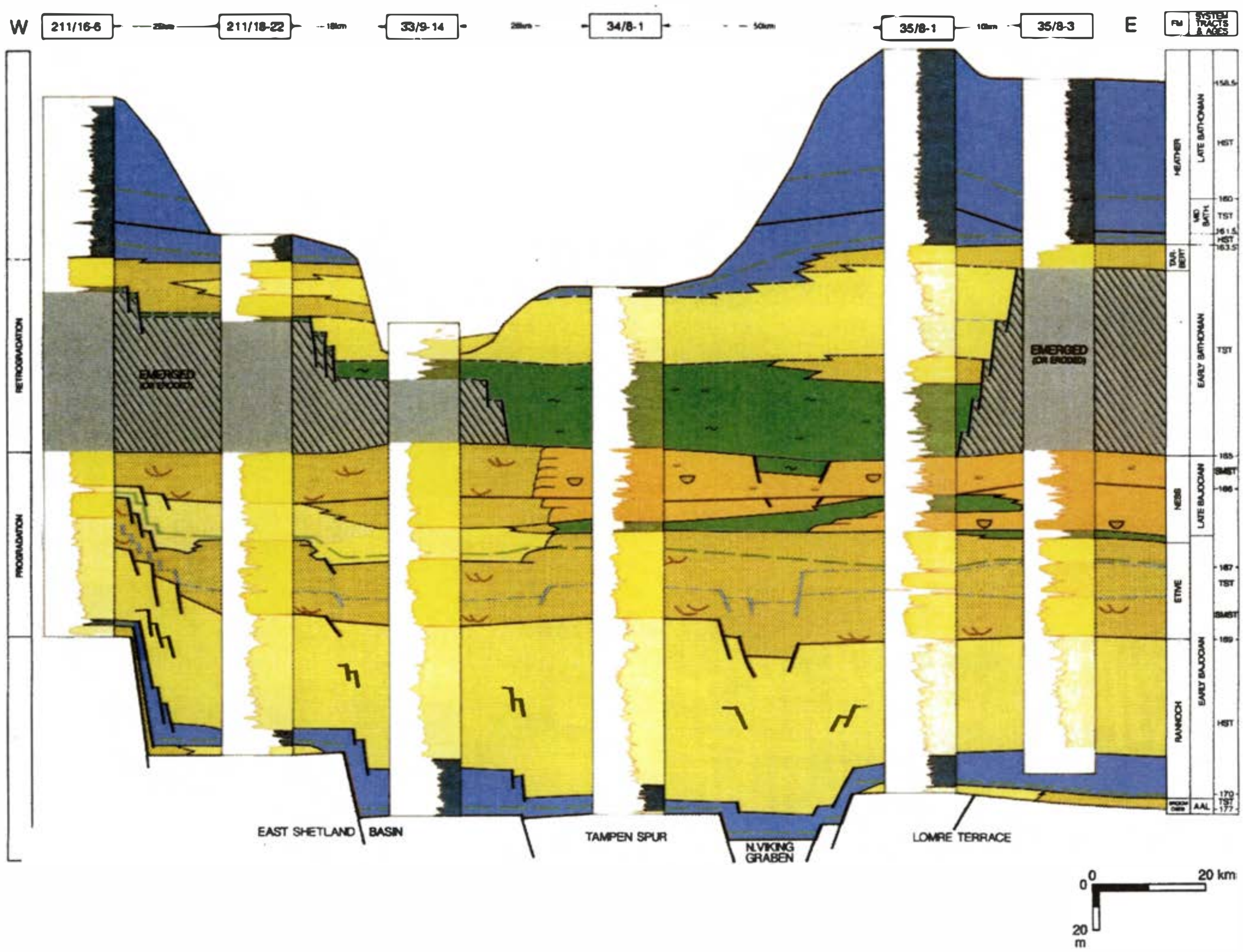

Fig. 11. E–W cross-section of the northern Brent delta. Gamma-ray log scale is 0–150 API. Legend as in Fig. 9. Location and geographical names are shown in Figs. 2a and 4.

quence boundary (SB 169 Ma) at the base and by a flooding surface at the top (Fig. 8).

In the northern part of the Tampen Spur area as well as to the east and west, the deposits of the shelf-margin systems tract start at the base with the stacked '*E1 facies*' of Olsen & Steel (1995), and continue with the more 'classical' Etive nearshore facies (Fig. 5a). These Etive deposits are correlated southwards to stacked fluvial channels within the delta plain facies association of the Ness Formation (Figs. 5b, 9).

The stacking pattern is interpreted as representing the shelf-margin systems tract (sensu Posamentier et al. 1988) of the second Brent cycle (Fig. 8). The shelf-margin systems tract is often slightly progradational to aggradational, since it is deposited after the point of slowest rate of RSL rise, but before the rate of RSL rise is sufficient to cause transgression and deposition of backstepping sedimentary packages.

Transgressive systems tract (Seq. 2). – The transgressive systems tract is observed as a marine incursion during the period of delta aggradation (Fig. 15a). It is bounded by a flooding surface at the base and a maximum flooding surface (MFS 167 Ma) at the top. The basal flooding surface is recognized by a return to more distal facies associations, within both shoreface and delta plain environments.

In the northern Tampen Spur area a shift from the upper shoreface to foreshore and mouth-bar facies associations of the Etive Formation (SMST) to the lower/middle shoreface facies association of the Rannoch Formation is observed (Fig. 5a). The boundary surface separating these facies associations is overlain by a few centimetres thick lag of quartz pebbles with a diameter up to 0.50 cm. It is interpreted as a transgressive lag and is seen in several wells in blocks 34/7, 34/8 and 33/9 including the well 33/9-14 (Fig. 5a).

In the southern Tampen Spur area and on the flanks of the North Viking Graben, the transgressive systems tract comprises fine-grained lagoonal and embayment deposits of the bay-fill sub-association within the Ness Formation. In well 34/10-17 the maximum flooding surface (MFS 167 Ma), which bounds the top of the transgressive systems tract, is thought to be close to the base of a prograding parasequence, where the most marine conditions are envisaged (Fig. 5b).

In the East Shetland Basin the deposits of the transgressive systems tract are often developed as a 5–10-m-thick interval of fine-grained, organic-rich lagoonal shale within the coarser-grained delta plain deposits of the Ness Formation. This shale interval is known as the 'Mid-Ness-Shale' or as the 'Oich Member' of the Ness Formation (Cannon et al. 1992). The maximum flooding event at 167 Ma is defined within this interval when present. However, a regional correlation of the maximum flooding surface is hampered by the fact that the 'Mid-Ness-Shale' is diachronous within the studied area (e.g. Cannon et al. 1992). Although the flooding event recorded at the delta front will enhance the extension of lagoons on the delta plain, these will be located in different places at different times, and it is therefore inaccurate to define all drilled lagoonal deposits as correlative time events. Furthermore, several candidates (i.e. shale intervals) for the 'Mid-Ness Shale' marker exist in some wells when correlating across major fault blocks (e.g. well 211/28-5 in Fig. 12). Therefore, the maximum flooding surface has been correlated through the most marine intervals or alternatively the most likely candidate for the 'Mid-Ness Shale' marker when preserved in the rock record.

In the Central Viking Graben an approximately 60-m-thick coal-free lagoonal interval is recognized within the delta plain deposits (Fig. 9). Here, the flooding event is defined where a slight increase in the ratio of marine to brackish palynomorphs is recorded by quantitative biostratigraphy. The marine character is strongest for the wells positioned closest to the centre of the graben (e.g. wells 30/11-3 and 30/10-6, Fig. 4). The transgressive systems tract also thickens here compared to the flanks and further north.

The transgressive systems tract is terminated by a major flooding surface marked by the acmes of the palynomorphs *Nannoceratopsis gracilis* and *Nannoceratopsis senex*, and the down-hole extinction of *Sentusidinium* spp. This flooding event reached its maximum landward position at 167 Ma in the Late Bajocian and is defined as a maximum flooding surface (cf. Mitchener et al. 1992).

Highstand systems tract (Seq. 2). – A phase of rapid progradation occurred after the maximum flooding event at 167 Ma, bringing the delta front to a position slightly north of its position prior to the flooding event. This is shown by a second progradation of the Rannoch Formation in well 33/9-14 and by a prograding parasequence in the lower Ness Formation in well 34/10-17 (Figs. 5a, b). The deposits of the highstand systems tract are bounded by a maximum flooding surface (MFS 167 Ma) at the base and a type 2 sequence boundary (SB 166 Ma) at the top (Figs. 8, 9).

In the northwestern Tampen Spur area, the deposits of the highstand systems tract are developed as micaceous sandstones of the lower/middle shoreface association (Fig. 5a). On the eastern part of the delta front (i.e. on the northeastern Tampen Spur and on the northern Horda Platform) the deposits of the highstand systems tract are developed as nearshore deposits of the upper shoreface to foreshore sub-association of the Etive Formation. The nearshore deposits pass upwards into the delta plain facies association of the Ness Formation. This is the first time that delta plain facies associations have been brought so far north (e.g. wells 34/8-1 and 35/8-3 on Fig. 11).

On the Gullfaks terrace the deposits of the highstand systems tract are found within the lower part of the delta plain deposits of the Ness Formation as a characteristic, coarsening-upward parasequence, interpreted as embayment facies (bay-fill sub-association) deposited under brackish to marine conditions (Fig. 9). This parasequence is well developed in well 34/10-17 (Fig. 5b) and is seen to thicken towards the Viking Graben (Fig. 12). The prograding parasequence is overlain by a 10-m-thick unit of shale-rich lagoonal or bay deposits. Possibly, continuous barrier sandstones flanked the delta plain around the marine embayment in the Viking Graben and along its margins (Fig. 5a). A good candidate for this barrier sandstone can be found in the upper part of the prograding parasequence in well 34/10-17 (2844-2834 m) (Fig. 15b).

The sequence boundary at the base of Sequence 3 (SB 166 Ma). – A new basinward shift of facies of the Etive Formation terminates the overall aggradational sequence 2 of the Brent delta. In the northern Tampen Spur area the lower/middle shoreface facies association of the Rannoch Formation, which represents the highstand system tract of sequence 2, is abruptly overlain by nearshore facies of the upper shoreface to foreshore and mouth-bar sub-associations of the Etive Formation (Fig. 5a). The Rannoch and Etive Formations are once more separated by a sharp erosional surface associated with a pronounced change in grain-size, sedimentary structures and petrography. This second, sharp contact can be traced southwards to the base of a second interval of stacked channels in the delta plain facies association of the Ness Formation in exactly the same manner as the sequence boundary at 169 Ma (Figs. 5b, 9), and are therefore analogously interpreted as a type 2 sequence boundary (Fig. 8). The sequence boundary is attributed an age of 166 Ma by comparison to the cycle chart of Haq et al. (1987).

