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Tectonic influence on the Jurassic sedimentary architecture in the northern North Sea with focus on the Brent Group

ATLE FOLKESTAD*, TORE ODINSEN*, HAAKON FOSSEN[†,a] and MARTIN A. PEARCE[‡]

**Statoil, Bergen, Box 7200, Bergen 5020, Norway (E-mail: atlef@statoil.com)*
[†] Department of Earth Science, University of Bergen, Allégaten 41, 5007 Bergen, Norway
[a] Centre of Integrated Petroleum Research, PO Box 7800 N, 5020 Bergen, Norway
[‡] Statoil Gulf Services LLC, 2103 CityWest Boulevard, Houston, Texas, 77042, USA

ABSTRACT

It is known from previous studies that the Middle Jurassic succession in the northern North Sea has been influenced and controlled by syn-depositional fault activity. In this study from the Gullfaks-Kvitebjørn area, we build upon that knowledge with seismic cross-sections, well-correlations and cored intervals to evaluate features that can be linked to Middle–Late Jurassic rifting in the northern North Sea. A regional east–west transect shows an overall wedge-shaped Jurassic succession in the strike-section between two long-lived Permo–Triassic faults, with a marked asymmetric thickness distribution from the Ness Formation and upward. In a local section across the Kvitebjørn Field the same pattern is identified, but here the thickness differences are more pronounced. We suggest that the sedimentological response to this Middle Jurassic tectonic activity is reflected by the formation of local depocentres with stacked tidal dunes, differences in lithological characteristics along strike within stratal units and facies variability along an irregular coast with enhancement of tidal currents in the funnel-shaped hangingwall areas of rotated fault-blocks. These integrated data suggests that the Middle–Late Jurassic rift phase started in the Early Bajocian (basal Ness Formation) within the Gullfaks to Kvitebjørn transect and with flexing at the crest of the Permo–Triassic mega-block leading to a complex stratigraphic development of the Brent Group at that location.

Keywords: Brent Group, syn-sedimentary tectonics, Middle Jurassic, early to main rift-phase, northern North Sea.

INTRODUCTION

The Jurassic northern North Sea (Fig. 1) is one of the best-studied extensional rift basins in the world, due to extensive hydrocarbon exploration and production, especially within the economically important Middle Jurassic Brent Group. The deposition of clastic Jurassic formations in this basin is directly or indirectly influenced by tectonic activity. Accordingly, it is important to understand how this activity affected the depositional environment. The interaction between tectonics and deposition of the Jurassic succession of the northern North Sea has been discussed in a series of studies, albeit with different focus and interpretations (e.g. Helland-Hansen *et al.*, 1992; Steel, 1993; Johannessen *et al.*, 1995; Færseth, 1996; Fjellanger *et al.*, 1996; Ravnås *et al.*, 2000; Davies *et al.*, 2000; Hampson *et al.*, 2004).

The North Sea Basin is built upon a structural framework of faults and shear zones formed during the Caledonian orogeny and the subsequent extensional collapse of this orogenic belt in the Devonian (e.g. Fossen *et al.*, 2008). The basin was affected by two post-orogenic lithospheric rift episodes, one during the Late Permian–Early Triassic (Beach *et al.*, 1987; Gabrielsen *et al.*, 1990; Færseth *et al.*, 1995a) and one during the

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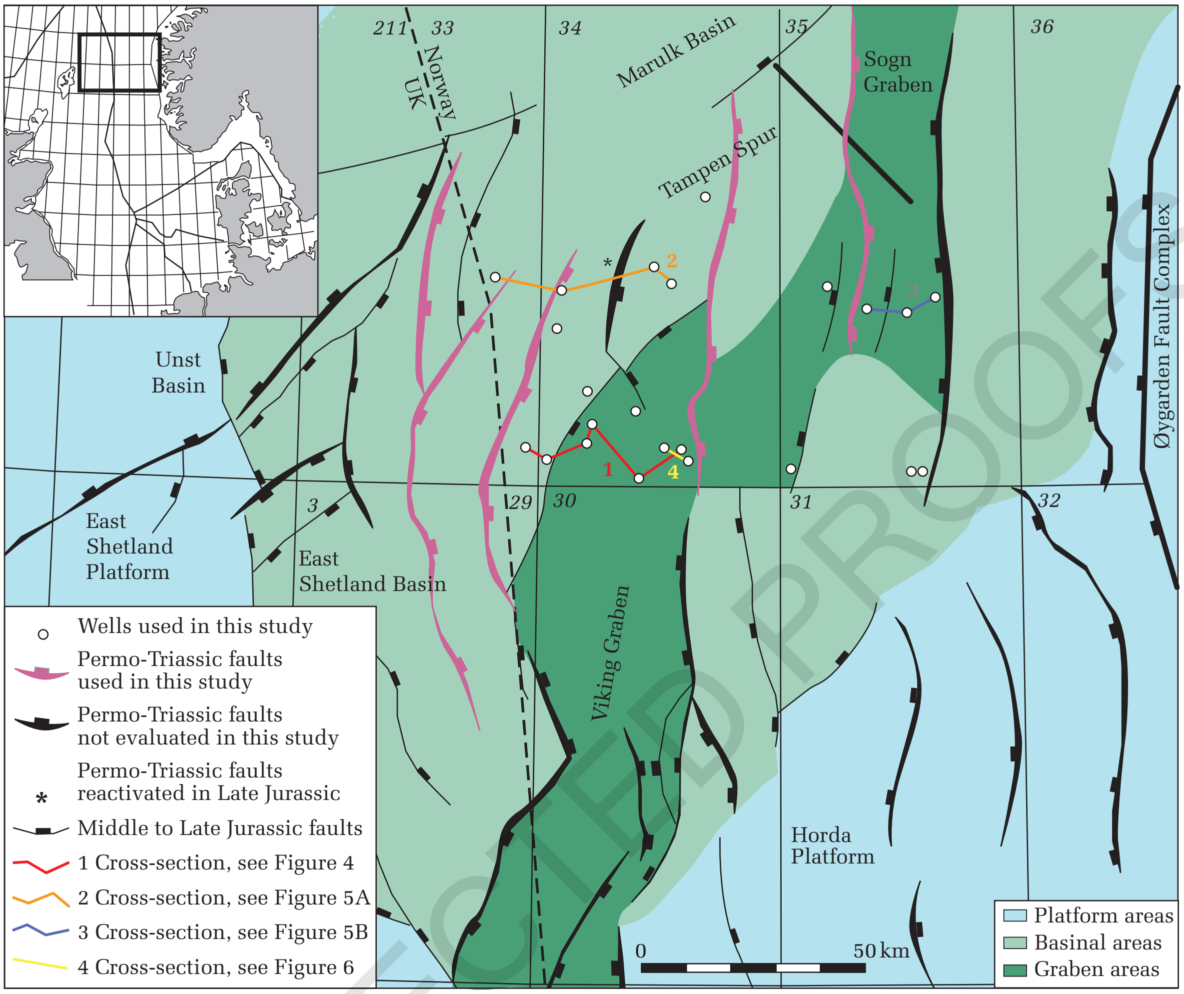

Fig. 1. Main structural elements of the northern North Sea with indication of cross-sections and wells used. Modified from Færseth (1996).

Middle–Late Jurassic (Leeder, 1983; Badley *et al.*, 1988; Rattey & Hayward 1993: Færseth *et al.*, 1997). The details regarding the timing, significance and lateral extent of the Permo–Early Triassic stretching has been a matter of debate for a long time (Giltner 1987; Gabrielsen *et al.*, 1990, Færseth *et al.*, 1995a; Roberts *et al.*, 1995; Færseth, 1996). Large tilted fault-blocks bounded by master-faults with throws of the order of several kilometres formed in a 150 km wide, north–south oriented basin in the Late Palaeozoic. During the thermal subsidence that followed the rifting, faulting occurred on both margins (Steel & Ryseth, 1990) due to the interaction between lateral variations in thermal subsidence, sediment loading, compaction and flexure (Badley *et al.*, 1988).

Precise dating of the initiation of the Jurassic rifting has also been the subject of debate (e.g. Gabrielsen *et al.*, 1990). Evidence of increased subsidence and early fault-block rotation in Bajocian–Bathonian times has led many workers to conclude that rifting was initiated at this time (Badley *et al.*, 1988; Helland-Hansen *et al.*, 1992; Ravnås *et al.*, 1997). Permo–Triassic master-faults were reactivated during the Jurassic rifting and, together with newly-formed Jurassic master-faults, influenced the general structural pattern of the entire basin, promoting segmentation and controlling the subsidence pattern in some areas (Yielding *et al.*, 1992; Færseth, 1996; Odinsen *et al.*, 2000a; Hampson *et al.*, 2004).

