Role of forced regression in controlling Brent Group reservoir architecture and prospectivity in the northern North Sea

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ABSTRACT: The Middle Jurassic Brent Group of the northern North Sea presents a mature and highly productive reservoir play fairway where a combination of effective facies analysis and depositional sequence stratigraphy offers real potential to optimize exploitation. The north of the Brent province differs from classically studied southern areas in being dominated by marginal-marine delta-front facies. A core- and log-based study of 37 wells around the Don fields was performed to establish a sequence stratigraphic framework, map facies and thereby describe facies architecture. The results demonstrate that reservoir quality and productivity are regionally and locally controlled by facies. Of particular interest are intervals of fluvio-estuarine channel to sharp-based shoreface sandstone that formed during sea-level lowstands, since it is these packages that boost well productivity but, conversely, also increase the risk of early water breakthrough on production. Analogy with the Saloum Delta of Senegal highlights the importance of rapid and continuous barrier migration and destruction in controlling the deflection and switching of fluvio-estuarine channels, explaining also the preferential preservation of channel-floor deposits over continuously eroded barrier and delta-top facies. Interpretations suggest that deposition in the study area was dominated by punctuated progradation of the Brent Delta, as periods of delta plain incision alternated with episodes of base-level rise and delta aggradation/progradation. A model of regression for the Brent Delta is presented, where the Rannoch, Etive and Ness formations are an amalgam of highstand, falling stage and lowstand systems tract deposits, and the Tarbert Formation is a transgressive systems tract deposit, with the delta responding to regional relative sea-level changes driven by uplift and deflation of the mid North Sea dome. The prograding Brent Delta is characterized as a succession of attached shorefaces formed by alternating periods of normal and forced regression. Significantly, this explains the long distance (>200 km) build out of the Brent Delta and the continued presence of coarse-sandstone packages, as well as the potential for high-quality reservoirs even in the distal reaches of the system. It also suggests that there is limited potential for lowstand fan plays beyond the northernmost tip of the delta.

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INTRODUCTION

The Middle Jurassic Brent Group of the northern North Sea offers one of the most established and productive petroleum plays on the UK Continental Shelf (UKCS) (Lee & Hwang 1993; Husmo et al. 2003). Much data have been collected and analysed from the Brent province during a period of over 40 years (e.g. Deegan & Scull 1977; Budding & Inglis 1981; Brown et al. 1987; Graue et al. 1987; Helland-Hansen et al. 1992; Mitchener et al. 1992; Hampson et al. 2004), and, despite the maturity of the province, the area still provides opportunities for hydrocarbon exploration today.

Despite its long production history, the Brent continues to present economic opportunities, especially at the field development scale, and our understanding of its deposition has continued to improve. Historically, basic facies and lithostratigraphic study proved adequate for subdividing the basin fill at a gross level (Deegan & Scull 1977), and much detailed work has been published illustrating the reservoir geology of individual fields (e.g. Budding & Inglis 1981; Livera 1989; Livera & Caline 1990). More recently, biostratigraphic schemes have been developed that allow for basin-wide chronostatigraphic correlation at second- and third-order sequence scale (e.g. Helland-Hansen et al. 1992; Partington et al. 1993; Johannesson et al. 1995).
These biostratigraphic schemes have been used in conjunction with sedimentological analyses to propose a high-frequency sequence stratigraphic framework that describes the evolution and permits a better understanding of the Brent Delta (e.g. Mjos et al. 1998; Hampson et al. 2004). To test these schemes, detailed semi-regional evaluations that bridge the gap between field-scale descriptions and basin-scale evaluations are required (Olsen & Steel 2000).

The purpose of this paper is to determine the detailed facies architecture of the Brent Group in the Don fields area of the East Shetland Basin at the northernmost part of the Brent province. The study allows a new model to be built that accurately reflects the stratigraphic evolution of the delta at this time, the impact of facies and stratigraphy on reservoir quality distribution, and, hence, the implications for prospectivity and field development. Whilst the results challenge existing sequence stratigraphic models, they provide a new basis for evaluating reservoir play fairways, as well as exploration and field development opportunities.

LOCATION AND GEOLOGICAL SETTING
The Brent province extends from approximately 60.5ºN (Dunbar) to 61.6ºN (Magnus) in the UK northern North Sea and adjoining areas of the Norwegian Continental Shelf. The Brent Group is divided into five regionally correlatable formations. The lowermost Broom Formation is a marine sandstone, thought to have been supplied laterally from the flanks of the basin (Helland-Hansen et al. 1992). The succeeding Rannoch, Etive and Ness formations are typically regarded as linked delta-front and delta-top depositional systems.

These four units are generally considered as pre-rift deposits, representing components of a northwards building delta that formed during transient doming of the North Sea (Underhill & Partington 1993, 1994). The overlying Tarbert Formation forms the uppermost part of the Brent Group, and comprises a marine sandstone that records the onset of synrift deposition (Davies et al. 2000, Davies et al. 2001), and was deposited during the transgression and drowning of the delta. The Tarbert is in turn overlain by the Heather and Kimmeridge Clay formations, which are developed as synrift, deep-water mudstones.

The study area is located in the East Shetland Basin in the northernmost part of the UK sector of the northern North Sea and, whilst focused on the Dons cluster that comprises the West Don, Don South West and North East Don fields (Fig. 1), the study also extends towards the Thistle and Murchison fields in the south, and the East Penguin Field in the north. This part of the Brent province is notable for the absence of the thick delta plain deposits that characterize the Ness Formation in the classically described areas of the Brent province lying further to the south. The present study focuses sedimentological investigation on the marginal-marine part of the delta front, with the aim of understanding the stratigraphic development of the Brent sequence towards its northerly seawards limit.

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Figure 1 provides a summary of the regional setting for the study area, including the timing of Brent Group deposition relative to periods of rifting and doming. The present-day structural configuration represented on the top structure map (Fig. 1c) largely reflects development of large NE–SW striking faults resulting from Late Jurassic extension during the main rift phase in the northern North Sea (Platt 1995; Ravnas et al. 2000;
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Nevertheless, some structural elements, notably the so-called Halibut High in the centre of the study area, appear to predate this Late Jurassic phase, most probably recording formation during an earlier phase of east-west extension which was associated with the development of older, Triassic blocks and basins (Fig. 1b) (Roberts et al. 1995; Zanella & Coward 2003; Tomasso et al. 2008).

These older structures appear to have been active during Brent deposition in the study area, with subtle fault movements and differential subsidence influencing not only the thickness of sediment deposited but also the geographical location of environments, and, consequently, the resulting facies distributions. Thus, although the Broom, Rannoch, Etive and Ness formations are classically regarded as pre-rift deposits, there is strong evidence for synsedimentary fault control on sedimentation and depositional processes during delta construction in these intervals.

DATABASE AND METHODS

This study evaluated all 37 released wells in the area, 23 of which contain cored sections. Sedimentary logging and detailed facies analysis were carried out on 5102 ft of core, with data and facies interpretations calibrated to uncored intervals via core-to-log correlation and petrophysical evaluations.