Shelf-margin systems tract (Seq. 3). – The overall aggradational phase of the Brent delta system is terminated by a shelf-margin systems tract of sequence 3. The aggrading interval of sequence 3 extends slightly seaward of sequence 2, and represents the maximum progradation of the Brent delta as far as 61°30′N (Fig. 15b). The shelf-margin systems tract is bounded by a type 2 sequence boundary at 166 Ma below and a flooding surface at 165 Ma above (Fig. 8).

Analogous to the shelf-margin systems tract of sequence 2, the shelf-margin systems tract starts with the

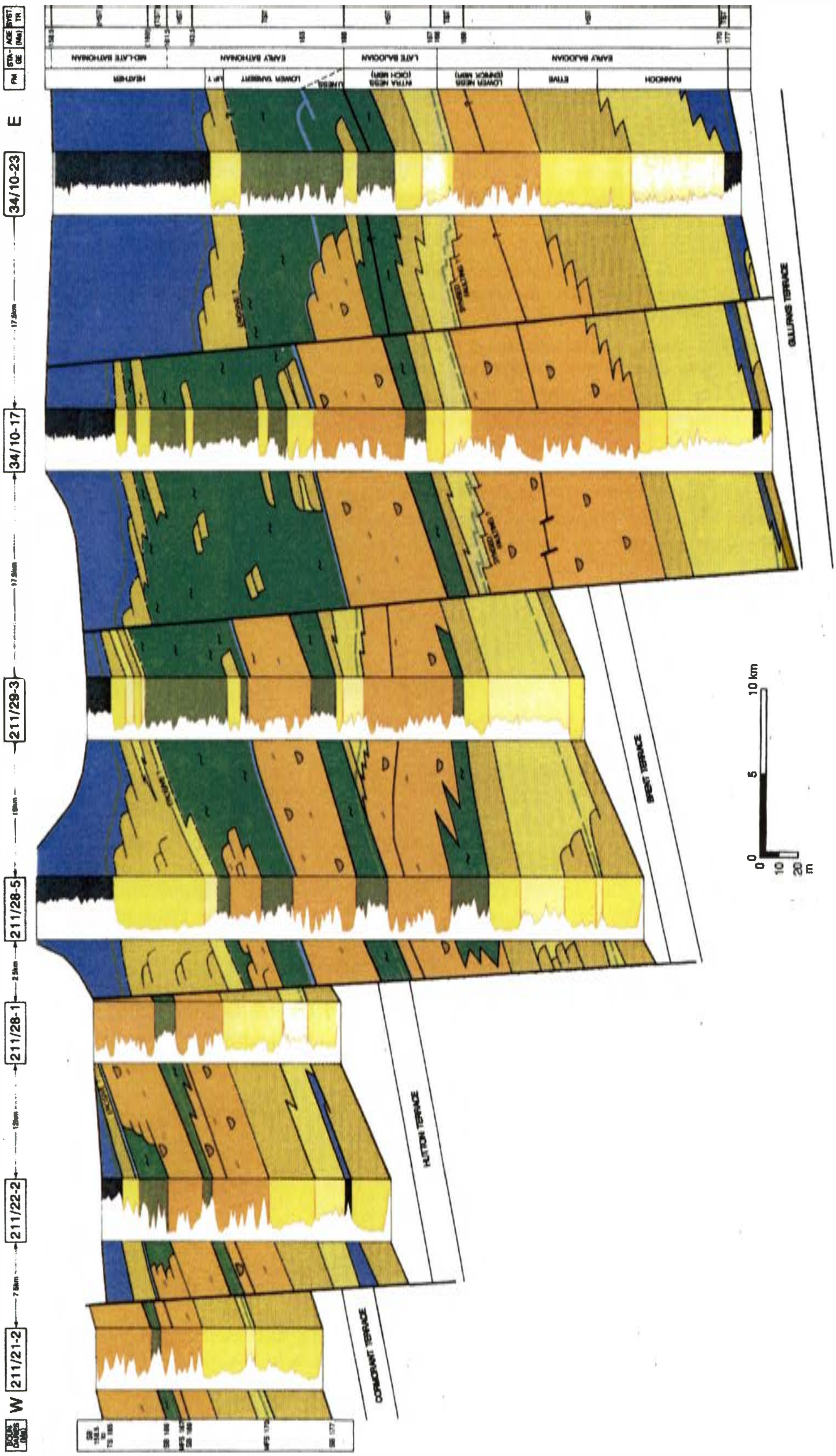

Fig. 12. Synsedimentary faulting of the Brent delta in the East Shetland Basin. Gamma-ray log scale is 0–150 API. Legend in Fig. 9. Location and geographical names are shown in Figs. 2a and 4.

stacked '*E1 facies*' of Olsen & Steel (1995), and also here this particular sub-association includes the overlying deposits of the upper shoreface to foreshore and mouth-bar sub-associations. On the Horda Platform and in the eastern Tampen Spur area and southwards, the sequence boundary is less pronounced and is interpreted to be present at the base of a stacked fluvial channel interval in the delta plain facies association of the Ness Formation (Fig. 9). The stacked fluvial channels constitute the sediments of the SMST.

In the northern part of the East Shetland Basin, lagoons, embayments and coaly swamp facies of the delta plain facies association (Ness Formation) overlie the Etive nearshore facies (Figs. 5a, 11). This suggests a phase of slight progradation of the delta during the generally aggradational phases of Sequence 3. As for Sequence 2, this is explained by a continued but limited progradation of the delta *after* minimum RSL was reached, but before the RSL rise caused transgression and a landward facies displacement. Alternatively, the slight progradational phase may be due to autocyclicity and local progradation of the delta plain on the northern part of the East Shetland Basin.

Brent deltaic retrogradation and drowning (Sequence 3 – TST)

The aggradational phase of Brent deltaic deposition was terminated by an abrupt flooding event (165 Ma) in Late Bajocian–Early Bathonian times, which marked the onset of delta retrogradation and drowning. At this time the creation of accommodation space outpaced the amount of sediments supplied to the basin, causing a backstepping of the whole Brent delta system with the deposition of the upper Ness, Tarbert and basal Heather Formations (Figs. 7, 8) (Helland-Hansen et al. 1992; Mitchener et al. 1992; Eschard et al. 1993).

During the basal initial flooding event (165 Ma), the delta front retreated slightly and a marine incursion proceeded as far south as 60°N along the Viking Graben (Fig. 15c). Several minor flooding events occurred during the delta retrogradation, accompanied by an encroachment of lagoonal or delta plain facies deposition on previously drier areas. Thus, during retrogradation the general increase in accommodation space caused a change in the nature of the depositional environments from fluvially dominated delta plain and nearshore sands to a predominance of lagoons, embayments and wave- or tide-dominated delta-front deposits (Figs. 9, 10).

Transgressive systems tract (Seq. 3). – The transgressive systems tract comprises the period of overall retrogradation of the Brent delta and is bounded by a flooding surface (FS 165 Ma) at the base and a maximum flooding surface (MFS 163.5 Ma) at the top (Fig. 8). The initial basal flooding surface is marked by the first appearance of the dinocyst *Dissiliodinium willei* in well 30/11-3 (Figs. 4, 9) in the Central Viking Graben, suggesting an Early Bathonian age for the first retrogradational phase of the Brent delta (Fig. 15c). Several successive retrogressive cycles occurred (Figs. 10, 15d), until the drowning of the 'classical' Brent delta was completed by a maximum flooding in the Early Bathonian (MFS 163.5 Ma on Fig. 16a). The Horda Platform was also flooded at this time and covered by silty sands called the Heather A sands (Hellem et al. 1986). The maximum flooding surface is recognized as a biostratigraphic acme of the dinocyst *Dissiliodinium willei*, characteristic of an Early Bathonian age (Fig. 7) (e.g. Mitchener et al. 1992).

In the Tampen Spur area fine- to coarse-grained marine sandstones (Tarbert Formation) alternate with delta plain mudstones, fine-grained sandstones and coals (Ness Formation). The Tarbert Formation is here organized in coarsening-upward and shallowing-upward littoral sequences representing lower shoreface to foreshore facies associations, which pass northwards into fully marine offshore mudstones of the Heather Formation and southwards into the delta plain sediments of the Ness Formation (Graue et al. 1987).

The deposits of this major transgressive systems tract are made up of several genetic units, separated by minor flooding surfaces with an overall landward stepping stacking pattern (Figs. 5, 9, 10). Each genetic unit was itself deposited during a minor transgressive–regressive cycle. The flooding events created ravinement surfaces from the marine domain moving landward into the delta plain, recognizable by a conglomeratic lag at the base of the transgressive–regressive cycles (Rønning & Steel 1987). Sediments representing these small transgressive phases are fine-grained sediments and coals of the bay-fill (lagoonal and embayment) and stagnant swamp sub-associations of the Ness Formation, and barrier sandstone complexes of the Tarbert Formation (Fig. 5b). During the following small regressive depositional phase of each genetic unit, a clastic sand-dominated wedge of nearshore and shoreface sediments prograded rapidly seawards (e.g. blocks 34/10 & 34/7), while time-equivalent delta plain sediments consisting of thin mud-rich deposits of the overbank sub-association were deposited (cf. Eschard et al. 1993). Between times of regression and transgression, the Brent delta complex aggraded with vertically stacked foreshore, back-barrier and delta plain sediments (Eschard et al. 1993). The retrogressive nature of the backstepping is particularly well developed in the Hild-Alwyn area through four main repetitive cycles (Fig. 10) (Rønning & Steel 1987).

In the northern part of the South Viking Graben the successive flooding events during the retrogradation led to a southward onlap of the delta plain deposits onto the older rocks below, often associated with a drowning of swamps and the development of thick coal layers. These coal layers can be recognized as a strong seismic reflector, and are known as the 'Near Base Brent coal marker'. The delta plain deposits were covered by tidally influenced estuarine deposits that gradually developed into the Central and Southern Viking Graben as the flooding continued (Richards 1991).