The Brent Group (Fig. 2) is the main reservoir unit in the northern North Sea and its development

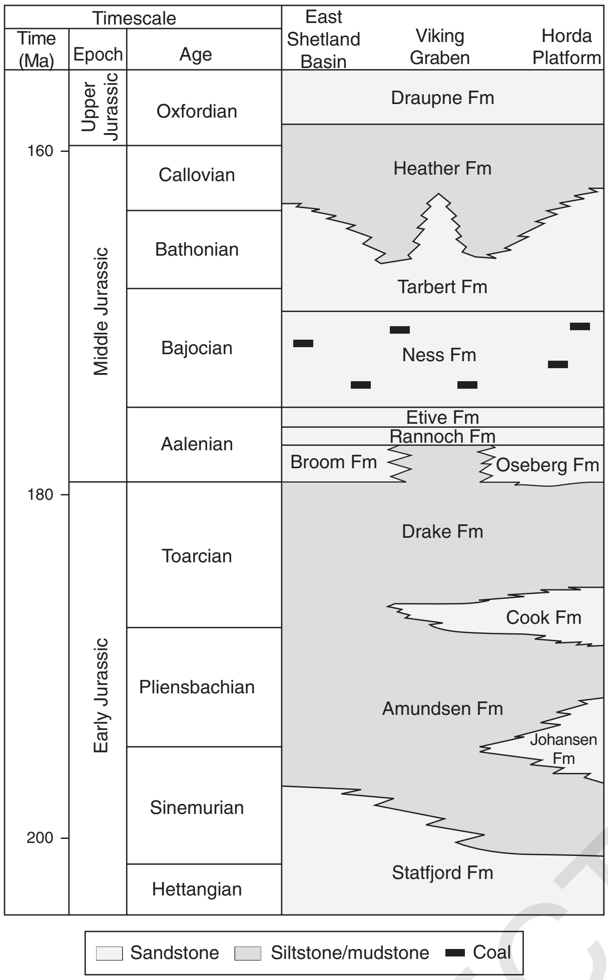

Fig. 2. Stratigraphic column of the Jurassic northern North Sea. Modified from Husmo *et al.* (2003).

is strongly linked to the North Sea dome uplift and to the late pre-rift and early syn-rift tectonic subsidence in the northern North Sea. The 'Brent delta' advanced northward as a consequence of the uplift and erosion of the North Sea dome. It reached as far north as about 62° N, where its advancement was halted by a combination of three factors: (1) increased fault activity and subsidence related to the onset of the Jurassic rift phase (Ravnås *et al.*, 1997); (2) a relative sea-level rise; and (3) exhausted sediment supply due to an over-extended delta front (Helland-Hansen *et al.*, 1992). Several studies have speculated on the exact timing and duration of the Jurassic phase of rifting. Some authors (Jennette & Riley, 1996; Hampson *et al.*, 2004) assigned the rift-phase to the Late Jurassic, which renders the Middle Jurassic Brent Group entirely pre-rift (or post-rift with respect to the preceding Permo–Triassic phase). Others have suggested that rifting started during deposition of the upper Brent Group (Tarbert Formation of Late Bajocian age; Johannessen *et al.*, 1995; Løseth *et al.*, 2009; Davies *et al.*, 2000). A few studies, including Helland-Hansen *et al.* (1992), Fjellanger *et al.* (1996); Færseth (1996) and Ravnås *et al.* (1997) have suggested that syn-rift sedimentation started within the Bajocian Ness Formation (upper) (Fig. 2). Fält *et al.* (1989) pointed to the thick delta plain succession of the Ness Formation as a possible indication of syn-sedimentary fault activity.

As stated by Davies *et al.* (2000), the early phase of Jurassic rifting is poorly understood due to subtle rift-initiation indicators. Importantly, fault activity involved in both the early and main stages of the Jurassic rift phase would have had a pronounced impact on the sedimentary infill style, drainage pattern, facies distribution and shoreline complexity (e.g. Gawthorpe & Leeder, 2000). In order to investigate the initiation of the rifting and the sedimentary response and its potential impact on Brent Group stratigraphy, a framework of generic pre-rift to syn-rift models is presented below.

Conceptual pre-rift to syn-rift models

Nøttvedt *et al.* (1995) emphasized that rift systems are generally described by a three-stage model, where active crustal stretching and faulting (the syn-rift stage) is preceded by a proto-rift (pre-rift; Fig. 3) and followed by a post-rift stage. The proto-rift stage is characterized by gentle basin flexure and minor vertical movements along pre-existing faults (Gabrielsen *et al.* 1990). The post-rift stage is characterized by sediment infilling of the basin topography inherited by the active stretching stage and where minor fault movements may occur along some of the Jurassic master-faults (White & McKenzie, 1988; Nøttvedt *et al.* 1995). The rift stages are described below in more detail.

Generic pre-rift to syn-rift structural models

The Jurassic active stretching evolution of the northern North Sea has generally been described as a three-stage structural model, as summarized below (e.g. Nøttvedt *et al.* 1995; Færseth *et al.*, 1995a; Ravnås *et al.*, 2000):

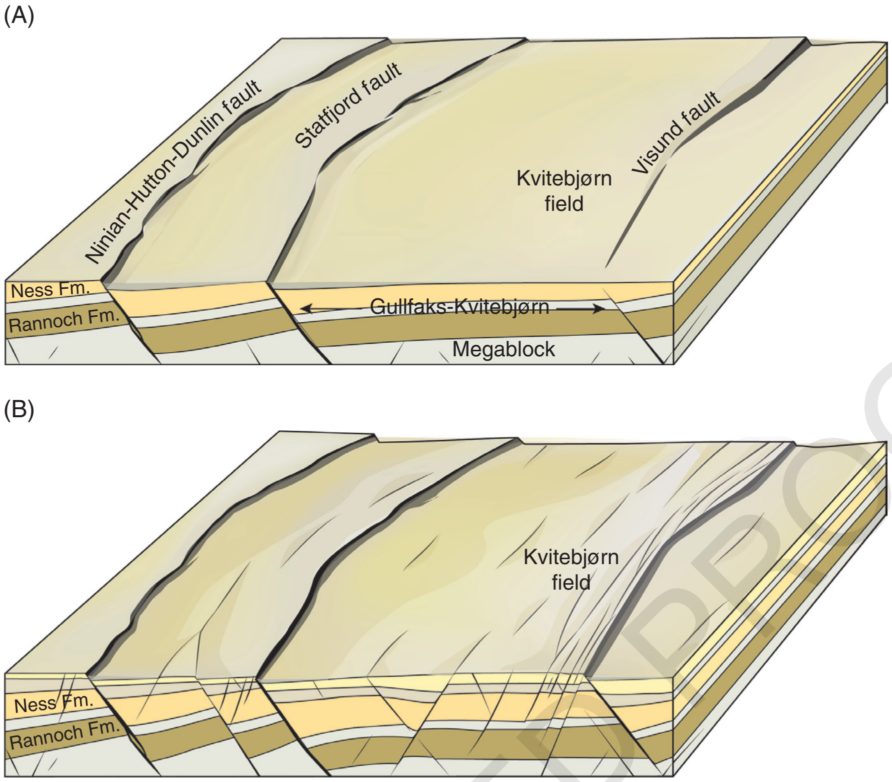

Fig. 3. Fault population and fault linkage trough time during rift development. (A) Pre-rift with Permo–Triassic faults indicated. (B) Initial rift-stage. The isolated small faults of the initial rift are interpreted to be responsible for the local depocentres recorded within the base Ness sandstone.

- Early (initial) rift stage:
  - Initial rift stage is characterized by scattered normal fault population and development of scattered local depressions;
  - Fault propagation with initial fault linkage and early fault death of some of these faults;
  - Initial footwall flexing;
  - Initial fault-block tilting;
- Main rift stage:
  - Transition to rift-climax is correlated with a sharp increase in the rate of basin-wide subsidence early in the rift event (e.g. Steckler *et al.*, 1988). Gupta *et al.* (1998) suggested that the transition from rift-initiation to rift-climax occurs as fault activity became localized onto linked arrays (Fig. 3). With a decline in the number of active faults, rates of fault displacement increase; hence, rate of tectonic subsidence increases;
  - Increasing degree of fault linkage and fault death;
  - Escalating rotation of fault blocks and potential slumping at footwall fault crests;
  - Episodic fault movement leading to variations in tilt rate and accommodation space;
  - Footwall flexing;
- Late rift (or transition to post-rift) stage:
  - Reduced tilt .rates;
  - Submerged fault-block crests;
  - Initial rotation toward the rift axis of the basin.

Generic pre-rift to syn-rift infill models

To identify the different stages within the transition from pre-rift to syn-rift in a sedimentary basin, a set of sedimentary signatures can be recognized within each stage, as outlined by Yielding *et al.* (1992); Prosser (1993); Nøttvedt *et al.* (1995); Ravnås & Steel (1998) Gawthorpe & Leeder (2000); Sharp *et al.* (2000) and Nøttvedt *et al.* (2000):

- Pre-rift stage characterized by tabular/evenly thick stratal units within each fault-block. The thicknesses of these units may vary from block to block due to differential subsidence.
- Proto-rift stage characterized by near-tabular stratal units due to minor fault movements of pre-existing faults.
- Early rift stage showing the following characteristics:
  - Early-stage scattered local depocentres;
  - Asymmetrical stratal units, typically shaped as wedges (downflank) as a response to the fault-block rotation;
  - Potential erosion, starvation or low deposition-rates at footwall crests, due to fault-block rotation and isostasy-driven footwall uplift;
  - At the coast, the hangingwall areas show a high palaeo-shoreline trajectory with an aggradational style, whereas the footwall areas have a low palaeo-shoreline trajectory that reaches farther basinward;
  - Facies and lithological segregation within rotating fault-blocks. The hangingwall area is prone to show transgressive strata, whereas footwall areas are dominated by progradational events;
  - Occurrence of isolated fluvial channels in the hangingwall area due to axial drainage being steered into the subsiding areas;
  - Development of irregular coastline morphology in terms of spit and embayments, due to contrasting/asymmetric subsidence rates along strike as the shoreline of the footwall areas extends further into the basin compared to the shoreline at the hangingwall areas;
- Main rift stage:
  - Enhanced stratal thickness development in hangingwall and stratal wedge-shaped units toward the footwall crest;
  - Development of footwall islands with erosion of elevated areas;
  - Flooding of fault-blocks and landward retreat of shoreline;
- Late rift (or transition to post-rift) stage:
  - Passive infill with parallel build-up and onlap strata;

The aim of the study

The purpose of this paper is to describe and interpret the stratal architecture of the Jurassic packages and depositional environment variability within the Brent Group with regard to the generic pre-rift to syn-rift structural and infill models, as listed above. This has been achieved by examination of four east–west profiles (Fig. 1), using a combination of seismic, biostratigraphic and well data. We discuss how the early stage of rifting can be interpreted from the sedimentological response to fault population and their influence on coastal morphology.