Correlation panels were prepared to facilitate comparison of facies sequences over the area of interest. One well (211/19-6) studied in detail by Hampson et al. (2004) was also included in order to tie our evaluation to their biostratigraphically calibrated sections from the area immediately to the south. Sequence stratigraphic principles were used as the basis for correlation, with the identification of depositional sequences made both from erosional surfaces marking basinwards shifts in facies belts and from flooding surfaces associated with abrupt landwards shifts in facies.

The identification of correlative surfaces and genetically related intervals allowed the preparation of detailed facies distribution maps for each depositional sequence. Simplified versions of the maps were then integrated into the regional database and maps compiled by Hampson et al. (2004), permitting identification of the key driving forces controlling facies architecture across the Brent province as a whole.

**FACIES ANALYSIS**

Brent Group facies have been described in a number of previous studies (e.g. Richards & Brown 1986; Brown & Richards 1989; Livera 1989; Livera & Caine 1990; Hampson et al. 2004) and it is not the purpose of this paper to review each facies in great detail. Nevertheless, the sequence stratigraphic significance of certain facies is sometimes overlooked, and an overview of facies interpretations is a helpful foundation for describing Brent architecture and sequence stratigraphy. Figure 2 therefore provides a tabulated and graphical summary of the principal facies relevant to the study area. The facies are further illustrated in the core photographs in Figure 3, and are briefly described and interpreted below.

**Facies 1: Offshore mudstones**

*Description:* These are dark grey mudstones containing thin, very fine sand laminae or locally coarser sand lenses, and display horizontal burrows including Teichichnus and Terebelina. These deposits are typical of the Dunlin Group.

*Interpretation:* The trace fossils contained in these mudstones are characteristic of low-energy marine environments. Consequently, these rocks are interpreted as offshore mudstones. The coarse sand lenses are interpreted as the very distal expression of the time-equivalent, characteristically coarse-grained, Broom Formation (which is uncored in the study area wells).
Facies 2: Lower shoreface sandstones

Description: These are typically micaceous, slightly argillaceous, very-fine- to fine-grained sandstones, showing planar and inclined stratification with common discordant surfaces, features consistent with the development of hummocky cross-stratification (Richards & Brown 1986). Locally, there are intervals
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showing wave- and current-ripple lamination and bioturbation, with the latter being more common in the very-fine-grained sandstones and dominated by deposit feeding traces such as *Teichichnus*. Beds containing *Skolithos*, a suspension feeding trace, are occasionally present. Upwards-coarsening facies transitions are common in this facies, which is typical of the bulk of the Rannoch Formation (Fig. 4a, b).

**Interpretation:** The development of sand-dominated, upwards-coarsening sequences containing stacked units of hummocky cross-stratification (HCS) points to the preservation of storm deposits on the lower shoreface (Cheel & Leckie 1993; Reading & Collinson 1996; Howell et al. 2008). The localized intervals containing abundant wave ripples and *Skolithos* are interpreted as recording periods between storms of gentle wave agitation and reworking of the HCS on the lower shoreface.

**Facies 3: Upper shoreface sandstones**

**Description:** This facies is characterized by clean to slightly argillaceous, fine- to medium-grained sandstone showing weak planar, irregular and inclined stratification, and scarce burrows and wispy laminations. These sandstones are commonly interbedded with Facies 2 and Facies 4 in upwards-coarsening sequences up to 45 m thick.

**Interpretation:** This facies is interpreted, on the basis of grain size and sedimentary structure, to have been deposited in the upper shoreface environment. Sedimentary structures are typically poorly defined, but are considered consistent with deposition by the action of everyday waves (Reading & Collinson 1996). The grain size and position of this facies within upwards-coarsening transitions is consistent with the progradation of a shoreface (Heward 1981; Howell et al. 2008).

**Facies 4: Barrier sandstones**

**Description:** These are very-well-sorted, fine- to medium-grained sandstones showing weak planar, irregular and inclined stratification, and localized burrows and rootlets. The sandstones are typically preceded by upper shoreface sandstones and are commonly succeeded by and interdigitated with, lagoonal deposits. They are characteristic of the uppermost part of the Etive Formation.

**Interpretation:** These rocks are interpreted as barrier deposits. The enhanced sorting indicates high wave energies, and the development of rootlets points to periodic exposure. The characteristic position of this facies within the stratigraphic succession furthermore points to deposition in an environment located between the upper shoreface and the lagoons of the delta plain, consistent with a barrier interpretation.

**Facies 5: Fluvio-estuarine channel to sharp-based shoreface sandstones**

**Description:** This facies comprises erosively based intervals, 2–7 m thick, of medium- to very-coarse-grained sandstones displaying stacked sets of trough cross-stratification (Figs 3c & 4b). Intervals of this facies can be correlated in well logs over many kilometres. Petrographical observations locally show...
evidence for mechanically infiltrated clay (Fig. 4d). Reworked coal fragments are common in this facies and \textit{in situ} coals with rootlets are also locally present. This facies typically occurs within and at the base of the Etive Formation.

\textbf{Interpretation:} These rocks are interpreted as fluvio-estuarine channel to sharp-based upper shoreface deposits (Van Wagoner \textit{et al.} 1990; Zaitlin \textit{et al.} 1994; Went 2013). The stacking of trough cross-stratified sandstones is consistent with the transport and deposition of bedload as sinuous crested dunes. We interpret a depositional environment containing erosively based, migratory, fluvio-estuarine channels developed in the coastal zone (Fig. 5). At the seawards limit of these fluvio-estuarine channels, shoreline processes are envisaged interacting with the fluvial outflows. Hence, in the distal channel areas, some of the trough cross-stratification may have developed in unidirectional bedforms developed on nearshore bars and troughs associated with the upper shoreface. Up-dip, the broad fluvio-estuarine channels are interpreted to pass into entrenched fluvial distributaries (Fig. 5).

The presence of mechanically infiltrated clay in this facies suggests fluctuating groundwater levels, more consistent with a terrestrially influenced fluvial or fluvio-estuarine setting than a subtidal environment (Moraes & de Ros 1992). An association with subaerial environments is further supported by the local occurrence of rootlets and coals. The coals may mark omission surfaces, the lateral equivalent of fluvio-estuarine channel fills. Important to understand, given their inferred fluvio-estuarine channel origin, is the lateral extent of these erosively based sandstone bodies in strike section. The cutting of the basal erosion surface is interpreted to have resulted from the fluvial incision of migratory channels during sea level lowstand (Van Wagoner \textit{et al.} 1990; Zaitlin \textit{et al.} 1994; Went 2013). Likewise, the coarse grain size is interpreted to reflect base-level fall and sediment delivery via bypass of the delta plain. Analogy is drawn with the fluvio-estuarine Moor Grit Member of the Brent-equivalent sections of the Yorkshire Jurassic coast (Alexander 1992).