To summarize, a marine incursion developed along the Viking Graben as far south as 60°N following the initial flooding episode at 165 Ma. However, the delta front quite rapidly adjusted itself to a position not far from its original maximum extension, and the marine incursion was quickly replaced by a more restricted embayment with periodic connection to marine waters in the central northern areas (Fig. 15c). The embayment was seemingly flanked by barrier sandstones, protecting lagoons and delta plain deposits. The delta plain and the lagoonal facies of the aggradational Brent phase were now covered by coarse-grained barriers, beach sands and mouth bars of the retrograding phase (i.e. the Tarbert Formation) (Fig. 15d).

The Early Bathonian maximum flooding event (MFS 163.5 Ma) completes the first major regressive–transgressive depositional cycle (the 'classical' Brent delta complex) in the North Viking Graben (Graue et al. 1987). During the deposition of the cycle, the character of the Brent delta changed from a wave- and fluvial-dominated river delta system during progradation to a wave- and tide-dominated delta system during retrogradation (Olaussen et al. 1992). This variation is related to changes in sediment influx, subsidence and basin morphology.

During progradation the sediment influx was high compared to the subsidence, and a fluvial/wave dominated deltaic system developed. A storm-wave-dominated delta system was established when the delta front aggraded and oscillated near its maximum extension along the northern margin of the Northern Viking Graben. Waves from the Jurassic seaway present between Greenland and the Norwegian mainland (Ziegler 1982) reworked the delta front and a balance between subsidence and sediment input avoided a further delta extension into the Møre Basin (Figs. 1, 15b). In the Early Bathonian, synsedimentary faulting along the Viking Graben is believed to have caused enhanced subsidence, and forced the delta to retreat (see below). The linear delta front was reshaped into an estuary following the graben structuration, where tidal processes had an increasing effect on the depositional geometry as the delta retreated southwards into the narrow seaway created by the pre-rift faulting (e.g. Figs. 15b–d).

The Vestland delta progradation (Sequence 3 – HST)

Following the major flooding event in the Early Bathonian (MFS 163.5 Ma) and the drowning of the 'classical' Brent delta (Fig. 16a), a delta system prograded northwards again (Fig. 16b). This deltaic sequence is referred to as the Vestland delta and is recognized as a progradational phase (HST) in the Central Viking Graben wells, extending almost as far north as the Oseberg field (Figs. 9, 16b). The extension of the Vestland delta is from south of 59°N to ca. 60°30N. Thus, the Vestland delta did not reach the northern North Viking Graben and the Tampen Spur area. Instead, the deposits of the Vestland delta system pass laterally northwards into shales and silty sands of the Heather Formation (Figs. 9, 16b).

Lithostratigraphically, the delta plain associations of the Vestland delta belong to the Sleipner Formation, whereas the shoreface and foreshore deposits belong to the Hugin Formation (Vollset & Doré 1984). In the Bruce Embayment, the C sands correspond to the prograding Vestland delta, whereas the B and A sands are related to the early and late phases of the retrogradation of the Vestland delta, respectively (Fig. 17).

Highstand systems tract (Seq. 3). – The highstand systems tract is bounded by the maximum flooding surface (MFS 163.5 Ma) at the base and a sequence boundary (SB 161.5 Ma) at the top (Fig. 8).

The deposits of the highstand systems tract are developed as a package of prograding, tidally influenced marine sandstones of the upper shoreface to foreshore association (Hugin Formation) passing southwards into delta plain and lagoonal deposits (Sleipner Formation) (Fig. 16b) (Richards 1991). The increased tidal influence in the South Viking Graben as compared to the North Viking Graben (e.g. Richards 1991) is a consequence of the narrow marine passage developing in the South Viking Graben between the East Shetland Platform and the Utsira High (Figs. 15d–16d). In the Bruce Embayment a fluvial system sourced from the East Shetland Platform caused a braided delta plain to prograde from west to east, being fluvially dominated in its proximal part and tidally influenced in more distal areas (Fig. 17). These deposits are referred to as the C sands (e.g. Mitchener et al. 1992).

The prograding highstand is best illustrated by well 30/11-3 in the Central Viking Graben, where the gamma-ray log profile shows the characteristic coarsening-upwards motif of a prograding lower to upper shoreface succession (Figs. 2a, 4, 9). The highstand progradation culminates in the deposition of two coal layers in a nearshore environment (Fig. 5c). This 'coal doublet' has been recognized on a semi-regional scale (Fig. 16b), and is a good correlation marker also in the northern parts of the South Viking Graben (Peik, Heimdal and Vale Fields) and it overlies the C sands in the Bruce Embayment (Fig. 17). The recognition of the coal doublet also led to a reliable identification of the Vestland delta highstand in the South Viking Graben. The base of the highstand is defined at the interval of maximum marine influence (e.g. at the acme of *D. willeii*) and the top at the coal doublet level (e.g. Fig. 5c and well 24/6-1 on Fig. 9). These criteria for recognizing the systems tracts are important since the tidal estuarine facies associations typical of the area show rapid variations and heterogeneities that otherwise would have made a reliable correlation difficult.

On the Horda Platform and along its flanks to the west (Oseberg area), the silty offshore sandstones of the

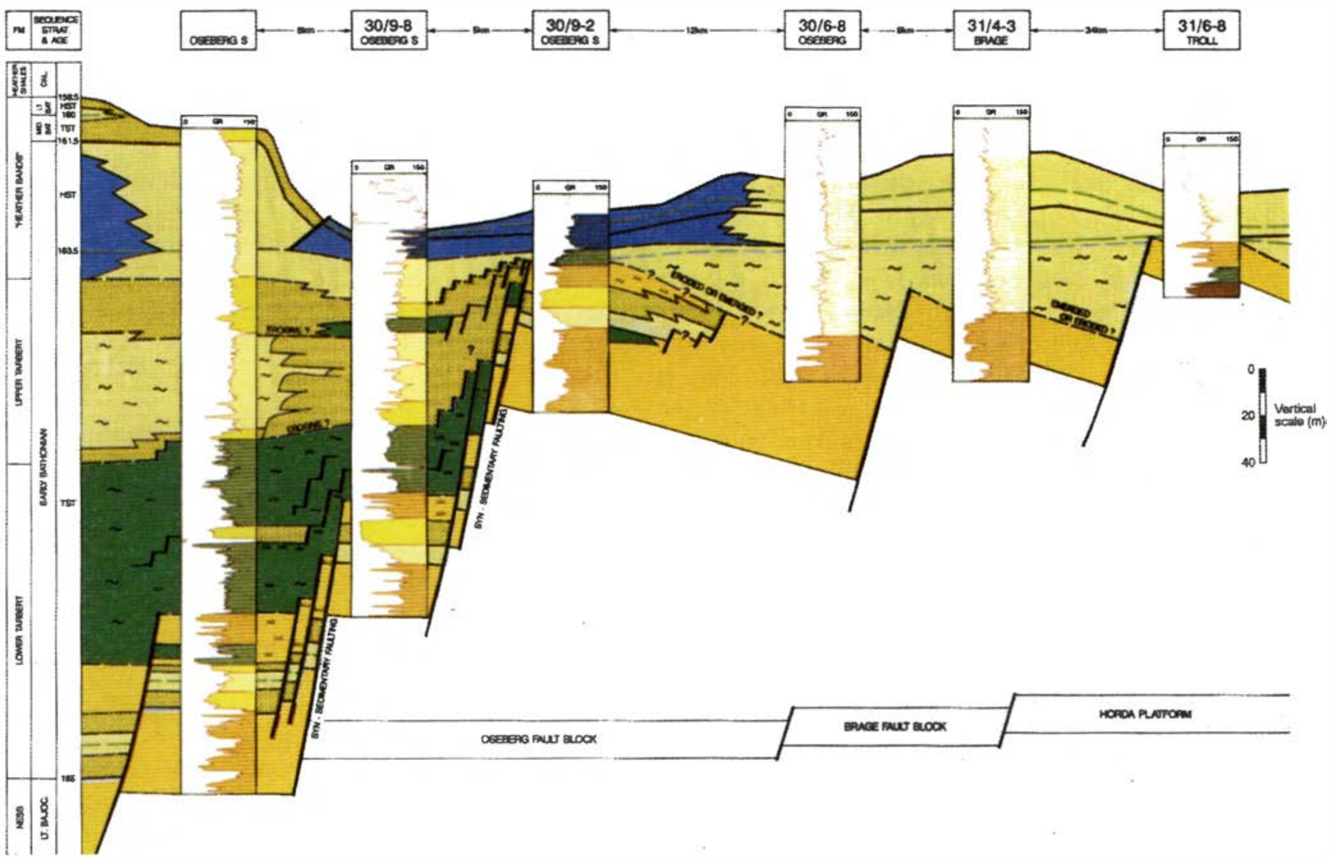

Fig. 13. Synsedimentary faulting during the Brent retreat on the Horda Platform. Distances between wells are not to scale. Legend as in Fig. 9. Location and geographical names shown in Figs. 2a and 4.

Heather A sands are age equivalent to the Vestland delta. The highstand systems tract is, however, condensed here and has not always a clear coarsening-up motif (Fig. 13).

The Vestland delta retreat and drowning (Sequence 4 – LST, TST and HST)

The retreat and drowning of the Vestland delta is bounded by two sequence boundaries; one at the base (SB 161.5 Ma) and one at the top (SB 158.5 Ma). The sequence is subdivided into lowstand, transgressive and highstand systems tracts (Fig. 8).

The sequence boundary at 161.5 Ma. – In the Bruce Embayment the 'coal doublet' is abruptly overlain by proximal alluvial fan and distal braided delta plain deposits, prograding from the East Shetland Platform into the tidal estuary of the South and Central Viking Graben. The abrupt change is most probably related to a tectonic phase, where sediments were eroded on the Shetland Platform and deposited in great thickness on the down-faulted margins, thinning towards the Viking Graben axis away from the main bounding faults (Figs. 4, 9, 16c, 17). The presence of the 'coal doublet' below thick, immature sediments in several wells on a semi-regional scale indicates that the coal layers were most probably protected from erosion by being preserved in down-faulted, grabenal positions relative to the uplifted and eroded Shetland Platform.

The sharp transition from coal layers on top of a prograding highstand to immature, aggrading sandstones above is considered to represent a sequence boundary. It is defined as a type 1 sequence boundary due to assumptions of a (regional?) uplift which caused severe erosion of the Shetland Platform.