GEOLOGICAL SETTING AND BASIN HISTORY

Following the Permo–Triassic rift phase, the Early Jurassic northern North Sea experienced thermal subsidence along the inherited rift topography (Gabrielsen *et al.*, 1990; Odinsen *et al.*, 2000a, b). This subsidence led to the transgression (north-directed) of the fluvial-dominated Statfjord Formation and a north–south seaway was established through the Viking Graben at approximately Sinemurian time (Steel, 1993). The lower part of the Dunlin Group (Sinemurian–Pliensbachian) encompasses the Amundsen and Burton formations, which consist of shales and siltstones (Vollset & Doré, 1984) deposited in a shelfal setting (Husmo *et al.*, 2003). The shallow marine Cook Formation built out into this seaway from the Norwegian mainland during Pliensbachian time, in response to basin margin uplift and erosion (Charnock *et al.*, 2001; Folkestad *et al.*, 2012). Subsidence continued in the northern North Sea, as the Cook Formation was draped by offshore mudstones of the Drake Formation. The overall thickness distribution of the Lower Jurassic Statfjord Formation and the Dunlin Group suggests that the future Viking Graben was built on a broader, possibly asymmetric basin (Færseth & Ravnås, 1998); a basin configuration inherited from the Permo–Triassic stretching phase (Færseth, 1996).

The Oseberg and Broom formations have traditionally been included in the Brent Group but they are not genetically linked to the other formations of the group (Steel, 1993). The Broom and the time-equivalent Oseberg formations (Aalenian) represent coarse-grained fan deltas that prograded into the basin from the uplifted margins of the Viking Graben and are restricted to the western (Broom Formation) and eastern

(Oseberg Formation) basin margins due to basin-margin uplift (Ziegler, 1982; Underhill & Partington, 1994). In Aalenian time, the thermal uplift of the 'Mid North Sea Dome' created a regional high at the triple junction between Viking Graben, Moray Firth and Central Graben (Underhill & Partington, 1993; Fjellanger *et al.*, 1996). This elevated area was subjected to erosion and shed sediments into the adjacent basins. As a result, the 'Brent delta' prograded northward over a time-span of only 2 million years (Helland-Hansen *et al.*, 1992) with a pinch-out of the delta at about 62° N (Mjøs, 2009). This axial, southerly-derived sediment input is illustrated by the coastal plain and delta top depositional environment passing into shallow-marine sandstones in the north (Husmo *et al.*, 2003). Additional sediment supply for the 'Brent delta' came from the uplifted flanks on the margins of the northern North Sea basin (Helland-Hansen *et al.*, 1992; Steel, 1993; Johannessen, *et al.*, 1995; Fjellanger *et al.*, 1996).

The Middle Jurassic northern North Sea basin was a ramp basin without shelf-edge topography, flanked by the Hordaland and Shetland platforms (Fjellanger *et al.*, 1996) and with the Møre Basin (Dorè, 1991; Gabrielsen, 1999) to the north. The Møre Basin had probably started to subside at this time (Brekke, 2000) and that promoted wave-currents which affected the Brent Group. Such a ramp basin promoted very low-gradient clinoforms and was partly the reason for the rapid northward deltaic progradation (Helland-Hansen *et al.*, 1992). In the Tampen area, the lateral thickness distribution of the prograding part appears uniform due to high sedimentation rates, onlaps and thins above the Broom and Oseberg formations in the platform areas (Helland-Hansen *et al.*, 1992; Johannessen *et al.*, 1995; Fjellanger *et al.*, 1996; see Fig. 1). The 'Brent delta' reached its regressive maximum in the northern part of the Tampen Spur area in the Early Bajocian (Helland-Hansen *et al.*, 1992; Løseth *et al.*, 2009).

The progradational part of the 'Brent delta' consists of the Rannoch, Etive and lower Ness formations (see Table 1 for detailed facies interpretations). The Rannoch Formation forms a wave-reworked lower delta front environment overlying and interfingering with the offshore mudstones of the Drake Formation. The overlying Etive Formation represents an upper delta front with shoreface and mouth-bar successions. The Ness Formation constitutes a delta top environment, with coal layers and mudstones in the lower part, followed by fluvial channel, bay-head delta and mouth-bar deposits. At the time of maximum extension, the stacking style of the 'Brent delta' changed from progradational to aggradational, due to eustatic sea-level rise and increased tectonic activity (Helland-Hansen *et al.*, 1992; Johannessen *et al.*, 1995).

The aggradational shoreline trajectory (see Helland-Hansen & Gjelberg, 1994) changed to retrogradational during transgression, resulting in the retreat of the delta plain of the Ness Formation and the formation of shoreface and embayment environments (estuaries, bay and barrier; see Table 1 for detailed facies interpretations) of the Tarbert Formation. The Tarbert and Ness formations retreated southwards along the Viking Graben in an offset backstepping manner (Helland-Hansen *et al.*, 1992, Johannessen *et al.*, 1995; Fjellanger *et al.*, 1996; Ravnås *et al.*, 1997). South of 60°N, the delta front and delta top deposits are named the Hugin and Sleipner formations, respectively (Fält *et al.*, 1989). The Tarbert and Hugin formations are draped by, and interfinger with, the offshore mudstones of the Heather Formation, which is then capped by the organic-rich shales of the Draupne Formation (Kyrkjebø *et al.*, 2001; Kjennerud *et al.*, 2001).

Several studies have pointed out that fault-block rotation started in the Bajocian (Helland-Hansen *et al.*, 1992, Johannessen *et al.*, 1995; Fjellanger *et al.*, 1996; Ravnås *et al.*, 1997) but increased fault-related subsidence may have started earlier, during Late Aalenian–Early Bajocian in parts of the wide, asymmetrical basin. This is probably best seen as an increase in thickness per time unit of the lower Brent Group, compared to the underlying Dunlin Group (Steel, 1993; Færseth & Ravnås, 1998). This tectonic activity and fault-block rotation accelerated through the Middle Jurassic with the development of footwall islands and submerged half grabens in Bathonian (Ravnås *et al.*, 1997), until maximum strain rates were achieved in the Late Jurassic (Yelding *et al.*, 1992). Primarily N–S striking faults controlled the basin geometry in the Middle Jurassic and it is suggested that the Viking Graben retained the asymmetry inherited from the Permo–Triassic block tilting until faults with a more NE–SW orientation became active in the Late Jurassic (Færseth *et al.*, 1997; Færseth and Ravnås, 1998; Gabrielsen *et al.*, 2001).

Table 1. Facies associations of the Rannoch, Etive, Ness and Tarbert formations within the study area: description and interpretation of the facies associations.

Formation	Description	Interpretation	Comments
Tarbert Fm	Coarsening upward units (2 to 7 m) from mudstones to fine-grained sandstones with micro-hummocks, wave and current ripples, planar lamination, trough cross-bedding, lenticular-bedding and flaser -bedding capped by palaeosols. Bioturbation, syneresis cracks and coal clasts occur.	These units are probably bay-head deltas building into bays or lagoons.	See Figs 9A and 12B,C.
	Fining-upward units from medium to very-fine grained sandstones with cross-bedding, sharp/erosive bases, current ripples and coal-clasts.	Crevasse splays.	See Figs 9B and 12D.
	Well-sorted and planar laminated units of fine-grained sandstones generally with bioturbation, wave and current ripples.	Back barrier deposits and washover fans.	See Figs 9A, 12C.
	Up to 20 m-thick units of medium-grained to coarse-grained sandstones with erosive lower boundary and cross-bedding with even-spaced mud or organic drapes.	Channel complex with fluvial and tidal interaction in an estuarine setting.	See Fig. 12B. Also recorded by Davies *et al.*, (2000) in block 34/7.
	Medium to very fine-grained sandstones constitute the upper part of the Tarbert Formation with trough cross-stratification, high and low-angle lamination, swaley cross-bedding, wave and current ripples (Fig. 3A).	Beach barrier complex with shoreface at the top.	See Figs 9A and 12A,D.
Ness Fm	Interbedded coal-layers and mudstones (Fig. 4D) with minor amounts of thin silt and very fine-grained sandstones with root-horizons.	Delta plain with overbank deposits and stagnant swamp forming coals-beds.	See Figs 9A,B,C and 12B,C.
	Coarse to fine grained sandstones, 1 to 5 m-thick fining upward units with erosive or sharp-based, cross-bedding and current ripples.	Fluvial channels.	See Figs 9A,C and 12C.
	1 to 8 m-thick siltstones coarsening-upward to fine-grained sandstones with wave ripples, syneresis cracks, mud-drapes, micro-hummocks and laminated beds capped by palaeosols.	Bay head deltas.	See Figs 9A and 12B.
	Tens of metres (~20 to 40 m) of medium to fine-grained (bimodal) cross-bedded sandstones, mud-drapes (Fig. 4J) and sporadically bioturbation.	Stacked tidal dune deposits in an estuarine setting.	See Figs 9A, C. See also Mjøs (2009) who has similar interpretation of the depositional environment.
Etive Fm	Moderate sorted medium sandstones (coarse to fine) with massive, cross-bedded and planar-laminated units with some coal-clasts and mud-clasts. Sharp or erosive bases, stacked in a general fining-upward trend. Palaeosols are common at the top of these sandstones.	Mouthbars to wave-reworked mouthbars.	See Figs 9A,C and 12D.
Rannoch Fm	Very fine-grained to fine-grained and well-sorted sandstones with horizontal, low-angle lamination, hummocky and swaley cross bedding, wave ripples. Some muddrapes and stylolites.	Shoreface environment in a delta front setting.	See Figs 9A, C and 12D.
	Alternating mudstones, siltstones and very-fine grained sandstones with lenticular and flaser bedding, horizontal lamination, micro-hummocks, wave and current ripples, muddrapes, syneresis-cracks, coal-fragments and clasts. Abundant *Botryococcus* (Batten & Grenfell, 1996).	Pro-delta deposits. The occurrence of abundant *Botryococcus*, syneresis cracks, current ripples and coal-material indicates strong fresh water influx. The bioturbation, wave-ripples and micro-hummocks indicates marine influence. The muddrapes indicated tidal influence.	Fig. 12A, (well 35/4-1) show this facies as a 90 m-thick aggrading unit. Palynological data indicate that the lower part was deposited under freshwater condition that became progressively more brackish in the upper part.