The broad extent of the fluvio-estuarine channel to sharp-based shoreface sandstone facies is consistent with deposition in a coastal setting, where entrenched fluvial channels occurring up-dip pass downstream on the delta top and towards the coastline into a broad belt of laterally migrating braided fluvio-estuarine channels, which are developed behind successively evolving shoreline bars and spits. Meanwhile, the vertical transition into overlying marine units of Facies 2 or Facies 3, deposited following a rise in sea level, is also consistent with deposition in close proximity to the shoreline.

\textbf{Facies 6: Distal sharp-based shoreface sandstones}

\textbf{Description:} This facies comprises medium- to coarse-grained, subhorizontally stratified sandstones that occur interbedded with lower shoreface HCS strata. The presence of mechanically infiltrated clay in this facies suggests fluctuating groundwater levels, more consistent with a terrestrially influenced fluvial or fluvio-estuarine setting than a subtidal environment (Moraes & de Ros 1992). An association with subaerial environments is further supported by the local occurrence of rootlets and coals. The coals may mark omission surfaces, the lateral equivalent of fluvio-estuarine channel fills. Important to understand, given their inferred fluvio-estuarine channel origin, is the lateral extent of these erosively based sandstone bodies in strike section. The cutting of the basal erosion surface is interpreted to have resulted from the fluvial incision of migratory channels during sea level lowstand (Van Wagoner \textit{et al.} 1990; Zaitlin \textit{et al.} 1994; Went 2013). Likewise, the coarse grain size is interpreted to reflect base-level fall and sediment delivery via bypass of the delta plain. Analogy is drawn with the fluvio-estuarine Moor Grit Member of the Brent-equivalent sections of the Yorkshire Jurassic coast (Alexander 1992).

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\textbf{Facies 7: Lagoon, bay and lake margin sandstones}

\textbf{Description:} These are very-fine- to fine- and, locally, medium-grained sandstones. They are variably argillaceous, commonly

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig5}
\caption{Gross depositional environment for the Dons area of the Brent Delta: (a) at sea level lowstand emphasizing the lowstand fluvio-estuarine channels; and (b) at sea-level highstand emphasizing the progradational shoreface and back barrier facies.}
\end{figure}
micaceous, ripple cross-laminated sandstones, containing burrows and localized rootlets. This facies is not volumetrically abundant within the study area, but where present may be organized into thin upwards-coarsening sequences a few metres thick.

Interpretation: We interpret these rocks as lagoon, bay and lake margin deposits, including lagoon shoreline, crevasse splay, mouthbar and levee sediments. Lagoon margin sandstones predominate over the bulk of the study area, but fluvial influences become stronger in the extreme south (around Murchison) where levee and crevasse splay sandstones occur. Owing to their low volumetric significance, the lagoon, bay and lake sandstones are considered together as a single facies here.

Facies 8: Lagoon mudstones
Description: This facies is characterized by dark grey silty mudstone with localized interbeds of wave- and current-rippled very fine sandstone. The sandstone beds and layers of heterolithic strata commonly display convolute or deformed bedding.

Interpretation: These are interpreted as lagoon or bay-fill sediments. The deformed strata reflect loading of sand deposited rapidly onto swamp mud during flood events.

Facies 9: Peat swamp coals
Description: This facies comprises coals and rootleted sandy mudstones. These lithologies are commonly associated with Facies 8 (lagoonal sediments) and locally Facies 5 illuvio-estuarine sediments.

Interpretation: These rocks are interpreted as peat swamp deposits. The coals and rootlet-bearing sandstones (peat earths) clearly record the growth of vegetation under subaerial conditions, followed by marine flooding.

Facies 10: Fluvial channel sandstones
Description: These are trough cross-stratified, fine-to medium-grained sandstones, organized in blocky to fining-upwards sequences several metres thick. They are present only in the far south of the study area, where they occur associated with other delta plain deposits within the Ness Formation.

Interpretation: These rocks are identified as fluvial channel sandstones. The presence of trough cross-strata reflect bedload transport within confined channels, and the identification of these as fluvial rather than fluvo-estuarine channels reflects their limited lateral extent and their association with facies of delta floodplain origin.

Facies 11: Bioturbated marine shelf sandstone
Description: This facies comprises clean to argillaceous, very-fine- to fine- and, locally, medium-grained, bioturbated sandstones. This facies is characteristic of the lower part of the Tarbert Formation, but is also locally present in the Rannoch Formation in the north of the study area. This facies locally contains marine macrofossils (belemnites) and trace fossils characteristic of open-marine shelf environments (e.g. Terebelina). In the Tarbert Formation in the south of the area, cross-bedded, coarser-grained sandstones are also present (Hampson et al. 2004).

Interpretation: These are interpreted as shallow-marine shelf sandstones. The characteristic bioturbation of the sandstones is consistent with deposition on the storm-dominated part of the shelf, mostly below fair-weather wave base. The intervals of cross-bedded sandstone to the south of the study area are consistent with a shallower, tidally influenced marine setting (Hampson et al. 2004).

Facies 12: Distal marine shelf sandstones
Description: This facies is dominated by micaceous, very-fine-grained silty sandstone, displaying planar lamination, inclined lamination and discordant bedding fabrics, which are interpreted as hummocky cross-stratification. This facies is locally bioturbated and similar in appearance to Facies 2, but is finer grained and with shallower internal dip angles.

Interpretation: These rocks are interpreted as storm wave deposits of the outer shelf. They are typical of the Upper Tarbert Formation in the study area.

Depositional environment for the Lower Brent Group in the Don fields area
The depositional environment for the Lower Brent Group in the Don fields area is summarized in Figure 5. The development of certain facies is interpreted to have been determined by relative sea level. Figure 5a emphasizes the environment and facies relationships at sea-level lowstand, whereas Figure 5b shows the relationship of facies and environment at relative sea-level highstand.

Environmental analogue: Saloum Delta, Senegal
The lateral arrangement of environments is here visualized by comparison with the Saloum Delta of Senegal, an actively constructional delta that has been prograding throughout the second half of the Holocene (Diara & Barusseau 2006). The delta is characterized by strong coastal wave action with active sediment movement along the coast associated with longshore drift towards the south (Barusseau & Radakovitch 1996).

Figure 6 shows the location of the Saloum Delta in West Africa, providing an environmental interpretation for each of the facies elements summarized in Figure 2, whilst Figure 7 illustrates some of the key processes determining channel evolution and sediment transport routes offshore.

The Saloum Delta covers an area of approximately 3000 km², with elevations of 2 m or less across its entire area. The delta lies in the microtidal domain, with a tidal range from 0.5 to 1.6 m. Rainfall is moderate and seasonal, associated with the migration of the tropical wet zone northwards during July–October (Niang-Diop et al. 2002). The delta is dominated by three major distributaries (Niang-Diop et al. 2002). The Saloum in the north is 1–2 km wide and 13–25 m deep. The central Diomboss channel is 4 km in width and 8–25 m deep, whilst the Bandiara channel in the south is 500 m across and less than 10 m deep.