This tectonically induced sequence boundary is considered time equivalent to an early phase of rifting and fault block rotation in the northern North Viking Graben (Fig. 16c). In the north, erosion on the crests of the tilted fault blocks may have given rise to some of the thickened sediments on the down-thrown side of the faults. This is discussed in greater detail later.

Lowstand systems tract (Seq. 4). – The lowstand systems tract is bounded by a sequence boundary (161.5 Ma) at the base and a flooding surface (TS 161 Ma) at the top (Fig. 8).

Figure 17 shows the presence of alluvial fan deposits on the fault terrace, grading into braided delta deposits eastwards. The braided delta deposits, resting on the 'coal doublet', are fluvial-dominated in proximal settings and tidal-dominated in distal parts. They thin rapidly northwards toward the Central Viking Graben (Fig. 9).

These sediments are referred to as the B sands in the area of the Bruce Embayment (e.g. Mitchener et al. 1992). They are slightly prograding to aggrading, and constitute the lowstand systems tract of the retreating Vestland delta (Sequence 4). There is a general increase in abundance of dinocysts during the lowstand aggradation compared to the highstand below. The dinoflagellate *D. willei* is present in combination with dinocysts indicative of a Middle Bathonian age (Fig. 7). *D. willei* is considered limited to the Early Bathonian on many palynology charts, but Mitchener et al. (1992) record its appearance in the Middle Bathonian as well. This is taken as support for a Middle Bathonian age of the interval, and that the age of the basal sequence boundary is 161.5 Ma.

Mitchener et al. (1992) interpret the C and B sands of the Bruce Embayment to be of Aalenian and Bajocian age, respectively. In this study, Early to Late Bathonian ages are considered more likely due to the presence of *D. willei* within the B and C sands, and the correlation of the C sands to the Early Bathonian flooding event as seen in wells in the Central Viking Graben.

Transgressive systems tract (Seq. 4). – The flooding event at 161 Ma brought more marine conditions to the South Viking Graben, with deposition of shoreface and foreshore sands (Hugin Fm.) on top of fluvio-deltaic deposits (Sleipner Fm.). The continuation of braided delta deposition (A sands) was limited to parts of the Bruce Embayment (Figs. 9, 16d). The flooding event caused an increase in the abundance of dinocysts, and the palynology changed from a *D. willei* dominance to an assemblage dominated by *C. perireticulata*, *K. gochti*, *E. evitti*, and others (Fig. 7). The palynological assemblage is interpreted to be of Late Bathonian age.

In the northern South Viking Graben a shaley layer appears within the shoreface interval, recorded as a peak on the gamma-ray log (e.g. well 24/6-1 on Fig. 9). The peak is also found within the A sands in the Bruce Embayment. It is correlated to a gamma-ray maximum near the base of a slightly prograding A sands interval in well 9/13-12 of the Beryl Embayment. In the Troll area the maximum flooding event at 160 Ma has been recognized within the silty marine Heather A sands. These observations have been taken as support for a maximum flooding surface within the A sands (MFS 160 Ma).

Highstand systems tract (Seq. 4). – The highstand systems tract is defined between the maximum flooding surface at 160 Ma at the base and a sequence boundary at 158.5 Ma at the top in the latest Bathonian.

There are only minor facies variations registered within the highstand systems tract of Sequence 4, which shows an aggradational rather than a progradational character. Shoreface deposition continued in the northern South Viking Graben, while the estuarine, lagoonal and delta plain environments that were displaced southwards during the maximum flooding event at 160 Ma remained more or less stationary in the South Viking Graben.

An alternative interpretation to the one proposed for Sequence 4 is that the A sands (proposed TST and HST) are retrograding in a similar manner as observed for Sequence 3 (Fig. 8). This would imply that the maximum flooding surface at 160 Ma was never reached and that a highstand systems tract did not develop before the onset of the sequence boundary above. The entire A sands interval would then belong to the transgressive systems tract of Sequence 4.

Termination of the Brent and Vestland deltas

The sequence boundary at 158.5 Ma. – In latest Bathonian times a major rifting phase occurred in the Northern North Sea. During this rifting phase the Brent deposits were eroded in crestal positions on tilted fault blocks and along the basin margins (SB 158.5 Ma) (Figs. 7–13). The rifting and the corresponding uplift of the basin margins caused deposition of the Upper sands in the Bruce Embayment. On the Horda Platform the Krossfjord, and later the Fensfjord and Sognefjord Formations (Vollset & Doré 1984), which constitute the reservoir sandstones of the Troll field, were sourced by erosion of the Norwegian mainland (Hellem et al. 1986; Steel 1993).

The dinoflagellate *S. grossii* is age diagnostic for deposits younger than SB 158.5 Ma in the latest Bathonian, and identification of the dinoflagellate *C. hyalina* suggests an age equal to (or younger than) the significant flooding MFS 156 Ma in the Early Callovian (Fig. 7). Both dinoflagellates are often identified, and mark the introduction of sediments younger than the Brent deltaic sequence.

The tectonic influence on Brent deposition

Tectonic movements had a significant effect on sediment distribution and stacking patterns during Brent deposition, during both prograding and retrograding stages (cf. Johannessen et al. 1995). The Brent sediment package thickens from less than 100 m on the Horda Platform and the western East Shetland Basin to more than 600 m in wells closest to the centre of the Viking Graben. However, relatively constant sediment thickness is observed within the major north–south trending fault terraces on both sides of the North Viking Graben (Fig. 2b). These observations suggest that synsedimentary faulting took place along the main bounding faults of the North Viking Graben during Brent deposition (e.g. Yielding et al. 1992).

During progradation of the delta, synsedimentary faulting was very subtle. A thickness increase is recorded for all depositional units (i.e. Broom, Rannoch, Etive and lower Ness Formations) across the main faults towards the basin centre, but abrupt facies changes, such as from delta plain to marine deposition, are not observed, only gradual transitions into more marine conditions (Figs. 11, 12). Hence the sediment supply was sufficient to adjust to the additional accommodation space created by the synsedimentary faulting. There are, however, indications of a pronounced tectonic influence on the flooding event at MFS 167 Ma by synsedimentary faulting along the structural outline of the Viking Graben: The characteristic prograding bay-fill sequence above MFS 167 Ma, as observed in the well 34/10-17, is only present close to the Viking Graben margin. Maximum thicknesses are developed closest to the graben axis with a pinch-out towards the Hutton terrace (Fig. 12).

In Late Bajocian/Early Bathonian times the Brent delta started to retreat (Fig. 7) (Graue et al. 1987; Helland-Hansen et al. 1992). An overall transgressive system tract formed by repeated flooding events, associated with deposition of deltaic aggradational parasequences that were backstepping through time (Graue et al. 1987). The depositional environments typically changed from fluvial-dominated delta plain during progradation to a predominance of lagoons and embayments during retrogradation (Fig. 9). The initial change is recorded in the Viking Graben and on the Tampen Spur, but is only occasionally observed on the Horda Platform and in the western East Shetland Basin (Fig. 11). This is probably related to exposure of the basin margins at the onset of the delta retreat, linked to a phase of synsedimentary down-faulting of the Viking Graben and its terraces. The basin margins may have acted as deltaic bypass areas, probably with periods of local erosion, while lagoonal and restricted marine sediments were deposited in axial positions on the Tampen Spur and in the Viking Graben. Through time, repeated flooding events caused by synsedimentary fault adjustments gave rise to increasingly marine conditions, with sediments deposited progressively onto the margins. Finally, the marine Tarbert sandstones completely covered both flanks of the Viking Graben (Mitchener et al. 1992).

The periods of local erosion on the basin margin fault terraces may have removed all or parts of the Late Bajocian sediments deposited shortly before the delta retreat (e.g. the Cormorant and Hutton terraces on Fig. 12). However, in axial parts of the basin a complete delta succession is preserved (e.g. Brent and Gullfaks terraces on Fig. 12). Hence, no sequence boundary is defined at the onset of the delta retreat in the Late Bajocian/Early Bathonian since the erosion is limited to the outer basin margins and does not affect the delta on a regional scale. An example is envisaged in the Oseberg area. Across the Oseberg fault block and onto the Horda Platform the lagoonal facies (uppermost Ness Fm.) of the retreating delta are limited to the western, down-faulted blocks. Only later the eastern margins were progressively flooded and covered by shallow marine sands and offshore shales (Tarbert/Heather Formations) (Fig. 13). However, a complicated relationship between synsedimentary faulting, margin emergence and erosion is observed. For instance, the marine flooding event at the onset of the retrogradation (base of Lower Tarbert Fm. in the Oseberg South wells on Fig. 13) is easily correlatable, but are the thickness differences of the overlying lagoonal and marine sands related to synsedimentary faulting or caused by later erosion of these sediments on the elevated blocks? At least on the westernmost fault panels synsedimentary faulting is likely to have occurred, since several events are recognized in wells on different fault blocks, but always being more condensed on the shallower panels (e.g. the two deepest wells in Fig. 13). On the easternmost elevated blocks the relationship between condensation and erosion is less obvious, but limited thickness variations of the delta plain deposits within each fault panel support sedimentary condensation or limited erosion rather than regional severe erosion (cf. Ryseth & Fjellbirkeland 1995). Admittedly, the sporadic, thick channels penetrated by some wells on the Oseberg fault terrace may have been caused by erosion and incision during base level falls. But they may also have been formed by episodes of local erosion during synsedimentary faulting on the delta plain, causing a slight disturbance of the fluvial profile.

Conglomeratic lags at the base of marine sandstones on the Oseberg fault block (e.g. the upper Tarbert Fm. in Fig. 13) may be interpreted as erosive unconformities, but bearing in mind the depositional model presented above, the lags are more likely to represent ravinement surfaces created during the transgressive flooding episodes that characterize the Brent retrogradation. Thus, the synsedimentary faulting with corresponding flooding and ravinement surfaces on the basin margins, combined with local erosion on the elevated fault blocks, seems to be a more likely depositional model for the Brent retrogradation in the Oseberg area than a scenario of elevation and severe erosion of the basin flanks at the onset of the delta retreat (cf. Helland-Hansen et al. 1992; Ryseth & Fjellbirkeland 1995).