DATABASE AND METHODOLOGY

Well data

This study from the Gullfaks–Kvitebjørn area in the central parts of the Northern Viking Graben is based on 31 wells with wireline logs from blocks 33/12; 34/7, 8, 10, 11; 35/4, 10, 11 (Fig. 1). Slabbed core material (2875 m) of the Brent Group has been examined in terms of grain size, internal sedimentary structures and bioturbation and interpreted in terms of depositional environment as identified from wireline logs. Palynological data from consultant biostratigraphic reports has been re-analysed to provide a chronostratigraphic framework for the evolution of the basin and to provide palaeoenvironmental support for the sedimentological interpretations.

Timelines

Unlike in fully-marine shelf environments, where high diversities and the continued basinward transport of well-mixed dinoflagellate cyst assemblages result, characteristically, in the relatively uniform distribution of marker taxa, care must be taken in marginal marine areas, where changing environmental conditions play a more significant role in the distribution of key taxa. The palynological assemblages from the studied wells are dominated by spores and pollen throughout, indicating a clear proximity to land but the presence of a generally moderate to high diversity of dinoflagellate cysts in the Bathonian interval (that broadly includes the lower Heather and upper Tarbert formations), which suggests relatively normal marine conditions. As a result, confidence is relatively high that the uppermost occurrence of biostratigraphically significant dinocyst species in the studied wells represents predictably correlateable stratigraphic events (e.g. their last regional occurrence/extinction); and industry-standard palynological markers for the Upper and Lower Bathonian can be used to pick these horizons.

Despite the marked evolutionary radiation of dinocysts known to occur through the preceding Bajocian, the number of dinocyst taxa in the studied wells from the Bajocian sections is generally much lower than expected, suggesting a significantly more stressed, marginal marine environment than during the Bathonian. Although confidence is inherently reduced due to a reduction in number of marker taxa, picks for the Late and Early Bajocian are almost consistently picked on distribution characteristics of the dinoflagellate cyst *Nannoceratopsis gracilis* and/or *N. deflandrei senex* (hereafter *Nannoceratopsis gracilis*/*senex*). Species of *Nannoceratopsis* are considered to have been derived from dinoflagellates that were well-adapted to euryhaline conditions (Riding, 1983, 2006) and particularly to marginal marine (and even estuarine) settings. As a result, it is reasonable to assume that the presence of *Nannoceratopsis gracilis*/*senex* is correlateable in time across the study area since they tolerate a wide salinity range and are palaeo-environmentally *in situ*. In other words, basing stratigraphic events on the distribution of species that are derived from a more offshore setting will clearly result in correlations with a palaeoenvironmental overprint driven by sea-level change.

The highest stratigraphic occurrence of *Nannoceratopsis gracilis*/*senex* is used to place the position if the Bajocian/Bathonian boundary, whilst the highest consistent occurrence (or significant increase) in the relative number of these taxa is traditionally employed as a marker for the end of the Early Bajocian. Occasionally, where *Nannoceratopsis gracilis*/*senex* are particularly sporadic, the first down-hole occurrence of *Evansia granulata*, down-hole occurrence of common *Batiacasphaera* spp (including *B. rudis*) and the last down-hole occurrence of common *Dissiliodinium willei* were used in conjunction with *Nannoceratopsis gracilis*/*senex* to pick the Bajocian/Bathonian boundary.

The significant increase in relative abundance of *Nannoceratopsis gracilis*/*senex* (as a common to abundant constituent of the marine assemblage) is used to position the Aalenian/Bajocian boundary. Although the placement of this boundary is beyond the scope of the present study, this relative abundance characteristic serves to highlight the principle that a significant increase in number or bloom of a species with respect to the background assemblage, is characteristic of an adaptation to stressful environments (e.g. low salinity), further increasing confidence in the biostratigraphic use of *Nannoceratopsis* in deltaic palaeoenvironments of the Brent Group.

Palynological sample density is generally high throughout the Bajocian and Bathonian, typically much better than one sample per ten metres. Much of the Bajocian sections were cored and sample spacing is often on the sub-metre scale, indicating that biostratigraphic precision is potentially high. Over uncored sections, where the majority of

Table 2. Stratigraphic thicknesses of the different formations seen in wells 33/12-6 and 35/11-A-15 in Fig. 4: depth of top formation (TVD = true vertical depth), thicknesses (m Ma^{-1}), thickness-expansion rates (E-W incr.) and time span of formation.

W					E	
33/12-6					34/11-A-15	
Formation	Top TVDm	Thickness (m)	E-W incr	~Million years	Top TVDm	Thickness (m)
Heather	2645	295 (29.5 m per my)	37x	10	3970	8 (0.8 m per my)
Ness-Tarbert	2940	250 (50 m per my)	3.5x	5	3978	72 (14.5 m per my)
Rannoch-Etive	3190	65 (26 m per my)	1.2x	2.5	4050	55 (22 m per my)
Drake	3255	115 (10.5 m per my)	1.9x	11	4105	60 (5.5 m per my)
Cook	3370	100 (33 m per my)	1.3x	3	4165	75 (25 m per my)
Amundsen-Burton	3470	220 (36.6 m per my)	1.2x	6	4240	185 (30.8 m per my)
Statfjord	3690				4240	

Million years estimates from Husmo *et al*. (2003).

biostratigraphic samples were derived from cuttings, stratigraphic tops are favoured over bases, due to the inherent problem of caving.

Seismic data

The three reprocessed 3D seismic surveys ST11M12, ST11M07 and ST09M01 (Figs 4 and 6) have been used for reflection seismic interpretation. They are partly overlapping and have a total areal extent of ~1730 km^2, with a 585 km^2. In-line direction is east–west with a line spacing of 12.5 m and cross-line direction is north–south with a line-spacing of 25 m. The vertical seismic resolution (reflection separation) is depth-dependent and varies throughout the area from ~25 ms Two-Way-Time to ~50 ms TWT at a depth of 3500 ms TWT. Lateral resolution is dependent on line-spacing and depth and would typically be 200 m to 300 m at 3500 ms TWT.

The seismic lines have not been depth-converted since they are used to show relative lateral thickness variations of the sedimentary strata (see also Table 2 for thickness-variations of the formations). However, velocity well data have been utilized for both time and depth migration of the seismic surveys and show that the velocity field is generally uniform laterally for regional (km-scale) interpretation or depth conversion purposes. Hence, the thickness variations in time reflect true stratigraphic thickness variations. Time-to-depth relationships are derived from well data and show that the equivalent true vertical depth (TVD) at 3500 ms TWT is approximately 4000 metres.

Interpretation of the seismic data was based on correlation with the well data. Chronostratigraphically significant and lithostratigraphically significant surfaces identified from the interpretation of core samples, electrical logs and biostratigraphic information were tied to the seismic volumes using velocity log data.

PRE-RIFT TO SYN-RIFT SIGNATURES

Geological cross-section across the Gullfaks–Kvitebjørn area

Fig. 4 shows a regional geological cross section that runs from the Kvitebjørn Field via the Valemon Field and across the southern part of the Gullfaks Field toward the Statfjord Field (Fig. 1, cross-section 1). The wells along this correlation have a complete section of the Jurassic stratal package. Fig. 4 shows the east–west stratal thickness trends for the Dunlin, Brent and Viking groups. The Dunlin Group shows a tendency to thicken westward with a gentle (~1.3 times, see Table 2) thickness increase. The Brent Group shows a more pronounced (~2 times) westward increase in thickness towards a Permo–Triassic master-fault (See Fig. 1) but with significant internal variations. The Rannoch and Etive formations have a near tabular thickness distribution, whereas the Ness and Tarbert formations together show clearer wedge-shaped geometries that involves a pronounced (~3.5 times; Table 2) westward thickness increase. Internally, the sedimentary architecture of the lower Ness–Tarbert formations show near tabular strata while the upper part show a gradual angular variation upward in the form of westward bed expansion. An apparently isolated and several tens of metres thick sandstone unit occurs locally at the base of Ness Formation (see well 34/10-23 in Fig. 4).