These and a multitude of smaller channels dissect the delta plain into over 200 main islands and islets. The major part of the delta area comprises mangrove forest, with an Atlantic marine environment along the coast and dry forest inland (IUCN 2011). Consideration of the Saloum Delta coastline provides important insights into some of the key processes acting in the littoral sector of a prograding delta, within an area similar to that represented by the Don fields area of the Brent province.

A key observation is that the downstream, estuarine reaches of the major distributary channels are highly mobile, with their courses constantly modified in response to the extremely rapid lateral migration of beach barriers as a result of wave action and longshore drift directed to the south.

The Sangomar barrier in front of the main Saloum channel is presently migrating southwards at rates of 20–120 m each year (Diaw et al. 1991). During the twentieth century, this led to an accelerated and progressive deflection of the Saloum distributary towards the south (Bhattacharya & Giosan 2003). Subsequent breach of the Sangomar barrier during an ocean storm in February 1987 (Diaw et al. 1991; Thomas & Diaw 1997) resulted in more direct outflow from the Saloum and the development of
a new route for sediment supply offshore, clearly visible in the astronaut image shown in Figure 7.

Conversely, the absence (and inferred destruction) of a coherent barrier system at the mouth of the Diomboss distributary has apparently favoured the development of straightened, braided channel courses for some distance inland, with consequent lateral erosion of delta plain environments at channel banks, and the development of a direct and shortened sediment transport path offshore.

The continuous lateral deflection and switching of the fluvio-estuarine channels observed in the downstream sectors of the Saloum Delta as a result of rapid barrier migration provides a mechanism for the preferential preservation of fluvio-estuarine channel-floor deposits as laterally extensive sheet units, as inferred for the Brent Delta front in the study area.

Equally, the processes observed in the Saloum Delta of continuous barrier modification and destruction are consistent with the preferential erosion and relative scarcity of barrier facies in the Brent record, where barrier facies make up, at most, approximately 5–10% of the sedimentary sequence.

In addition, the barrier breach and destruction processes active in the Saloum are clearly associated with the formation of localized sediment transport paths into the offshore area, and offer a clear explanation not only for the presence of reworked fluvio-estuarine channel deposits in the Brent Group but also
their spatial and vertical association with offshore upper and lower shoreface deposits.

**STRATAL SURFACES, FACIES SEQUENCES AND CORRELATION**

In correlating facies sequences across the study area, we have, where possible, adopted the sequence boundary and flooding surface terminology used by Hampson et al. (2004), who carried out a sedimentologically and biostratigraphically constrained sequence stratigraphic correlation study over the bulk of the UK Brent province. The northern limit of the data presented in detail by Hampson et al. (2004) forms the southern limit of this evaluation. The sandstone-dominated nature of the Brent in the study area limits the usefulness of biostratigraphy in our correlation, but, fortunately, dense well spacing and an abundance of core in the Dons area allow a sedimentologically based approach to be used with some confidence, offering robust correlation with wells previously evaluated in the Murchison Field (Fig. 8). Table 1 lists the major stratigraphic surfaces identified in this study and their characteristic features. The bulk of the surfaces identified are demonstrably of subregional–regional extent and/or have correlative regional equivalents. The surfaces are, furthermore, associated with a systematic landwards or seawards shift in the facies present within the underlying and overlying strata. This suggests these are good candidate sequence stratigraphic boundary surfaces and flooding surfaces, which are unlikely to have been formed by autogenic processes alone. Examples of the appearance of sequence boundaries and flooding surfaces in core are presented in Figures 3f & 4b, c.

The names are adopted from their basal boundary. For example, SB100 forms the base of Sequence 100. We have added one candidate sequence boundary, SB200, to the scheme developed by Hampson et al. (2004). The definition of SB200 is based on the observation that the transition from shale to sandstone at the base of the Rannoch Formation in this region is sharp rather than transitional. Examples of the sharp base to the Rannoch are shown in our correlations, presented in Figures 9–12. Isopach maps showing thickness variations in the Brent Group as a whole, in the Tarbert Formation, and in the Rannoch–Etive–Ness formations are displayed in Figure 13. Maps illustrating the gross distribution of facies (gross depositional environment) are provided, by sequence, in Figure 14. Salient features of each sequence are further outlined below.

**Isopach maps and tectonic controls on sedimentation.** Isopach maps were generated predominantly from well data, locally supplemented by observations made from calibrated seismic data. Maps for SB100–FS1050 (total Brent Group), SB200–SB1000 (total Rannoch plus Etive plus Ness formations) and SB1000–FS1050 (total Tarbert) are illustrated in Figure 13. The maps highlight the principal patterns of sedimentation, and reveal the interaction of the depositional environment and basin tectonics. Broadly, the Brent Group thins towards the northern limit of the delta system as sandstones are replaced by offshore shales. Superimposed on this regional thickness change are trends in thickness variation that are oriented north–south. These trends reflect mid Jurassic syndepositional faulting that transected pre-existing Triassic horst and basin structures, and served to define the key horsts and troughs within the Dons and Penguin areas.

The pattern of structural control observed from within the Tarbert is slightly different from that in the Rannoch, Etive and Ness formations. The central horst in the Don fields area is broader, matching the morphology of the modern so-called Halibut High, which was defined in Late Jurassic times around a Triassic precursor structure (Tomasso et al. 2008). These high and the adjacent basins acted as important influences on facies and sediment thickness throughout Brent times (Fig. 1b).
Table 1. Stratal surface characteristics and relationship to facies and lithostratigraphy

| Surface name | Boundary type (Exxon) | Stratal surface characteristics inferred from cores and logs | Formation/Member equivalent |
|--------------|-----------------------|-------------------------------------------------------------|-----------------------------|
| FS1050       | Flooding surface      | Subregional, correlatable, sharp change to offshore mustone (OM) | Base Heather                |
| FS1000       | Flooding surface      | Subregional, correlatable, sharp change to distal shelf facies (DSS) | Base Tarbert                |
| SB1000       | Ravinement surface    | Subregional, correlatable, transgressive lag and abrupt shift to inner shelf (bioturbated shelf sandstone (BSS)) | Base Tarbert                |
| FS500        | Flooding surface      | Subregional, correlatable abrupt change to more seawards facies (typically upper shoreface (USF)) | Local Base Etive            |
| SB500        | Sequence boundary     | Subregional, correlatable, erosion surface and shift in facies (typically to fluvio-estuarine channels (EC)) | Base Mid Ness Shale equivalent |
| FS400        | Flooding surface      | Subregional, correlatable, marked shift to more seawards facies (typically to lower shoreface (LSF)) | Base Mid Ness Shale equivalent |
| SB400        | Sequence boundary     | Locally correlatable erosion surface overlain by EC, otherwise omission surface | Base Rannoch                |
| FS300        | Flooding surface      | Subregional, correlatable abrupt change to more seawards facies (typically to LSF/USF) | Base Rannoch                |
| SB300        | Sequence boundary     | Subregional, correlatable, erosion surface and shift in facies (typically to EC) | Local Base Etive            |
| SB200        | Sequence boundary     | Subregional abrupt change to more proximal facies (typically to LSF) | Base Rannoch                |
| SB100        | Sequence boundary     | Local sharp change to inner shelf sandstone (BSS) and correlative equivalent (OM) | Base Broom                  |

Fig. 9. North–south correlation through the Penguin and Don NE fields.