Increasing synsedimentary fault activity during the delta retreat caused a thickening of the marine sandstones of the Tarbert Formation on the hanging wall side of the basin margin bounding faults (Cannon et al. 1992; Yielding et al. 1992). This is seen in well 211/28-5 on the Brent terrace (Fig. 12). Owing to inadequate biostratigraphical resolution, deposition of the Tarbert sandstones may have been either contemporaneous with or subsequent to Ness deposition. The presence of retrograding Ness facies below the Tarbert sandstones in well 211/28-5 indicates that these coarse-grained sandstones are probably related to deposition during the gradual backstepping of the delta plain. The coarse-grained character was more pronounced close to the major bounding fault due to synsedimentary faulting. Sediments were probably provided by local erosion on the Hutton terrace, as exemplified by possible erosion of the uppermost Brent succession in well 211/28-1 (Fig. 12). The Brent thickness in this well is, however, comparable to other wells on the Hutton terrace, indicating that only limited erosion occurred on the crest of the terrace.

In the Dunbar field (Fig. 4) a similar development is seen. The field is situated across the main fault of the Hutton terrace (Fig. 2a). Also here, thick, coarse-grained, conglomeratic sandstones are recorded on the down-faulted side of the Hutton terrace, but they rest on a Tarbert barrier sandstone and a thin marine shale interval. Delta plain deposits are overlain by marine shales on the foot-wall side of the Hutton terrace. The thick, down-faulted sandstones may have been deposited as a second Tarbert interval during synsedimentary faulting and retreat of the delta, or during a period of erosion after the drowning of the Brent delta. The sequence boundaries at 161.5 Ma and 158.5 Ma are good candidates. These two events are related to precursor stages to the Late Jurassic rifting, and were associated with rotation and erosion of tilted fault blocks (Fig. 16c).

In summary, the Brent depositional thickness varies from 100 m along the margins to more than 600 m in the axial parts of the Viking Graben. Substantial depositional thickness variations are seen across the main north–south trending graben faults. This is taken as evidence for synsedimentary faulting during Brent deposition. Only subtle synsedimentary fault activity occurred during the delta progradation. In contrast, the retreat of the Brent delta was probably enhanced by synsedimentary faulting which caused successive flooding events to cover the previous delta plain areas in the Viking Graben. At the same time, emergence and possible erosion of the delta took place along the basin margins. Severe crestal erosion of tilted fault blocks is not evident during the Early Bathonian retreat, but wedge-shaped retrograding sediment packages on some fault panels indicate an initiation of rotational block-faulting at this time. A more advanced stage of rifting was, however, reached in the Middle to Late Bathonian, possibly as early as at SB 161.5 Ma and certainly at SB 158.5 Ma (Mitchener et al. 1992).

Conclusions

Four depositional sequences have been recognized within the Middle Jurassic Brent and Vestland deltaic systems within the studied area. The depositional sequences are defined between sequence boundaries according to Exxon's model. The depositional history of the Brent delta system can be described by phases of lowstand, progradation, aggradation, retrogradation and drowning, and, finally, development of a new delta (the 'Vestland deltaic system') from the south into the Central Viking Graben.

The Brent lowstand was deposited during the Aalenian as fan lobes shed off the basin margins into the shallow sea in the North Viking Graben (Fig. 14a, b). During Early Bajocian times the Brent delta prograded rapidly from south to north, filling the North Viking Graben sea with delta plain sediments (Fig. 14c, d). In the Late Bajocian, the delta aggraded near its maximum extension (approximately 61°30'N), only disturbed by a tectonically influenced flooding event (Figs. 14d, 15a, b).

In Early Bathonian times pre-rift fault activity increased the accommodation rate, forcing the Brent delta to retreat. The delta retreat developed in retrogressive pulses as tectonically induced flooding events followed by the establishment of more stable lagoonal and delta plain conditions behind tidal and delta front barriers. The rifting caused the basin flanks to be emergent relative to the basin and thus very limited amounts of sediments, if any, were deposited on the basin margins. The Brent delta was finally drowned by the Early Bathonian maximum flooding event at 163.5 Ma (Figs. 15c, d, 16a).

Towards the end of the Early Bathonian a new delta progradation, referred to as the Vestland delta, occurred in the Central Viking Graben, reaching a latitude close to 60°30'N (Fig. 16b). At or near its maximum extension, the Vestland delta culminated in a calm period with peat deposition, preserved as a correlatable coal doublet.

A more tectonically active period followed, with fault block rotation and erosion in the North Viking Graben, tidal estuarine deposits in the South Viking Graben and braided delta deposition in the Bruce Embayment (Fig. 16c). The deposits are of Middle (or Early) Bathonian age, deposited on top of the tectonically influenced sequence boundary at 161.5 Ma (or older). A major flooding event in the Late Bathonian drowned the basin margins in the north and the Vestland delta in the south, bringing marine and tidal conditions into the South Viking Graben (Fig. 16d).

In Latest Bathonian times a significant rift episode caused the development of a sequence boundary (SB 158.5 Ma) and terminated the Middle Jurassic delta deposition in the Viking Graben. The rifting event caused severe erosion of the Brent and Vestland deltaic systems, especially on the crests of rotated fault blocks, and resulted in the deposition of the Callovian–Oxfordian reservoir rocks of the Troll field and the Upper sands in the Bruce Embayment.

The Brent and Vestland deltaic systems were deposited in a setting where the relative sea level was generally rising, punctuated by periods of stillstand or very slow rise, causing sediment by-pass and rapid delta progradation. Synsedimentary faulting caused a thickening of the delta package from the flanks of the basin into the Viking Graben. During delta progradation the synsedimentary faulting was very subtle, as indicated by only subtle facies variations across the major basin faults. During the delta retreat, however, the fault activity increased, with a resultant uplift of the basin flanks relative to the axial parts of the basin. This caused reduced sediment thickness on the distal margins but thick sedimentary packages to be deposited in the axial parts of the deltaic system.

The stacking pattern of the Brent deltaic system shows continuous prograding or aggrading clinoforms during the delta advance. No disconnected major lowstand prograding wedge in front of the delta is envisaged. During

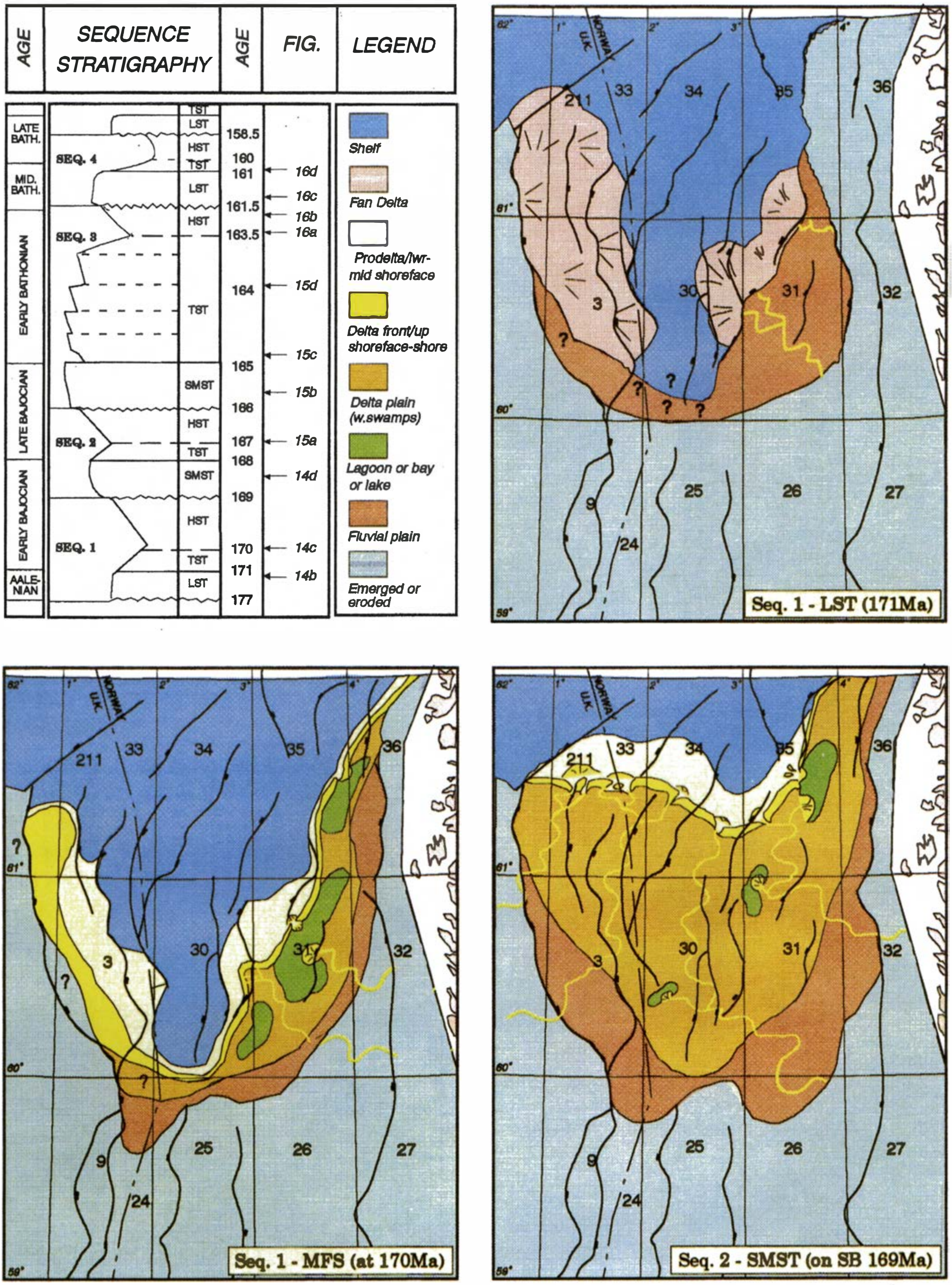

Fig. 14. Palaeogeography of the Brent lowstand and progradation. (a) Legend and stratigraphical position for Figs. 14b–16d. (b) The Brent lowstand (Broom and Oseberg Fms.). (c) The flooding of the lowstand (MFS 170 Ma). (d) Delta position after the main progradation (on SB 169 Ma).