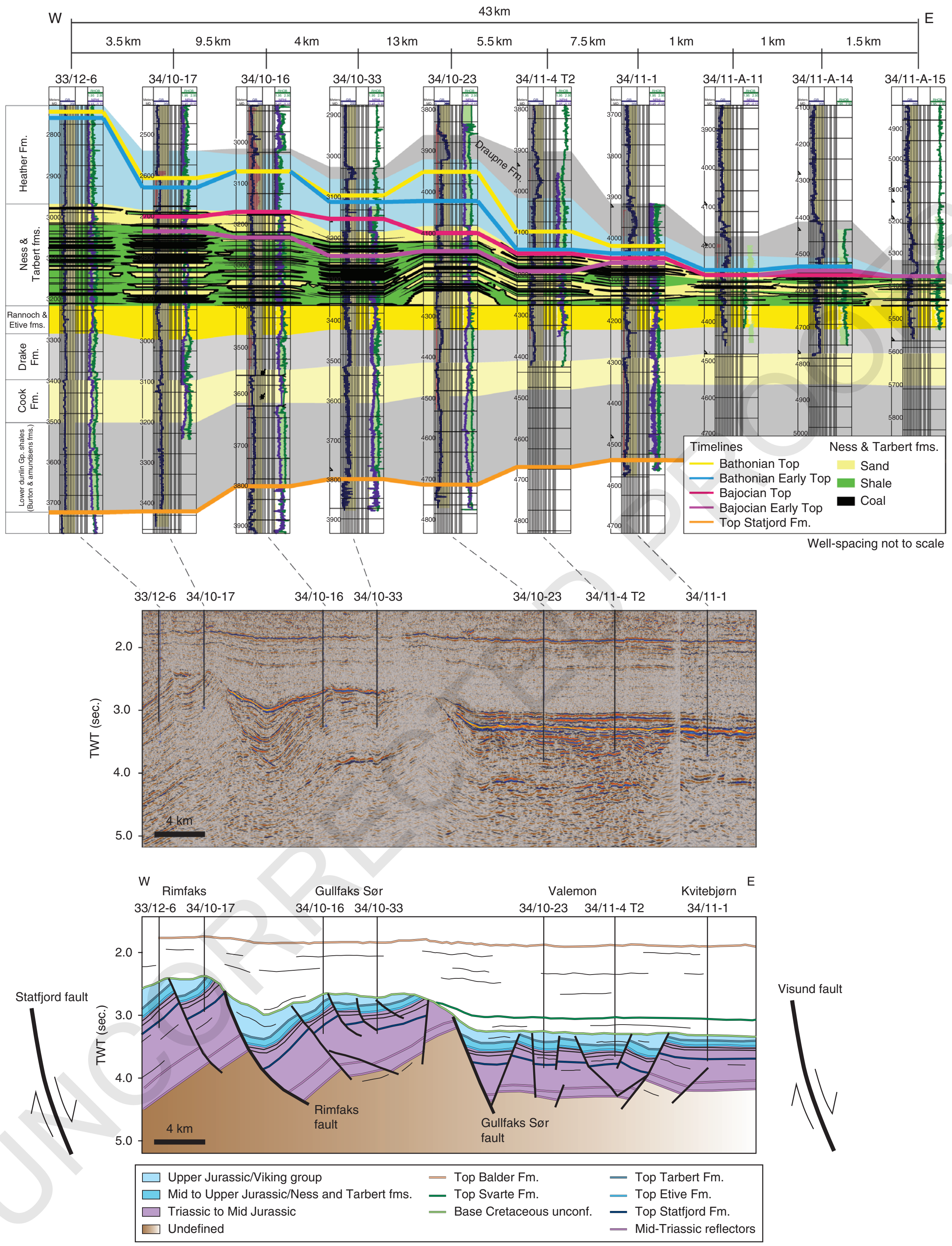

Fig. 4. A regional east-west cross-section of the Jurassic succession from the top Statfjord Formation (orange surface at the base) of the Tampen area (Gullfaks-Kvitebjørn); see Fig. 1 for location. The seismic section (in time) shows fault and horizon interpretation (lower) with well tie. The section displays the general Triassic-Jurassic thinning from west to east. An apparently isolated and several tens of metres thick sandstone unit occurs at the base of the Ness Formation (see well 34/10-23).

In terms of net-to-gross ratio (sand content *vs.* shale content) within the Ness-Tarbert formations, the western part shows lower ratios with low sand-connectivity and thicker and more abundant coal layers. In the eastern part of the well correlation panel (Fig. 4), there is a higher net-to-gross ratio with only a few thin coal layers. In the overlying Viking Group, the Heather Formation shows a pronounced (37 times) westward thickness increase (Table 2), whereas the Draupne Formation portrays a more irregular thickness distribution.

The seismic cross-section (Fig. 4) is tied to formation-picks in the wells. The quality of the seismic resolution at this depth is not sufficient to replicate the thickness trends within the Brent Group directly, as seen in the wells. However, a general westward-thickening trend of the combined Triassic and Jurassic package is seen on the seismic cross-section, with the wedge-shaped unit of the Late Jurassic syn-rift strata being the most obvious. Three major fault-blocks are seen in the seismic cross-section, which progressively steps down eastward, i.e. into the northern Viking Graben. The western Rimfaks fault-block is the shallowest and the Kvitebjørn fault-block to the east is the deepest. The smaller normal faults are predominately limited to the Jurassic or older strata and tend to terminate within the Upper Jurassic syn-rift strata. Only a few of these are seen to offset the Base Cretaceous.

Fig. 5 shows two well correlations across Permo–Triassic faults (according to Færseth,

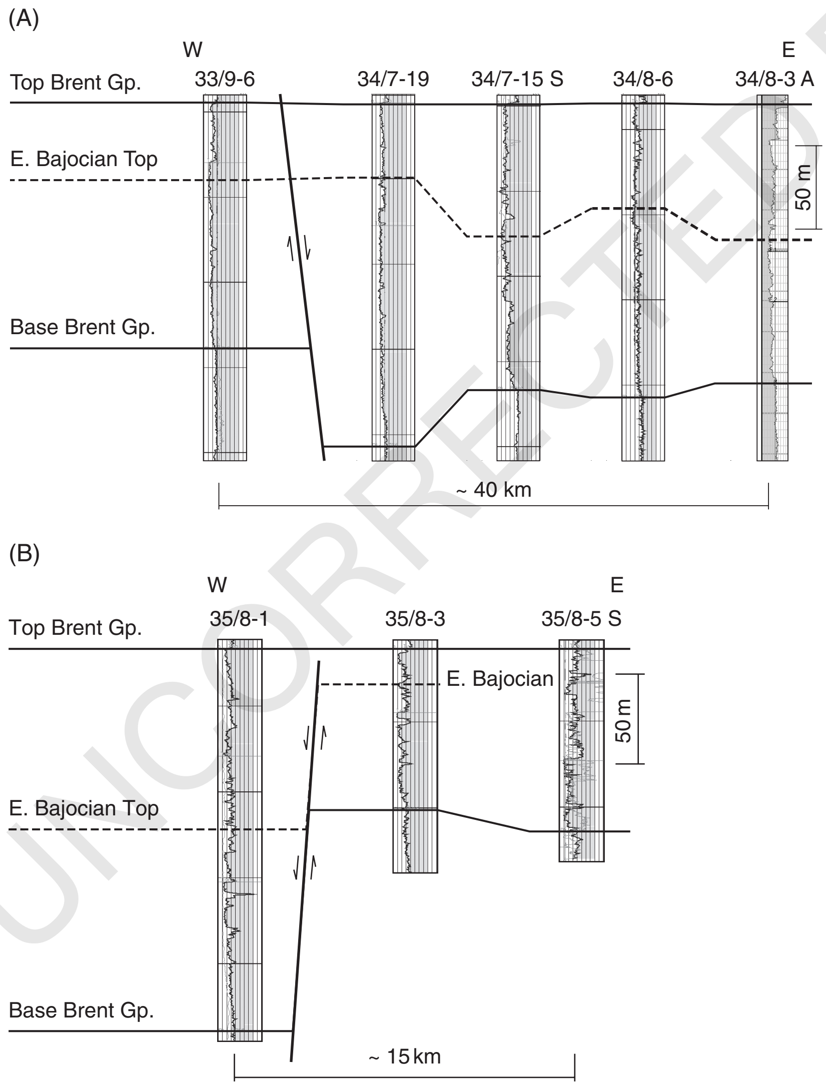

Fig. 5. (A) West-east well correlation across the Visund (34/8), Snorre (34/7) and the Statfjord Field (33/9), showing westward thickening of the Brent Group toward the Statfjord fault. (B) West-east well correlation across the Vega Field (35/8) showing increased Brent Group thickness across a Jurassic fault (see Fig. 1).

1996) in the western and eastern part of the North Viking Graben (Fig. 1). Both correlations show marked thickening of the Brent Group into the hangingwall of the Permo–Triassic faults. The same thickness variation is observed in the well-correlation in Fig. 4 between two deep-rooted Permo–Triassic faults (the Statfjord Fault in the west and the Visund Fault to the east. These faults are identified as Permo–Triassic faults by Færseth *et al.* (1996; see also Fig. 1) and define Permo–Triassic fault-blocks (mega-blocks) with widths of up to about 50 km (Færseth, 1996, fig. 2). Although the seismic data has limited resolution, it shows in combination with well data that this extensive fault-block, the Gullfaks–Kvitebjørn/Snorre-Visund mega-block (Figs 1 and 3) experienced block-rotation throughout Jurassic time. The displacement of the Statfjord Fault during the Jurassic seems to be of the same order as the movement of the Ninian-Hutton-Dunlin Fault reported by Hampson *et al.* (2004) in the same time-interval. Thus, it appears that these deep-rooted faults were active during the Jurassic. The well correlations in Figs 4 and 5 indicate similar marked thickness differences of the Brent Group across these Permo–Triassic faults. In summary, these observations suggest that the Permo–Triassic faults had a significant impact on the Brent Group in terms of subsidence and facies variation in the North Viking Graben. This interpretation is in agreement with observations made by several previous authors (Fält *et al.*, 1989; Fjellanger *et al.*, 1996; Ravnås *et al.*, 1997) and will be discussed further in the sections below.

On a finer scale, the basal Dunlin Group show a slightly westward thickness increase, which is probably due to minor movement of the Statfjord Fault during the Early Jurassic (Table 2). The slight wedge shape of this unit is negligible considering the timespan of this unit, rendering it as near-tabular. Therefore, a general proto-rift stage is interpreted for this unit. The Rannoch and Etive formations of the basal Brent Group are also near-tabular, which assigns them to the proto-rift stage. The Ness-Tarbert formations (~5 Myr; Table 2) form a pronounced east–west stratal wedge-shaped unit, which suggests that this interval was deposited during an interval with increased rates of rotational faulting. The transition from the proto-rift to an early syn-rift stage is therefore placed within the lower Ness Formation. The overlying wedge-shaped Heather Formation (~10 Myr; Table 2) shows a dramatic thickness expansion in the western part and this formation, together with the bulk of the Draupne Formation, represents the main stage of rifting with high rotation rates (Færseth *et al.*, 1995b; Færseth & Ravnås, 1998). The timelines in Fig. 4 suggest that the western part was transgressed earlier by the Heather Formation than the eastern part of the cross-section.