Sequence 100 (Broom and Broom equivalent). This interval is bounded by SB100 at the base and SB200 at the top. The sequence is shale-prone, but, in the west, it includes a sandstone interval approximately 10m in thickness (Fig. 14a).

Core control in this sequence is limited to the eastern part of the study area, where mudstones typical of Facies 1 (offshore mudstones) are developed and locally contain coarse-sandstone lenses. The correlative sandstone interval in the west is inferred to comprise marine facies of the Broom Formation, which are comparable to Facies 11 (bioturbated marine shelf sandstones).

Sand supply appears to have been derived both laterally into the basin from the west as well as axially from the south (Fig. 12a). The restriction of sandstone facies to the area west of the proto-Halibut High suggests the latter may have acted as a barrier, limiting the delivery of sand to the Don SW field area.
Fig. 10. North–south correlation through West Don.

Fig. 11. West–east correlation through southern SW Don.
Sequence 200 (Rannoch). This interval is bounded by SB200 at the base and SB300 at the top. The base of this sequence is typically fairly sharp and is marked by an abrupt influx of fine-grained sandstone (either lower shoreface sandstone, Facies 2, or locally bioturbated marine shelf sandstone, Facies 11). These facies units rest on offshore marine mudstone (Facies 1) typical of the Dunlin Group.

A fine-grained sand unit, around 2–5 m thick, developed at the base of Sequence 200 is characteristically overlain by a much thicker package of very-fine- to fine-grained micaceous sandstones. These lower shoreface sandstones of Facies 2 are arranged into a generally cleaning and coarsening-upwards package about 40 m thick. Locally, this cleaning-upwards profile contains abrupt intercalations of cleaner or more argillaceous sandstone (Figs 9–12), suggesting the possibility of a more complex history for this sequence.

Sequence 300 (Lower Etive–Upper Rannoch). This interval is bounded by SB300 at the base and SB400 at the top. In the south of the study area, this sequence has an erosional base that is overlain by a 2–10 m interval of coarse-grained, cross-bedded sandstones (fluvio-estuarine channel to sharp-based shoreface sandstones, Facies 5). In the north of the area, the sequence boundary occurs within an uninterrupted succession of micaceous Facies 2 lower shoreface sandstones, and is picked where the sands become slightly coarser and cleaner upwards. This change is evident in gamma ray, neutron and density logs, and in core. Between these two areas (e.g. in well 211/18a-21), the boundary is marked by a thin interval of coarser distal shoreface sandstones (Facies 6: Fig. 14b).

The distribution of these different successions is interpreted as reflecting a process of incision at the sequence boundary, which occurred during falling relative sea level. Aggradation was followed by repeated reworking events as the shoreline rapidly moved landwards. In the northern part of the study area, the upper part of Sequence 300 is dominated by lower shoreface sandstones of Facies 2, with upper shoreface sandstones (Facies 3) present further to the south (Fig. 14c). A transition from fluvio-estuarine channel to sharp-based shoreface deposits (Facies 5) in the lower part of this interval upwards into lower and upper shoreface deposits above (Facies 2 and 3) suggests a marked rise in base level. This is consistent with the development of a maximum flooding surface (MFS) between the two, here described as FS300. This flooding event was followed by a period of marine regression that led, eventually, to the development of rootlet sandstones and coals at the top of this sequence, as seen in well 211/18a-22.

Sequence 400 (Middle Etive and Mid-Ness Shale equivalent). This interval is typically around 20 m thick, and is bounded by SB400 at the base and SB500 at the top. Lowstand deposits, comprising fluvio-estuarine channel to sharp-based shoreface and distal sharp-based shoreface deposits (Facies 5 and 6), are restricted to the area immediately to the east of the so-called Halibut High (Fig. 14d). In well 211/18a-22, the sequence is represented by an erosively based 5 m-thick interval of coarse-grained cross-bedded fluvio-estuarine channel to sharp-based shoreface sandstones (Facies 5).

A short distance to the north in well 211/18a-21, sequence boundary 400 is weakly defined and overlain by a thin interval
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of coarse-grained distal sharp-based shoreface sandstones (Facies 6) developed within a thicker package dominated by fine-grained and micaceous lower shoreface sandstones (Facies 2). Further north and towards the correlative conformity, SB400 may be marked by the presence of just a few coarse grains within the lower shoreface sandstone package.

The limited development of lowstand deposits is in contrast to the widespread development of highstand facies within the upper part of the sequence. Lower shoreface sandstones (Facies 2) dominate in the north, with a narrow belt of upper shoreface (Facies 3), and lagoon and lake margin (Facies 7) present towards the south (Fig. 14e). These shoreline to delta plain facies form lateral equivalents of the well-documented Mid-Ness Shale highstand deposits, which are widely developed in the Brent province further to the south (Livera 1989; Hampson et al. 2004). In the study area, lagoonal facies typical of the Ness Formation characterize the highs (Facies 7), while lower shoreface deposits of Facies 3 dominate in structural lows and in areas located down depositional dip to the north.

Sequence 500 (Upper Etive and Ness). This interval is around 45 m thick, and is bounded by SB500 at the base and SB1000 at the top. Over most of the area, an erosional base is overlain by a 5–10 m interval of coarse-grained, cross-bedded fluvi-estuarine channel to sharp-based shoreface sandstones (Facies 5). This coarse-grained basin section thins in the north of the study area and over the eastern part of the so-called Halibut High (Fig. 14f).

The succeeding greater part of Sequence 500 is typically 20 m thick and composed of upper shoreface sandstones of Facies 3 (Fig. 14g), which thicken towards the north. These typically display a cleaning- and coarsening-upwards profile, and pass upwards in the central part of the study area into 5–10 m of clean, well-sorted barrier sandstones (Facies 4). In the centre of the study area these barrier sandstones begin to pass laterally into lagoonal and floodplain deposits of Facies 7, 8 and 9, typical of the Ness Formation. These are only a few metres thick in the Don fields area but thicken southwards to dominate the entire sequence near the Murchison Field, in well 211/19-3.

Fluvio-estuarine channel to sharp-based shoreface deposits are developed in the basal part of Sequence 500 on either side of the proto-Halibut High and over much of the study area immediately to the north of it. A lowstand shoreline is inferred within the Upper Etive and Ness at the north end of West Don, and in the north of East Penguin, but is only moderately constrained due to a lack of well and core data. Further south, the basal fluvio-estuarine channel to sharp-based shoreface sandstones of Facies 5 are overlain by upper shoreface (Facies 3) and barrier sandstones (Facies 4) in the centre of the area, and by lagoonal and delta plain deposits of Facies 7, 8 and 9 in the south. This succession records the occurrence of a transgressive event followed by shoreline aggradation and accompanying modest progradation.