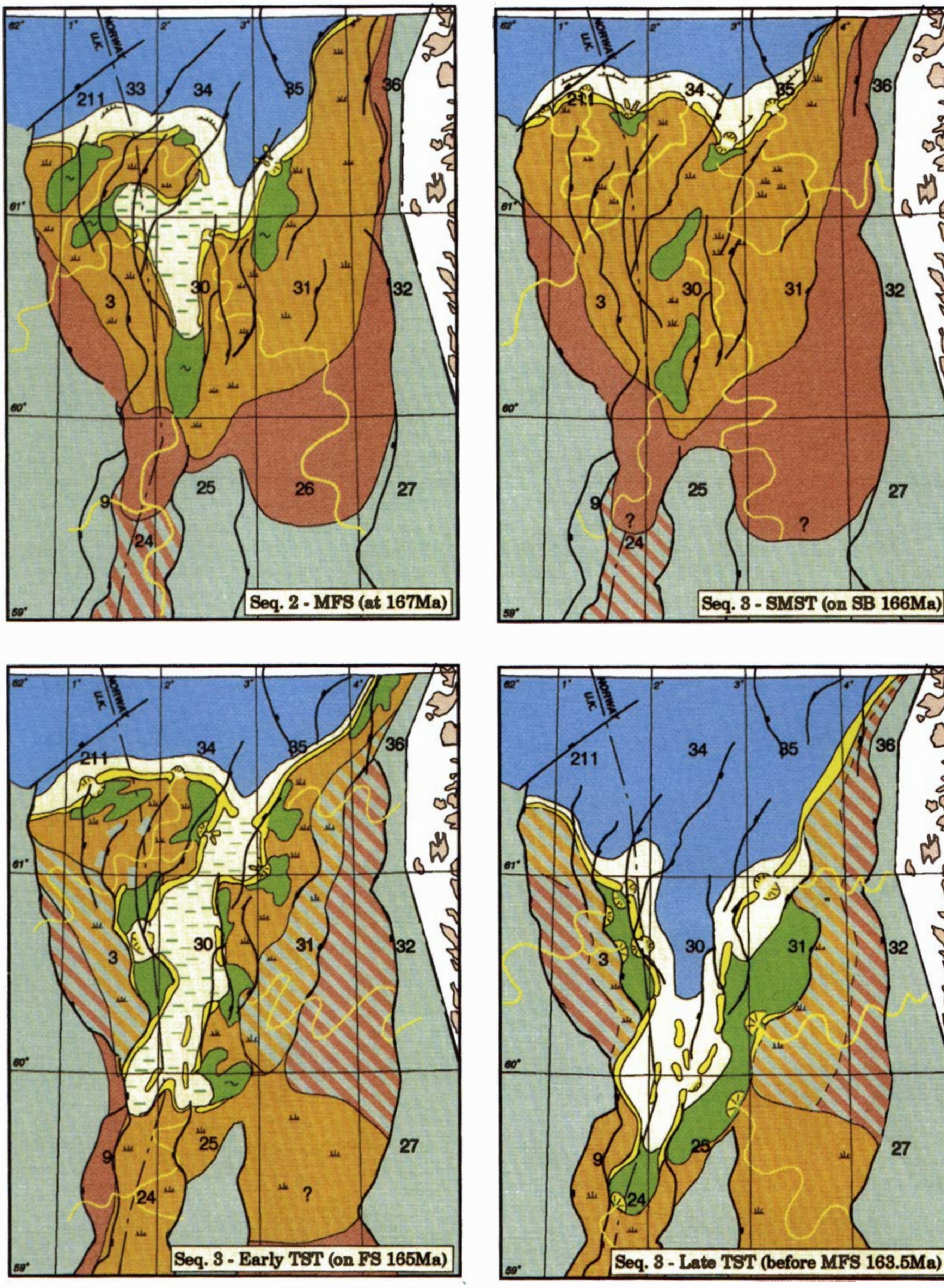

Fig. 15. Palaeogeography of the Brent delta aggradation and retreat. (a) The flooding during Brent aggradation (MFS 167 Ma). (b) The maximum delta extension (on SB 166 Ma). (c) The early Brent retrogradation (on FS 165 Ma.) (d) The late Brent retrogradation (before MFS 163.5 Ma). Legend and stratigraphical positions are shown in Fig. 14a.

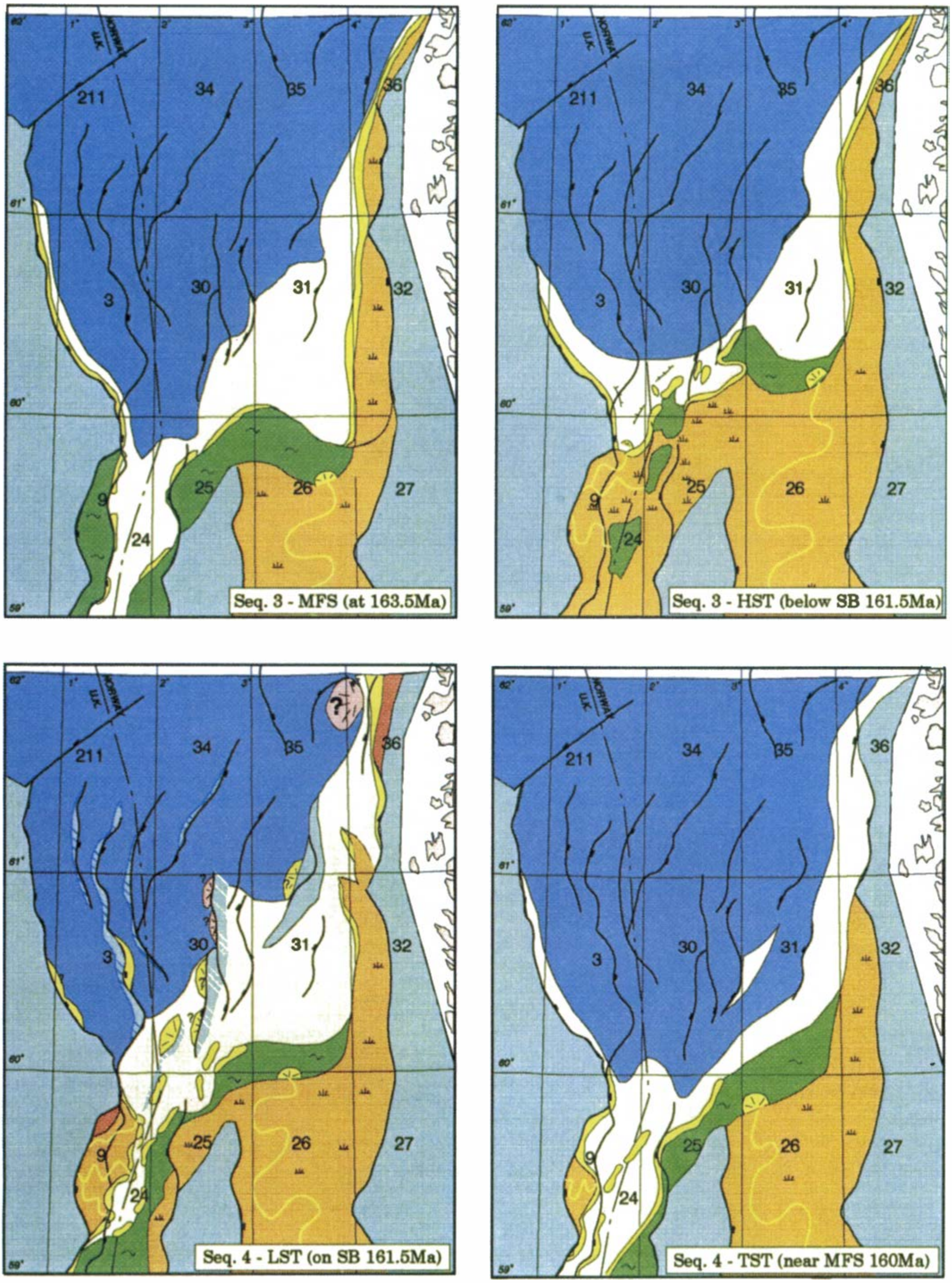

Fig. 16. Palaeogeography of the 'classical' Brent drowning and the Vestland deltaic development. (a) The Brent drowning (MFS 163.5 Ma). (b) The maximum Vestland delta progradation (below SB 161.5 Ma). (c) The early Vestland delta retreat (on SB 161.5 Ma). (d) The late Vestland delta retreat (MFS 160 Ma). Legend and stratigraphical positions are shown in Fig. 14a.

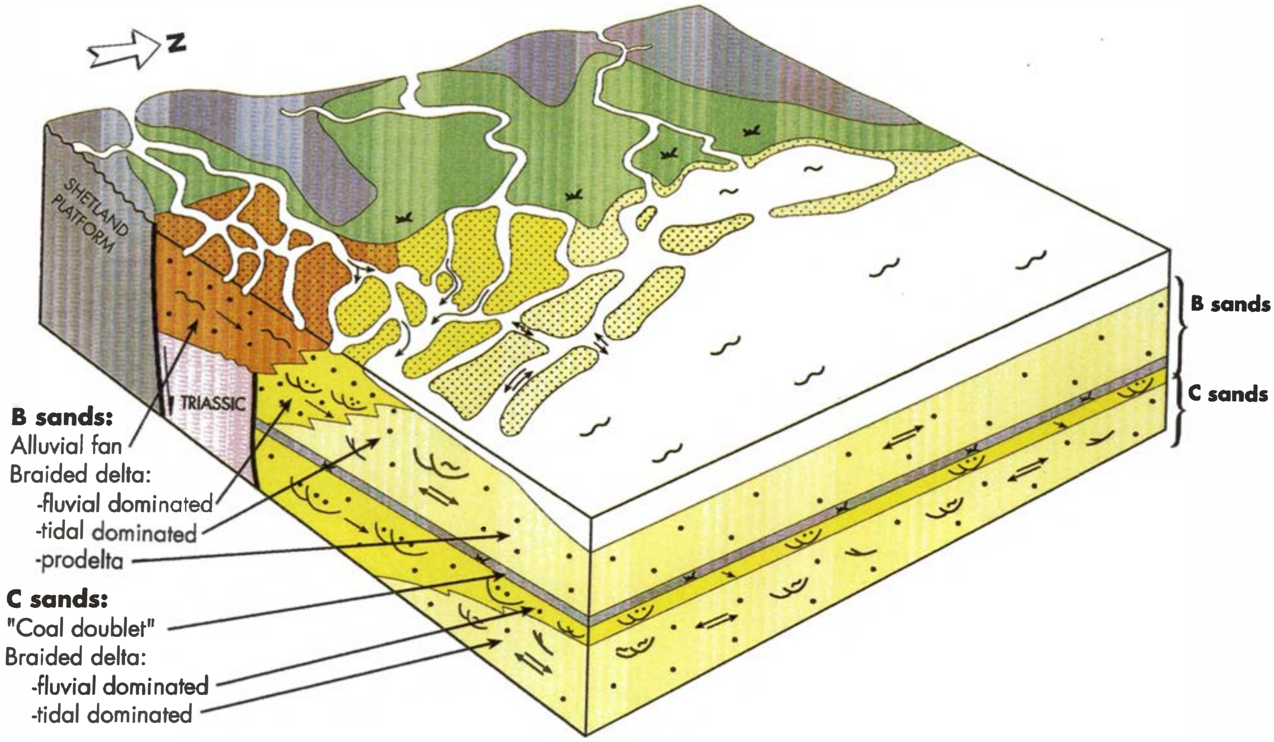

Fig. 17. Schematic palaeogeography of the B and C sands derived from core studies of wells in the Bruce Embayment and proximal areas. Location of illustration and wells shown in Fig. 4.

delta retreat, the successive flooding events caused a less continuous stacking of the clinoforms. However, the marine barrier sandstones (Tarbert Formation) deposited during the retrogradation are regionally present across the whole delta, unless eroded after deposition. Locally, synsedimentary faulting caused these sandstones to be thickly developed on the hanging wall side of the major basin bounding faults.