The exact timing of rift-initiation is difficult to constrain from the stratal architecture since early syn-rift beds would be near-tabular to slightly wedge-shaped. However, the thick (30 m) isolated sandstone unit at the basal Ness Formation in Fig. 4 (Well 34/10-23) may represent a local depocentre formed during rift-initiation as outlined above. This feature will be treated in more detail below.

The east–west lithological distribution of the Ness–Tarbert formations in Fig. 4 suggests low net-to-gross ratios towards the hangingwall area (western part) as compared to the area towards footwall (eastern part). This difference can be explained by increased rate of accommodation space generation and resulting in preferential preservation of strata in the western part through the trapping of river-supplied sediments such as sands and muds, resulting in isolated sandstone units (channels) and common formation of swamps (coal layers). In contrast, the eastern part shows higher net-to-gross ratios with significantly fewer coal layers and shale units, indicating lower rates of accommodation creation. Such a difference in net-to-gross as observed in the east–west lithological distribution of the Ness-Tarbert formations is another indication that rifting created variable accommodation space. An alternative interpretation for these east–west trends of net-to-gross ratio can be explained by differential compaction along the transect (Fig. 4). This would imply significant sea-bed topography prior to deposition of the Brent Group. The near tabular nature of Rannoch and Etive Formations supports the first interpretation.

Geological cross-section across the Kvitebjørn Field

The Early–Middle Jurassic geological evolution of the Kvitebjørn area is illustrated in Fig. 6 with the Rannoch, Etive, Ness and Tarbert formations with wells tied to the seismic cross-section. The Cook, Drake, Rannoch and Etive formations show a tabular thickness distribution whereas the Ness and

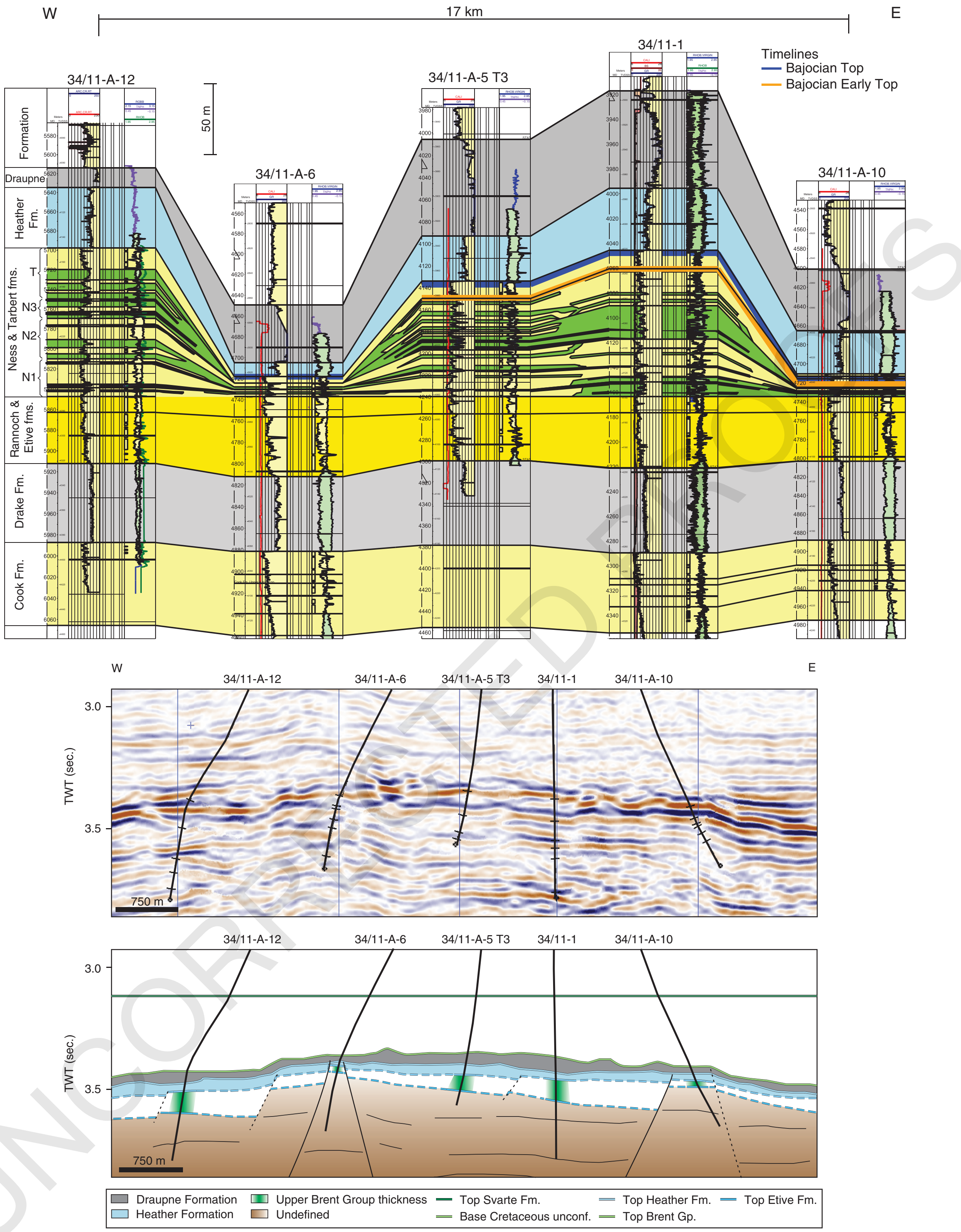

Fig. 6. East-west cross section of the Kvitebjørn Field, showing the Cook and Drake formations and the Brent and the Viking groups. See Fig. 4 for a colour legend for the well-correlation. The seismic cross-section is shown in time with interpretation based on stratigraphic well picks. The interpretation at the bottom shows fault-delimited thickness variations of the Ness and Tarbert formations across the field. Green-coloured intervals are well-defined Ness-Tarbert formation thicknesses, whereas the white intervals are interpreted thicknesses with uncertainties. Note the termination of faults in the Heather Formation (Upper Jurassic).

Tarbert formations show overall wedge-shaped stratal geometry from a very thin condensed section in well 34/11-A-6 through a thicker section in well 34/11-A5-T3, to an even thicker section in well 34/11-1. Internally, the beds in this package show a near-tabular appearance in the lower part with a more pronounced wedge-shaped geometry up-section. Further eastward, a dramatic reduction in thickness is observed from well 34/11-1 to a very condensed sequence in 34/11-A-10. This is associated with a westward-throwing normal fault (see the lower cross-section of Fig. 6) located between the two wells. Well 34/11-A-12 in the western part of the cross-section, shows another expanded thickness of the Ness and Tarbert formations, similar to well 34/11-1. In the wells 34/11-A-6 and 34/11-A-10, located in the footwalls, the combined chronostratigraphic and lithostratigraphic correlations and log-patterns show stacked thinly-bedded sandstones and mudstones with streaks of coal layers. In contrast, this suggests that these thinly-bedded Ness and Tarbert formations are condensed versions of the section found in the other wells (see Fig. 6). The Heather Formation shows a similar wedge-shaped stratal unit to the Ness and Tarbert formations in the same wells.

The tabular nature of the Cook, Drake, Rannoch and Etive formations (Fig. 6) is consistent with a pre-rift stage. The observed stratal wedge geometry of the Ness and Tarbert formations suggests that this unit represents the early-rift stage, possibly entering the main-rift stage as the internal stratal wedge architecture show a gradual angular variation up-section (Fig. 7; note the similarity to the wedge-shaped Ness-Tarbert unit in Fig. 4). The complex stratigraphic development of the Ness and Tarbert formations in the Kvitebjørn Field can be put into a more regional context, as this area is located at the footwall crest of the Kvitebjørn–Gullfaks Permo–Triassic mega-block (Figs 1 and 4). The westerly dipping faults, indicated in Fig. 7 with the stratal wedge in between, are antithetic when seen in relation to the deep-rooted Statfjord Fault (Figs 1 and 4). This complexity may be associated with footwall flexure at the location of the Kvitebjørn Field.

To explain the limited thickness of the Ness and Tarbert formations in the two wells in terms of erosion (or faulted out section) would also imply erosion in the nearby wells in order to create the observed stratal wedge shape. Such an interpretation seems unlikely, as it challenges the log-signatures and the biostratigraphic timelines. More importantly, it is contradicted by the wedge-shaped geometry of individual members of the Ness and Tarbert formations. Moreover, it seems unlikely that a scenario of faulted-out section would apply to all wells with anomalous Ness–Tarbert thicknesses.