Hampson et al. (2004) identified an additional flooding surface (FS850) and stratigraphic sequence, thus subdividing our Sequence 500 into two, with the upper part being slightly retrogradational. The possibility of two sequences being present is not excluded. However, we have been unable to identify a correlatable facies break here; in the wells studied, the upper shoreface deposits only show evidence for continued progradation.

Sequence 1000 (Tarbert). The laterally persistent Sequence 1000 interval, bounded by SB1000 at the base and FS1050 at the top, corresponds with the lithostratigraphically defined unit of the Tarbert Formation. In most wells in the study area, this sequence rests on an erosional base interpreted as a ravinement surface, which is overlain by a 3–7 m package of fine- to, locally, medium-grained, argillaceous, bioturbated marine shelf sandstones (Facies 11).

The lower part of the unit displays a blocky to upwards-cleaning signature, and is interpreted as a marine shelf succession. The upper part of Sequence 1000, from FS1000 to FS1050, comprises silty to very-fine-grained sandstone displaying HCS, interpreted as distal shelf deposits. These two retrogradationally
Fig. 14. Depositional model showing the environmental and sequence stratigraphic setting of the principal facies identified in the Don fields area: (a) Sequence 100 lower (Broom); (b) Sequence 300 lower (lower Etive); (c) Sequence 300 upper; (d) Sequence 400 lower; (e) Sequence 400 upper (mid-Ness shale); (f) Sequence 500 lower; (g) Sequence 500 upper; (h) SB1000–FS1000 (lower Tarbert); (i) FS1000–FS1050 (upper Tarbert). The regional facies distributions (left-hand of map pairs) are adapted from those shown in Hampson et al. (2004) with conceptual incised fluvial channel systems. Emergent areas are shown by clear polygons.
stacked parasequences characterize the Tarbert as a transgressive systems tract (Fig. 14h). Thickness variations within both the proximal and distal shelf deposits (Facies 11 and 12) in this sequence reflect active movement of the so-called Halibut High, with thickness maxima present in the hanging-wall lows defined by its main bounding faults (Fig. 13).

**Facies and reservoir quality.** Sedimentary facies is the principal control on reservoir quality. This is attributed to the control of grain size on porosity, which in turn is the most important predictor of permeability. Figure 15 provides a cross-plot of porosity and permeability representative of the study area. Much of the spread in this dataset can be explained in terms of facies control.

Thus, fluvi-estuarine channel to sharp-based shoreface sandstones (Facies 5) show high porosity as well as a high permeability for any given porosity, reflecting their clean and coarse-grained lithology. Similarly, barrier sandstones (Facies 4) are medium grained and well sorted, with high porosity and permeability. By contrast, upper shoreface sandstones (Facies 3) are finer grained and, although showing good porosity, have lower permeabilities owing to their finer grain size, and the presence of dispersed and illitized detrital clay. Lower shoreface sandstones (Facies 2) are generally quite clean but are very fine to fine grained, and are also highly micaceous. Consequently, they show reduced porosity due to their susceptibility to compaction, and low permeabilities due to their very fine grain size.

Similar textural constraints determine porosity and permeability in the other facies. Other important controls on porosity and permeability include an overall depth control on porosity and permeability, and a limited degree of water leg diagenesis. Although it is beyond the scope of this paper to consider all of the controls on reservoir quality, it is clear that facies is a key control on reservoir quality. Accurate maps detailing facies distribution are, therefore, fundamental to exploration and development success.

**Summary Model of Facies Architecture**

Facies analysis, sedimentology, sequence correlation and facies distribution maps form the basis of the stratigraphic model presented for the Brent Delta (Figs 16 & 17). The correlative stratigraphic schemes of Mjos et al. (1998) and Hampson et al. (2004) are readily reconciled with the major surfaces recognized in this study, although detailed comparison of these schemes reveals significant differences as outlined below.

The present work on facies architecture in this study suggests that the overall progradation of the delta was episodic rather than constant. Periods of deltaic build out were punctuated by repeated episodes of areally extensive subaerial erosion and incision, followed by flooding and back stepping of the depositional systems.

This model contrasts with a recent reinterpretation of the Rannoch–Eitve made further to the south and in the Norwegian sector of the Brent province, which emphasizes the role, under steady sea-level conditions, of a single episode of steady progradation towards a deep delta front (Helle & Helland-Hansen 2009). The study by Helle & Helland-Hansen (2009) was largely based on three, widely spaced wells, whereas this study and that of Hampson et al. (2004) were able to rely on closely spaced wells to identify candidate high-frequency, sequence boundaries with confidence. It seems possible, therefore, that high-frequency sequence boundaries are either obscured or have been overlooked in the three wells reviewed by Helle & Helland-Hansen (2009). The net level of climb of the shoreface observed here (about 0.1%) is similar to that observed by Helle & Helland-Hansen (2009). Significantly, however, within the study area an alternation of periods of erosion and progradation allow for the development of a thick compound shoreface without the need for an anomalously deep delta front.

Data presented in this study suggest that incision was extensive across the delta, but not so deep as to cut down and deposit sands beyond the delta toe (cf. Ainsworth & Pattison 1994). For example, the coarse-grained fluvi-estuarine channel to sharp-based shoreface deposits in Sequence 306 rest directly on, and are immediately overlain by, lower shoreface strata. This suggests that the observed sequence was generated by relatively modest sea-level change. Modern shorefaces typically show a submarine relief of 15–25 m across a 1–2 km zone parallel to the shoreline (Stive & de Vriend 1995; Howell et al. 2008; Helle & Helland-Hansen 2009). If we surmise that the base of the lower shoreface is likely to have been at a depth of around 20 m and the base of the upper shoreface at 7 m (cf. Howell et al. 2008), then a drop in relative sea level of 10 m would probably have been sufficient for erosion of the entire upper shoreface section, such that, for example, fluvi-estuarine channel deposits would then have been laid down directly on lower shoreface strata.

Periods of marine flooding can clearly be inferred from the periodic landwards movements of facies belts. Using the same logic as
we used to assess sea-level fall, the scale of the relative sea-level rise during transgression may be estimated as around 15m, sufficient for a 7m backfill of the fluvio-estuarine channels plus a further 8m rise in sea level across the area. This would result in the stacking in the study area of lower (rather than upper) shoreface units directly above fluvio-estuarine channel deposits. The modest scale of relative sea-level rise and fall inferred is consistent with the observed landwards shoreline recession between high- and lowstands of only around 30km, implying a lower delta plain gradient of 0.05º.

Consideration of a strike section through the study area (Fig. 17) demonstrates clearly that the Triassic proto-Halibut High remained high throughout Brent deposition. Mid Jurassic movement similarly controlled differential subsidence across the Ninian–Hutton–Dunlin Fault further to the south (Hampson et al. 2004) (Fig. 1b).