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References

Badley, M. E., Egeberg, T. & Nipen, O. 1984: Development of rift basins illustrated by the structural evolution of the Oseberg feature, block 30/6, offshore Norway. *Journal of Geological Society, London 145*, 455–472.

Bowen, J. M. 1975: The Brent oil field. *In* Woodland, A. W. (ed.): *Petroleum and the Continental Shelf of Northwest Europe*, 353–360. Applied Science Publishers, London

Brown, S. & Richards, P. C. 1989: Facies and development of the Middle Jurassic Brent delta near the northern limit of its progradation, UK North Sea. *In* Whateley, M. K. G. & Pickering, K. T. (eds.): *Deltas, Sites and Traps for Fossil Fuels*, 253–267. *Geological Society Special Publication No. 41.*

Brown, S., Richards, P. C. & Thompson, A. R. 1987: Patterns in the deposition of the Brent Group (Middle Jurassic) UK North Sea. *In* Brooks, J. & Glennie, K. W. (eds.): *Petroleum Geology of North West Europe*, 890–913. Graham and Trotman, London.

Cannon, S. J. C., Giles, M. R., Whitaker, M. F., Please, P. M. & Martin, S. V. 1992: A regional reassessment of the Brent Group, UK sector, North Sea. *In* Morton, A. C., Haszeldine, R. S., Giles, M. R. & Brown, S. (eds.): *Geology of the Brent Group*, 81–107. *Geological Society Special Publication No. 61.*

Davidson-Arnott, R. G. D. & Greenwood, B. 1976: Facies relationships on a barred coast, Kouchibouguac Bay, New Brunswick, Canada. *In* Davis, R. A. & Ethington, R. L. (eds.): *Beach and Nearshore Sedimentation*, 149–168. *Society of Economic Paleontologists and Mineralogists Special Publication No. 24.*

Daws, J. A. & Prosser, D. J. 1992: Scales of permeability heterogeneity within the Brent Group. *Journal of Petroleum Geology 15*, 397–418.

DeCelles, P. G. & Cavazza, W. 1992: Constraints on the formation of Pliocene hummocky cross-stratification in Calabria (southern Italy) from consideration of hydraulic and dispersive equivalence, grain-flow theory, and suspended-load fallout rate. *Journal Sedimentary Petrology 62*, 555–568.

Deegan, C. E. & Scull, B. J. 1977: A proposed standard lithostratigraphic nomenclature for the Central and Northern North Sea. *Institute of Geological Sciences, No. 77/25, Norwegian Petroleum Directorate Bull. No. 1.*

Eschard, R., Tveiten, B., Desabliaux, G., Lecomte, J. C. & Van Buchem, F. S. P. 1993: High resolution sequence stratigraphy and reservoir prediction of the Brent Group (Tampen Spur area) using an outcrop analogue (Mesa Verde Group, Colorado). *In* Eschard, R. & Doligez, B. (eds.): *Subsurface Reservoir Characterisation from Outcrop Observations*, 35–52. Éditions Technip, 27 rue Ginoux, 75015 Paris.

Eynon, G. 1981. Basin development and sedimentation in the Middle Jurassic of the Northern North Sea. *In* Illing, L. V. & Hobson, G. D. (eds.): *Petroleum Geology of the Continental Shelf of North-West Europe*, 196–204. Heyden, London.

Fjæran, T. & Spencer, A. M. 1991: Proven hydrocarbon plays, offshore Norway. *In* Spencer, A. M. (ed.): *Generation, Accumulation, and Production of Europe's Hydrocarbons*, 25–48. *Special Publication of the European Association of Petroleum Geoscientists No. 1*, Oxford University Press, Oxford.

Fält, L. M., Helland, R., Wiik Jacobsen, V. & Renshaw, D. 1989: Correlation of transgressive–regressive depositional sequences in the Middle Jurassic Brent Group megacycle, Viking Graben, Norwegian North Sea. *In* Collinson, J. D. (ed.): *Correlation in Hydrocarbon Exploration*, 191–200. Norwegian Petroleum Society. Graham and Trotman.

Gabrielsen, R. H., Færseth, R. B., Steel R. J. & Kløvjan, O. S. 1990: Architectural styles of basin fill in the northern Viking Graben. *In* Blundell, D. J. & Gibbs, A. D. (eds.): *Tectonic Evolution of the North Sea Rifts*, 158–179. Clarendon Press, Oxford.

Graue, E., Helland-Hansen, W., Johnsen, J., Lømo, L., Nøttvedt, A., Rønning, K., Ryseth, A. & Steel, R. 1987: Advance and retreat of the Brent delta system, Norwegian North Sea. *In* Brooks, J. & Glennie, K. (eds.): *Petroleum Geology of North West Europe*, 915–937. Graham and Trotman, London.

Haq, B., Hardenbol, J. & Vail, P. R. 1987: Chronology of fluctuating sea level since the Triassic (250 Ma to present). *Science 25*, 1156–1167.

Helland-Hansen, W., Steel, R., Nakayama, K. & Kendall, C. G. St. C. 1989: Review and computer modelling of the Brent Group stratigraphy. *In* Whateley, M. K. G. & Pickering, K. T. (eds.): *Deltas, Sites and Traps for Fossil Fuels*, 237–252. *Geological Society Special Publication No. 41.*

Helland-Hansen, W., Ashton, M., Lømo, L. & Steel, R 1992: Advance and retreat of the Brent Delta: recent contributions to the depositional model. *In* Morton, A. C., Haszeldine, R. S., Giles, M. R. & Brown, S. (eds.): *Geology of the Brent Group*, 109–127. *Geological Society Special Publication No. 61.*

Helland-Hansen, W. 1995: Sequence stratigraphy theory: remarks and recommendations. *In* Steel, R. J., Felt, V., Johannessen, E. P. & Mathieu, C. (eds.): *Sequence Stratigraphy on the Northwest European Margin*, 13–21. *Norwegian Petroleum Society Special Publication No. 5.*

Hellem, T., Kjemperud, A. & Øvrebø, O. K. 1986: The Troll Field: a geological/geophysical model established by the PL085 Group. *In* Graham & Trotman (eds.): *Habitat of Hydrocarbons on the Norwegian Shelf*, 217–238. Norwegian Petroleum Society.

Jennette, D. C. & Riley, C. O., in press: Influence of relative sea level on facies and reservoir geometry of the Middle Jurassic lower Brent Group, UK North Viking Graben. Submitted to *High Resolution Sequence Stratigraphy: Innovations and Applications*. Geological Society, London, Special Publication.

Hunter, R. E., Clifton, H. E. & Lawrence Phillips, R. 1979: Depositional processes, sedimentary structures, and predicted vertical sequences in barred nearshore systems, southern Oregon coast. *Journal Sedimentary Petrology 49*, 0711–0726.

Johannessen, E. P., Mjøs, R., Renshaw, D., Dalland, A. & Jacobsen, T. 1995: Northern limit of the 'Brent delta' at the Tampen Spur – a sequence stratigraphic approach for sandstone prediction. *In* Steel, R. J., Felt, V., Johannessen, E. P. & Mathieu, C. (eds.): *Sequence Stratigraphy on the Northwest European Margin*, 213–256. *Norwegian Petroleum Society Special Publication No. 5.*

Johns, C. R. & Andrews, I. J. 1985: The petroleum geology of the Unst basin, North Sea. *Marine and Petroleum Geology 2*, 361–572.

Johnson, H. D. & Stewart, D. J. 1985: Role of clastic sedimentology in the exploration and production of oil and gas in the North Sea. *In* Brenchley, P. J. & Williams, B. P. J. (eds.): *Sedimentology: Recent Developments and Applied Aspects*, 249–310. *Geological Society, London, Special Publication No. 18.*

Leckie, D. A. & Walker, R. G. 1982: Storm and tide-dominated shorelines in Cretaceous Moosebar-Lower Gates interval – outcrop equivalents of deep basin gas traps in Western Canada. *Am. Assoc. of Petroleum Geologists Bulletin. No. 18*, 138–157.

Livera, S. E. 1989: Facies associations and sand-body geometries in the Ness Formation of the Brent Group, Brent Field. *In* Whateley, M. K. G. & Pickering, K. T. (eds.): *Deltas: Sites and Traps for Fossil Fuels*, 269–286. *Geological Society Special Publication No. 41.*

Livera, S. E. & Caline, B. 1990: The sedimentology of the Brent Group in the Cormorant block IV oil field. *Journal of Petroleum Geology 13*, 367–396.

McCubbin, D. G. 1982: Barrier Island and Strand-Plain Facies. *In* Scholle, P. A. & Spearing, D. (eds.): *Sandstone Depositional Environments. Am. Assoc. of Petroleum Geologists, Memoir 31*, 247–279.

Mitchener, B. C., Lawrence, D. A., Partington, M. A., Bowman, M. B. J. & Gluyas, J. 1992: Brent Group. Sequence stratigraphy and regional implications. *In* Morton, A. C., Haszeldine, R. S., Giles, M. R. & Brown, S. (eds.): *Geology of the Brent Group*, 45–80. *Geological Society Special Publication No. 61.*

Olaussen, S., Beck, L., Fält, L.-M., Graue, E., Jacobsen, K. G., Malm, O. A. & South, D. 1992: Gullfaks Field-Norway. East Shetland Basin, Northern North Sea. *In* Foster, N. H. & Beaumont, E. A. (eds.): 55–83. *AAPG Treatise of Petroleum Geology, Atlas of Oil and Gas Fields Vol. A-24 Structural Traps VI.*

Olsen, T. 1993: Stacking patterns and architecture of fluvial deposits in a reservoir analogue perspective: examples, concepts and methodology. Dr. scient. thesis. University of Bergen.