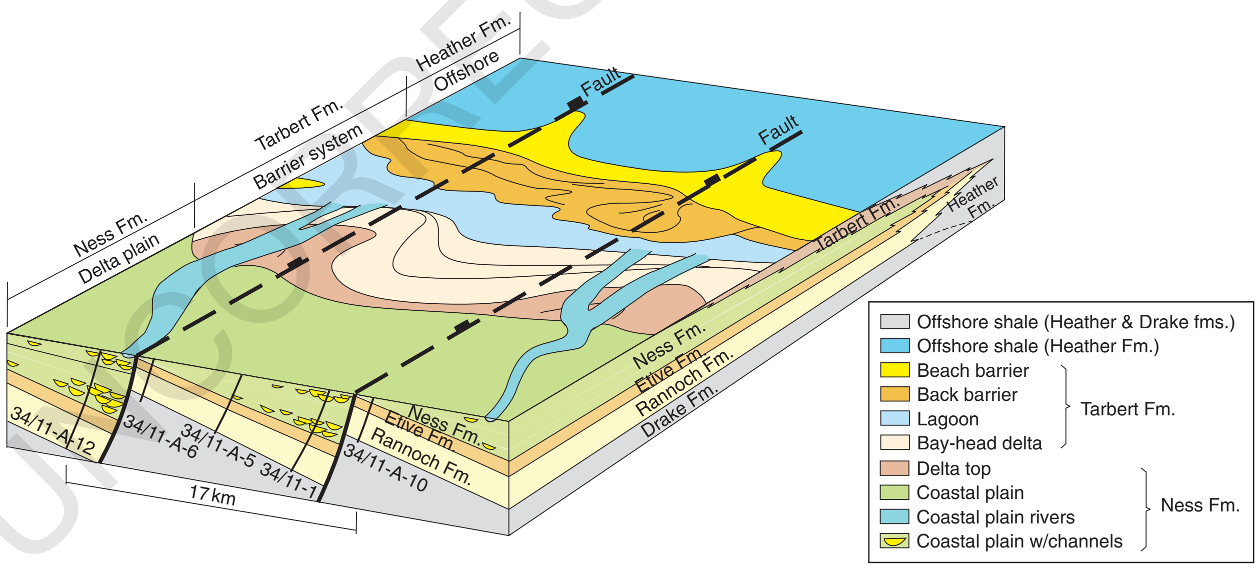

Fig. 7. Schematic 3D illustration of the Brent Group on the Kvitebjørn Field. Syn-sedimentary tectonic development, producing a wedge-shaped geometry for the Ness-Tarbert package across the Kvitebjørn Field contrasts the tabular Rannoch-Etive formations (below) and is taken to reflect early-stage rifting. The coastline undulations are largely formed by the fault crests (see Fig. 11).

Local depocentres

The stacked (tens of metres thick) sandstones at the basal Ness Formation in 34/10-23 (Fig. 4), are conspicuously anomalous in the correlation panel. Similar stacked sandstones at the basal Ness Formation are seen in several other wells (Figs 8, 9 and 10). These sand-units are geographically isolated and are not observed in the surrounding wells (see Fig. 8). Where these sand-units are cored (Fig. 9A and C), they display cross-bedding with mudstone-drapes. Dipmeter data for such a unit in 34/11-A-15, Fig. 10D) show landward-directed palaeo-currents (i.e. to the south). Palynomorphs are continuously recorded in all samples, particularly spores and pollen; however, marine palynomorphs including the dinoflagellate cyst *Nannoceratopsis gracilis* and sphaeromorphs acritarchs are sporadically present indicating episodic marine incursions. These sandstones are interpreted as stacked tidal dunes (see also Mjøs, 2009 with regard to 35/11-7, Fig. 9C), forming thick aggrading units in a nearshore position (above the Etive Formation) displaying similarities to estuarine depositional environments (e.g. Dalrymple & Choi, 2007). The interval from 35/11-7 is dominated by spores and pollen and, although no *in situ* dinoflagellate cysts have been observed, it contains sporadic acritarchs and a significant proportion of *Botryococcus* spp., especially towards the top of the unit. These data also suggest some influence of marine waters and the known tolerance of modern day *Botryococcus* spp. of 0-4ppt salinity (see Qin, 2005; Rao *et al.*, 2007) further suggests a brackish marine influence.

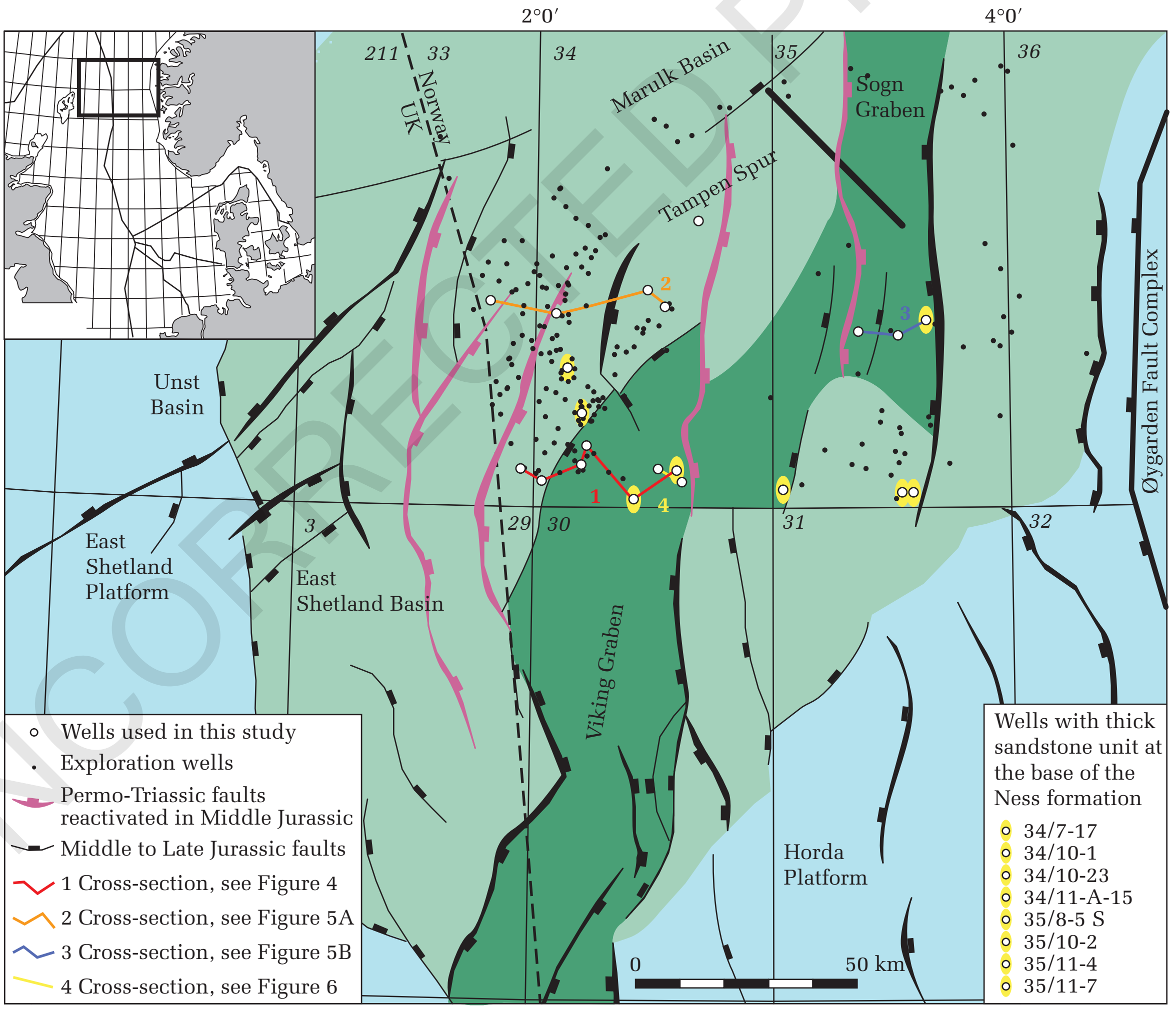

Fig. 8. Geographical location of wells at the base Ness sandstone level in the northern North Sea.