The proto-Halibut High seems to have been largely buried through deposition of Sequence 200 (Rannoch times), but was apparently exposed during lowstands when Etive Sequences 300, 400 and 500 were deposited down-dip. Exposure of the so-called Halibut High probably continued during deposition of the Tarbert, as the onset of Upper Jurassic rifting led to footwall uplift in excess of sea-level rise. Meanwhile, in hanging-wall areas such as Don SW, Sequences 300, 400 and 500 saw the formation of incised valleys and lowstand shorelines. Stacked, coarse-grained fluvio-estuarine channel-sharp-based shoreface sandstones show excellent reservoir quality here, offering high oil production rates on drilling.

**DISCUSSION**

**Implications for sequence stratigraphical models**

The detailed facies architecture models described here have implications for the understanding of Middle Jurassic sequence stratigraphy in the northern North Sea, permitting reliable correlation and reconstruction of the sedimentary response to globally or locally driven changes in relative sea level. The manner of sediment deposition remains intriguing, and requires further assessment of shoreline trajectory (Bullimore & Helland-Hansen 2009), sediment supply, global eustasy and regional tectonics.

**Shoreline trajectory.** The vertical path transcribed by a shoreline brink point as the shoreline migrates seawards or landwards is known as the shoreline trajectory (Henriksen et al. 2009). A horizontal or zero climb trajectory represents purely horizontal progradation with no component of aggradation or incision.

The Brent Delta shoreface prograded approximately 200km northwards during the Rannoch–Tarbert time interval, during which shoreface successions over 100m thick were laid down across the study area. Applying an analogy with the geometries of modern shorelines and their facies belts, Helle & Helland-Hansen (2009) concluded that, under conditions of ‘normal regression’, over 5km of relative sea-level rise would be required for a shoreface succession 100m thick to be deposited if the shoreline advanced seawards across a distance of 200km.

However, a relative sea-level rise on this scale would necessarily be accompanied by the deposition of an equivalent 5km thickness of facies laid down behind the shoreline. As also noted by Helle & Helland-Hansen (2009), this is clearly not the case; the progradational part of the Brent Group succession (comprising the delta-top facies of the Ness Formation) is typically less than 300m thick. Even if some allowance is made for modern shoreline geometries possibly being different from those in the Middle Jurassic, it is clear that Brent deposition did not reflect normal regression under rising sea level.
This study identifies two contrasting styles of shoreline trajectory. There are some intervals with negative angles of climb, whilst the Brent succession as a whole shows an overall net positive trajectory calculated at 0.1°.

Evidence for intervals of areally extensive fluvial incision (Fig. 14) suggests that erosion occurred during falling stage, with shoreline trajectory at a negative angle (Fig. 18). The model in Figure 18 infers incision not just during Etive time (Olsen & Steel 2000), but also during deposition of the Rannoch (see also Hampson et al. 2004). We envisage a basin floor sloping to the north (Fig. 18a), with sediment reworking and redistribution promoting seawards build out of the delta to the north (Fig. 18b, c).

We also see evidence in our study area for periodic rises in sea level, associated with landwards migration of the shoreline and followed by steady progradation. This configuration is most notable in Sequence 500 where a steep positive shoreline trajectory may be inferred, with the shoreline apparently aggrading significantly but with only slow progradation.

Discrete sea-level rise events may also be inferred in Sequences 300 and 400 from the presence of flooding surfaces, marked by a landward shift of facies belts. The shoreline did not retreat very far (around 30 km) and these landward shifts were each followed by episodes of shoreline progradation at a low angle. These successions are interpreted as highstand systems tracts (HSTs), the deposition of which reflected normal regression under conditions of rising sea level. However, the presence of a single cycle of sand-dominated sediment with no shale at the flooding surface in each case suggests a continuous and unbroken supply of sand to the delta front, leading us to speculate that the time-equivalent sections up-dip may have been experiencing a relative stillstand or a fall in sea level (i.e. erosion).

**Sediment supply.** The Broom Formation of the UK and the Oseberg Formation of Norway (J22 – Aalenian) were derived mostly from the erosion of the East Shetland Platform and the Fennoscandian Shield at the flanks of the basin (Morton 1992; Heland-Hansen et al. 1992). Uplift of the Mid North Sea Dome reached its maximum extent during this period. Evidence during the remainder of Brent time for steady and consistent sediment supply from the south is interpreted as a response to the continued uplift and erosion of Triassic and early Jurassic rocks on the Dome itself (Fig. 18) (Underhill & Partington 1993). Continued erosion of the East Shetland Platform and the Fennoscandian Shield may have resulted in additional sediment being supplied from these flanking regions (Morton 1992).

**Global sea level.** The evolution of global sea level during Middle Jurassic times is uncertain. The Haq chart shows a fall in global sea level in the Aalenian (Haq et al. 1987), and steady rise thereafter. This was questioned by Underhill & Partington (1994), who pointed out that the interpretations made by Haq et al. (1987) were based on data from the Dorset and Yorkshire coasts, in basins which were themselves affected by the North Sea volcanic dome, whereas the type sections at Aalen in southern Germany reflect a coeval deepening. Comparison of these various sections allowed Underhill & Partington (1994) to attribute Early–Middle Jurassic shallowing and subsequent Middle–Late Jurassic transgression in the North Sea to a period of doming and deflation resulting from the passage of a transient hotspot. Thus, they argued for a regional tectonic driver on relative sea level obscuring and opposing global eustasy, and the consequent impact upon the resultant sediment architecture as sea level fell.
Regional tectonics. The rise of the North Sea Dome was apparently a primary control on the sequence stratigraphy of the Brent Group. The rise of the North Sea Dome through the Aalenian and Bajocian (J22 Broom to J24 – J26 Rannoch & Etive) was coincident with the initiation of deposition in the Brent Delta on its extreme northern margin. Continued crestal rise was accompanied by deflation of the dome margins, plentiful sediment supply and possible tilting of the Viking Graben basin floor to the north. The dome was progressively onlapped by paralic sediments during the Bathonian (Underhill & Partington 1993, 1994).

Sediment supply generally outpaced basin subsidence and/or sea-level rise, causing the delta front to move basinwards through the Bajocian (J24 and J26). Sediment supply was clearly sufficient to fill all of the available accommodation space on the delta top, as the delta front built out basinwards, commonly under forced regression (Fig. 18), until the onset of Sequence 1000, (Tarbert; J32).

Regional correlations. Despite a number of publications dealing with the sequence stratigraphy of the Brent Group, regional interpretation remains less than straightforward. We suspect the apparent coherence of the Brent Delta facies masks a discontinuous offset patchwork of sediment layers and bodies that together comprise the Rannoch, Etive and Ness formations. This reflects alternating periods of locally varying erosion and aggradation, possibly with the periodic development of sub-deltas within the Brent system as a whole. Hence, sequence correlation is easily managed within individual lithosomes or genetically related bodies, but is problematic across the wider area of the entire Brent Delta where well control may be insufficient to identify the nature of discontinuities with certainty. Unfortunately, when sedimentological correlations break down, biostratigraphical control typically lacks certainty at the fine scale required.