Olsen, T. R. & Steel, R. 1995: Shoreface pinch-out style on the front of the Brent delta – a preliminary model. *In* Steel, R. J., Felt, V., Johannessen, E. P. & Mathieu, C. (eds.): *Sequence Stratigraphy on the Northwest European Margin*, 273–289. *Norwegian Petroleum Society Special Publication No. 5.*

Olsen, T. R. & Steel, R. J., in press: The significance of the Etive Formation in the development of the Brent Delta: a review of the likelihood of relative sea level falls during deltaic progradation. *In* Hunt, D. & Gawthorpe, R. (eds.): *Sedimentary Responses to Forced Regression*. Geological Society of London, Special Publication.

Parry, C. C., Whitley, P. K. J. & Simpson, R. D. H. 1981: Integration of palynological and sedimentological methods in facies analysis of the Brent Formation. *In* Illing, L. V. & Hobson, G. D. (eds.): *Petroleum Geology of the Continental Shelf of North–West Europe*, 205–215. Heyden, London.

Partington, M. A., Mitchener, B. C., Milton, N. J. & Fraser, A. J. 1993: Genetic sequence stratigraphy for the North Sea Late Jurassic and Early Cretaceous: Distribution and prediction of Kimmeridgian – Late Ryazanian reservoirs in the North Sea and adjacent areas. *In* Parker, J. R. (ed.): *Petroleum Geology of Northwest Europe, Proceedings of the 4th Conference*, 347–370. Geological Society of London, vol. I.

Pemberton, S. G. & Wightman, D. M. 1992: Ichnological characteristics of brackish water deposits. *In* Pemberton, S. G. (ed.): *Applications of Ichnology to Petroleum Exploration*, 141–167. SEPM Core Workshop No. 17, June 1992.

Posamentier, H. W. & Allen, G. P. 1993: Variability of the sequence stratigraphic model: effects of local basin factors. *Sedimentary Geology 86*, 91–109.

Posamentier, H. W., Allen, G. P., James, D. P. & Tesson, M. 1992: Forced regressions in a sequence stratigraphic framework: Concepts, examples and exploration significance. *Am. Assoc. of Petroleum Geologists Bulletin Vol. 76*, No. 11, 1687–1709.

Posamentier, H. W., Jervey, M. T. & Vail, P. R. 1988: Eustatic controls on clastic deposition I – conceptual framework. *In* Wilgus, C. K., Hastings, B. S., Kendall, C. G. St. C., Posamentier, H. W., Ross, C. A. & Van Wagoner, J. C. (eds.): *Sea Level Changes: An Integrated Approach*, 109–124. *Society of Economic Paleontologists and Mineralogists Special Publication No. 42.*

Posamentier, H. W. & Vail, P. R. 1988: Eustatic controls on clastic deposition II – sequence and systems tract models. *In* Wilgus, C. K., Hastings, B. S., Kendall, C. G. St. C., Posamentier, H. W., Ross, C. A. & Van Wagoner, J. C. (eds.): *Sea Level Changes: An Integrated Approach*, 125–154. *Society of Economic Paleontologists and Mineralogists Special Publication No. 42.*

Rattey, R. P. & Hayward, A. B. 1993: Sequence stratigraphy of a failed rift system: the Middle Jurassic to Early Cretaceous basin evolution of the Central and Northern North Sea. *In* Parker, J. R. (ed.): *Petroleum Geology of Northwest Europe: Proceedings from the 4th Conference*, 215–249. The Geological Society, London.

Reynolds, A. D. 1995: Sedimentology and sequence stratigraphy of the Thistle Field, northern North Sea. *In* Steel, R. J., Felt, V., Johannessen, E. P. & Mathieu, C. (eds.): *Sequence Stratigraphy on the Northwest European Margin*, 257–271. *Norwegian Petroleum Society Special Publication No. 5.*

Richards, P. C. 1991: An eustarine facies model for the Middle Jurassic Sleipner Formation: Beryl Embayment, North Sea. *Journal of the Geological Society, London 148*, 459–471.

Richards, P. C. 1992: An introduction to the Brent Group: A literature review. *In* Morton, A. C., Haszeldine, R. S., Giles, M. R. & Brown, S. (eds.): *Geology of the Brent Group*, 15–26. *Geological Society Special Publication No. 61.*

Roberts, A. M., Yielding, G., Kusznir, N. J., Walker, I. & Dorn-Lopez, D. 1993: Mesozoic extension in the North Sea: constraints from flexural backstripping, forward modelling and fault populations. *In* Parker, J. R. (ed.): *Petroleum Geology of Northwest Europe. Proceedings of the 4th Conference*, 1123–1136. Geological Society, London.

Ryseth, A. 1989: Correlation of depositional patterns in the Ness Formation, Oseberg area. *In* Collinson, J. D. (ed.): *Correlation in Hydrocarbon Exploration*, 313–326. Norwegian Petroleum Society, Graham and Trotman.

Ryseth, A. & Fjellbirkeland, H. 1995: Differentiation of incised valley systems from mobile streams: some examples from the Oseberg Field, Norwegian North Sea. *In* Steel, R. J., Felt, V., Johannessen, E. P. & Mathieu, C. (eds.): *Sequence Stratigraphy on the Northwest European Margin*, 51–73. *Norwegian Petroleum Society Special Publication No. 5.*

Rønning, K. & Steel, R. J. 1987: Depositional sequences within a 'transgressive' reservoir sandstone unit: the Middle Jurassic Tarbert Formation, Hild area, northern North Sea. *In* Kleppe, J., Berg, E. W., Buller, A. T., Hjelmeland, O. & Torsæter, O. (eds.): *North Sea Oil and Gas Reservoirs*, 169–176. Graham & Trotman, London.

Scott, E. S. 1992: The palaeoenvironments and dynamics of the Rannoch-Etive nearshore and coastal successions, Brent Group, northern North Sea. *In* Morton, A. C., Haszeldine, R. S., Giles, M. R. & Brown, S. (eds.): *Geology of the Brent Group*, 129–148. *Geological Society Special Publication No. 61.*

Simpson, R. D. H. & Whitley, P. K. J. 1981: Geological input to reservoir simulation of the Brent Formation. *In* Illing, L. V. & Hobson, G. D. (eds.): *Petroleum Geology of the Continental Shelf of North-West Europe*, 310–314. Heyden, London.

Steel, R. J. 1993: Triassic-Jurassic megasequence stratigraphy in the Northern North Sea: rift to post-rift evolution. *In* Parker, J. R. (ed.): *Petroleum Geology of Northwest Europe: Proceedings from the 4th Conference*, 299–315. Geological Society, London.

Steel, R. J. & Ryseth, A. 1990: The Triassic–Early Jurassic succession in the northern North Sea: megasequence stratigraphy and intra-Triassic tectonics. *In*

Hardman, R. F. P. & Brooks, J. (eds.): *Tectonic Events Responsible for Britain's Oil and Gas Reserves*, 139–168. *Geological Society, London, Special Publication No. 55.*

Threlfall, W. F. 1981: Structural framework for the central and northern North Sea. *In* Illing, L. V. & Hobson, G. D. (eds.): *Petroleum Geology of the Continental Shelf of North-West Europe*, 98–103. Heyden, London.

Underhill, J. R. & Partington, M. A. 1993: Jurassic thermal doming and deflation in the North Sea: implications of the sequence stratigraphic evidence. *In* Parker, J. R. (ed.): *Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference*, 337–345. The Geological Society, London.

Vail, P. R., Mitchum, R. M. Jr. & Thompson, S. 1977: Seismic stratigraphy and global changes of sea level, part 4: global cycles of relative changes of sea level. *In* Payton, C. E. (ed.): *Seismic Stratigraphy – Applications to Hydrocarbon Exploration*, 83–97. Mem. Am. Assoc. Petrol. Geol. 26.

Van Wagoner, J. C., Posamentier, H. W., Mitchum, R. M., Vail, P. R., Sarg, J. F., Loutit, T. S. & Hardenbol, J. 1988: An overview of sequence stratigraphy and key definitions. *In* Wilgus, C. K., Hastings, B. S., Kendall, C. G. St. C., Posamentier, H. W., Ross, C. A. & Van Wagoner, J. C. (eds.): *Sea Level Changes: An Integrated Approach*, 39–45. *Society of Economic Paleontologists and Mineralogists Special Publication 42.*

Van Wagoner, J. C., Mitchum, R. M., Campion, K. M. & Rahmanian, V. D. 1990: Siliclastic sequence stratigraphy in well logs, cores and outcrops: Concepts of high-resolution correlation of time and facies. *Am. Assoc. of Petroleum Geologists Methods in Exploration Series No. 7, 55.*

Van Wagoner, J. C., Jennette, D. C., Tsang, P., Hamar, G. P. & Kaas, I. 1993: Applications of high resolution sequence stratigraphy and facies architecture in mapping potential additional hydrocarbon reserves of the Brent Group, Statfjord Field. Abstract, Norwegian Petroleum Society.

Vollset, J. & Doré, A. G. (eds.) 1984: A revised Triassic and Jurassic lithostratigraphic nomenclature for the Norwegian North Sea. *Norwegian Petroleum Directorate Bulletin No. 3.*

Walker, R. G. & Plint, A. G. 1992: Wave- and storm dominated shallow marine systems. *In* Walker, R. G. & James, N. P. (eds.): *Facies Models. Response to Sea Level Change*, 219–238. Geological Association of Canada.

Whitaker, M. F., Giles, M. R. & Cannon, S. J. C. 1992: Palynological review of the Brent Group, UK Sector, North Sea. *In* Morton, A. C., Haszeldine, R. S., Giles, M. R. & Brown, S. (eds.): *Geology of the Brent Group*, 169–202. *Geological Society Special Publication No. 61.*

Yielding, G., Badley, M. E. & Roberts, A. M. 1992: The structural evolution of the Brent Province. *In* Morton, A. C., Haszeldine, R. S., Giles, M. R. & Brown, S. (eds.): *Geology of the Brent Group*, 27–44. *Geological Society Special Publication No. 61.*

Ziegler, P. A. 1982: *Geological Atlas of Western and Central Europe*. Elsevier Sci. Publ. Co., 130 pp.