Depositional systems tracts and cycles of forced regression. Our study area of the northern sector of the Brent Delta shows a facies architecture reflecting three periods of progradation, each followed by a period of delta plain incision. This evolution suggests the repeat ‘squeezing’ of up-dip accommodation space causes long distance build out of the delta. Note that the Ness Formation (delta plain) is expected to contain multiple extensive discontinuities (b), and the Rannoch (Facies 2) is deduced to be an amalgam of multiple systems tracts (c, d, e).
is quite thin (300m). As mentioned above, the relatively meagre thickness of the delta plain succession deposited argues against significant accumulation under conditions of rising sea level (i.e. multiple HSTs). An inferred accumulation of shoreface sequences as a succession of multiple falling stage system tracts (FSSTs) and lowstand system tracts (LSTs), as a response to forced regression, however, would have left much of the delta bypassed at any one time and would have severely limited the potential for substantial thicknesses of delta plain facies to have accumulated. This recalls the picture painted in the regional maps displayed in Figure 14.

Notwithstanding the above observations, the modest landwards shift in the shoreline associated with the base of the progradational sequences points to periods of sea-level rise, suggesting that these units are best described as HST deposits formed under normal regression. The erosion surfaces overlain by fluvio-estuarine channel and sharp-based shoreface deposits, by contrast, point to falling sea levels and periods of forced regression. The uppermost sequence S500 is overlain by a ravinement surface marking the base of the S1000 (Tarbert), whilst the Tarbert interval itself ($S1000$) displays a retrogradational set of two parasequences in the study area and is interpreted as a transgressive system tract deposit.

A sequence stratigraphic model for the Brent Delta explaining observations made in the study area is provided in Figure 18. Our interpretations suggest that the build out of the Brent Delta occurred under conditions of limited accommodation space, oscillating sea levels and forced regression. This is supported by the following regional observations:

- The Brent Delta built out axially over a long distance (>200 km) within a short time (~5 Ma), yet the delta sediments are quite thin (300m).
- Coarse-grained sandstones are present and abundant across the full >200 km axial extent of the Brent Group, suggesting significant sediment bypass.
- The Rannoch Formation in the study area is sharp-based but is not steadily upwards coarsening in all wells. It also contains interbedded sharp-based coarser or finer sandstone intervals. This may reflect its origin as a composite lower shoreface deposit resulting from amalgamated HST, FSST and LST deposits. This is readily envisioned with reference to Figure 18c–e and would explain its appreciable thickness. It is less easily envisioned as a response to steady progradation.
- An absence of laterally extensive mudstones developed above maximum flooding surfaces in this northern area reflects the continuous and relatively unbroken supply of sandy sediment to the delta front, even during periods of relative sea-level rise.
- The facies architecture in this northern area of the Brent Delta records discrete transgressive–regressive cycles, each truncated by incision surfaces. The local erosion and/or removal of entire sequences (Hampson et al. 2004) further south in the Brent province is consistent with an extensive delta depositional system that was developed during a long period when the creation of accommodation space was relatively limited.

**Implications for Hydrocarbon Exploitation Within the Brent Group and Beyond**

What are the implications of the Brent Delta ‘forced regressive’ model for exploration and production in Brent Group, and for other similar deposits formed with strong elements of forced regression?

The basin geometry and magnitude of relative sea-level fluctuations during deposition of the Brent Group together controlled a process of regression, which resulted in the successive formation of a series of attached shorefaces or sub-deltas (cf. Ainsworth & Pattisson 1994). The geometry of these bodies is not certain. We speculate that they may have been lobate, with each individual attached shoreface lithosome possibly covering an area of approximately 250 km$^2$. Together, these attached lobes coalesced to form the Brent Group, a composite sheet sandbody 200 km wide and 300 km long (Fig. 1).

Interpretation of the Brent Delta as a composite product of attached shorefaces and associated back barrier delta plain strata suggests that the delta front may have been lobate and embayed; noting that simple depositional regression would have tended to encourage a more linear coastline geometry. Meanwhile, the absence at the northern end of the Brent sand system of detached shoreface (Plint 1988) and lowstand fan deposits (Van Wagoner et al. 1988) leaves the topmost attached shoreface deposits as the most attractive reservoir target in this area.

A further implication of the attached shoreface–composite sheet sand model is that a very high sand/mud ratio and a medium-coarse sandstone grade are present across the full 200 km axial extent of the Brent Group. This consistent sand distribution is to be contrasted with, for example, highstand and rising sea-level shoreline plays, such as the Upper Jurassic Fulmar of the Central North Sea, in which sequences not only contain finer-grained sandstones but where grain size, reservoir thickness, net to gross and prospectivity each decline basinwards over much shorter distances of typically 20 km or less (Sansom 2010).

By contrast, sandbodies such as those of the Brent Group, which are here argued to have been deposited under strong forced regressive influences, are characterized by high net to gross and coarse grain size across a much more extensive fairway. This serves to facilitate regionally successful hydrocarbon migration into structural traps, whilst also controlling the development of excellent reservoir quality and favourable prospectivity across the entirety of an extensive hydrocarbon province.

The distribution of areally significant coarse-grained fluvio-estuarine channel to sharp-based shoreface deposits laid down following falling stage incision has also resulted in the formation of regionally important high-permeability pathways within the reservoir succession. These units provide enhanced fluid flow routes that offer the benefits of high oil production rates: many individual wells at depths of 10–11 000 ft produce at initial rates of over 20 000 bopd (barrels of oil per day). Later on in the production phase, however, the same high-permeability units commonly present reservoir management problems via early aquifer or injected water breakthrough, arguing against the perforation of these same reservoir units within wells drilled later in field life.

**CONCLUSIONS**

Detailed correlation and interpretation of the Brent Group from the Don fields area in the East Shetland Basin of the northern North Sea reveal important differences in facies and sedimentary architecture in comparison with studies carried out further south. The characteristic development of fluvio-estuarine channel sandstones, formed during sea-level lowstands, and a relative scarcity of delta-top facies are notable features of the successions in this area.

Analogy with the Saloum Delta of Senegal highlights the importance of rapid and continuous barrier migration and destruction as a control on the deflection and switching of major fluvio-estuarine channels, as well as the inferred preferential preservation of fluvio-estuarine channel facies over transient
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barrier and delta-top facies, which are easily eroded during channel migration and switching events.

The detailed facies architecture of the Brent Group in the northernmost part of the Brent province reveals at least four repeated cycles of progradation and delta incision related to fluctuations in relative sea level.

Prominent coarse-grained facies overlying an erosional base are interpreted as fluvi-o-eustuarine channel to sharp-based shoreface deposits, and occur interspersed with normal regressive marine shoreface facies throughout the Rannoch and Etive formations. These coarse sandstones form important high-permeability layers that enhance well deliverability.

The repeated cycles of progradation and incision are explained as a sedimentary response to repeated episodes of rising then falling stage, with an associated process of forced regression. The basin configuration and regional influences on sedimentation resulted in only moderate rises and falls in relative sea level, and the formation of a series of attached shorefaces. There is little evidence for sediment bypassing the delta front, suggesting that there is likely to be limited potential for pro-delta sand plays in this area.

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