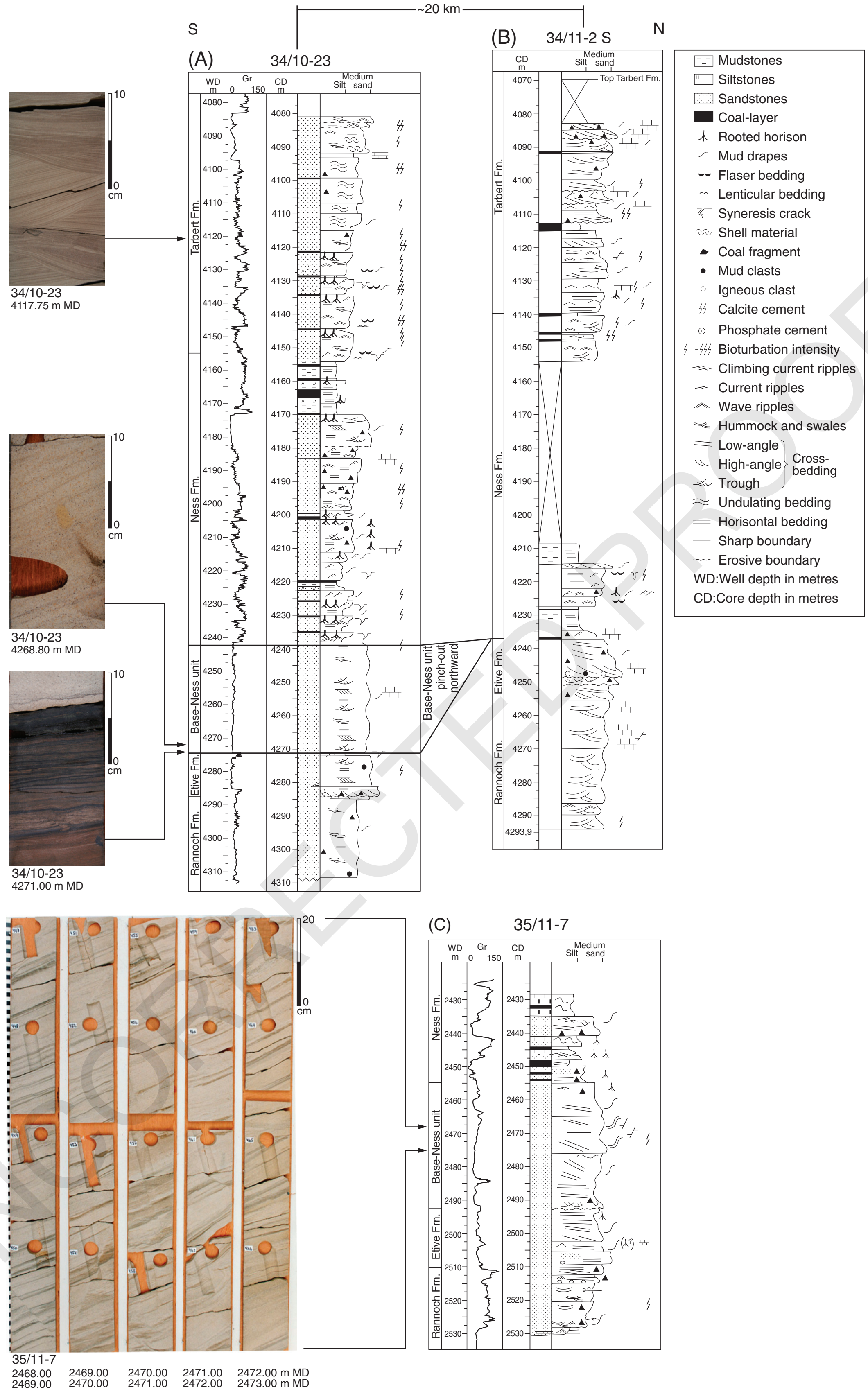

Fig. 9. (A) Log of the Brent Group in well 34/10-23 with the base Ness sandstone indicated. The palaeosol at the top of the Etive Fm is illustrated in the photo from 4271 m. The photo at 4268.8 m shows weak but rhythmic mudstone-drapes of the base Ness sandstone unit. A reactivation surface is also observed in the lower part of the photo. (B) Log of the Brent Group in well 34/11-2S (about 20 km north or basinward of 34/10-23; see Fig. 1) with the base Ness sandstone unit absent. (C) Log of the lower half of the Brent Group of well 35/11-7, including the base Ness sandstone unit. The core picture shows the mudstone-draped cross-bedded sandstones interpreted as stacked tidal dunes.

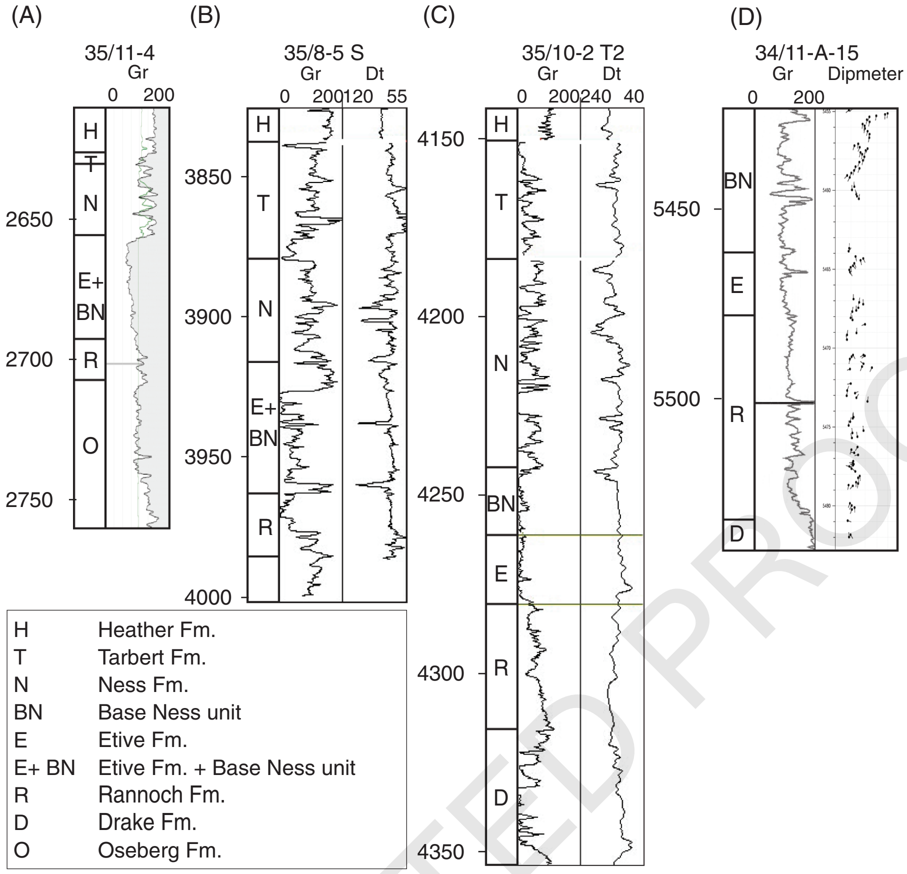

Fig. 10. Base Ness sandstone unit shown in selected well logs as a supplement to Fig. 9. Note that well 34/11-A-15 also shows dipmeter data from the Formation Micro Image log with the tadpoles directed generally southward (down-page) in the base Ness sandstone unit.

The local occurrence of these units (Fig. 8) with a thick stack of tidal dunes favours interpretation as local depocentres that experienced considerable accommodation space generation, formed during the initial stages of the early rift-phase. The initial rift-stage is characterised by fault population evolving into fault-linkage and fault-death (Gawthorpe & Leeder, 2000; Fig. 3). The stratigraphic occurrence of these local depocentres at the base of the wedge-shaped Ness and Tarbert formations (Figs 4 and 8) suggests that rift-initiation occurred at this stratigraphic level in the study area. A tidal influence has been recorded in the Rannoch Formation (Table 2) but tidal processes appear to have been suppressed by wave activity. The recognition of tidal influence in the deltaic intervals makes the suggested estuarine interpretation of these units probable, as tidal currents may have been amplified landward and not suppressed by other processes.

An alternative, non-tectonic interpretation of these thick sandstone units is to view them as distributary channels that were subjected to rapid sea-level rise. Such an interpretation is possible (as dunes are common within channels) but the strong tidal character of the sandstones and the occurrence of palynomorphs would be unusual within fluvial distributary channels due to the winnowing nature of these uni-directional high-energy environments. Interpreting these units as an aggrading backshore unit would contradict their local occurrence as shown in Figs 4 and 8. The stratigraphic occurrence at the base of the stratal wedge makes a tectonic influence during deposition a more likely scenario.

Coastal morphology – progradational part

The pinch-out morphology of the 'Brent delta' in Early Bajocian time has usually been interpreted to map as a linear E–W coastline (Olsen & Steel, 1995; Løseth *et al.*, 2009; Mjøs *et al.*, 2009). However, as indicated in Figs 4 and 5, the Permo–Triassic faults seem to have been active at that time. Active faults will affect the palaeogeography of the coastline in the sense that hangingwall areas generally show a transition of progradational to more aggradational shorelines due to increased accommodation. By contrast, the shoreline reaches further basinward at the footwall highs and are characterised by progradation with low-accommodation facies as wave-dominated strata, as indicated in Fig. 11 (see Gawthorpe & Leeder, 2000). This explains the observed lateral facies variability of the progradational part of the Brent Group (Fig. 12) in the pinch-out area within such a fault-influenced context.

Well 35/4-1 is located in a hangingwall position relative to a Permo–Triassic fault (Fig. 11) and shows heterolithic strata (low net to gross ratio of sand) displaying fluvial, tidal and wave influence (Fig. 12A). Biostratigraphic analysis of the Brent Group in this well indicates a gradual change from freshwater influence (abundant *Botryococcus*; see Batten & Grenfell, 1996) in the lower part of well 35/4-1 (see Table 2) to brackish-water to marine conditions towards the upper part (see Fig. 12A).

Well 34/8-1 is located at the footwall high of a Permo–Triassic fault (Fig. 11) and shows predominantly wave-dominated strata in the Brent Group. Here, the progradational portion extends as far into the basin as well 34/6-1. An alternative interpretation of the facies differences in the prograding 'Brent delta' would be to regard them as an effect of lateral deltaic variability owing to the distance between the feeder systems. However, in the context of the fault-block rotations at this time (Figs 4 and 5), the related fault locations (Figs 1 and 11) and the manner in which the coastline evolved later (see below) leads up to a strong impression that these faults had an impact on the shape of the coastline.

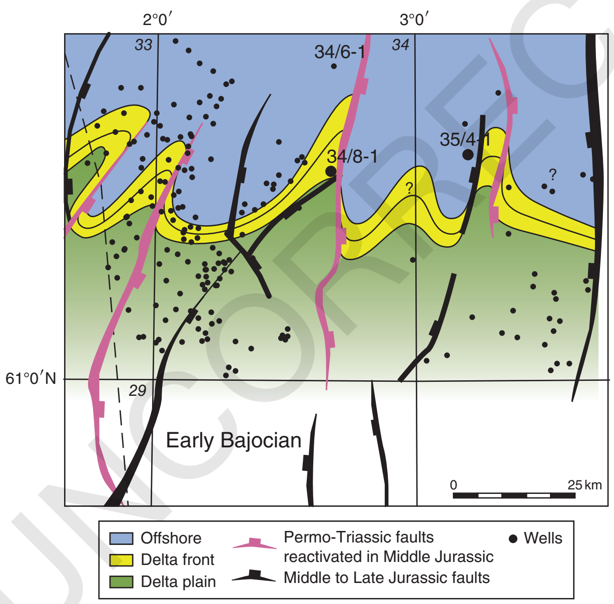

Fig. 11. Schematic illustration of the prograding Brent Group (not progradational maximum), portrayed as an undulating coastline where the footwall areas promote basinward deltaic extension with a relatively low shoreline trajectory and the hangingwall areas show aggrading shoreline trajectories with a pinch-out somewhat more southwards than the footwall areas.

Coastal morphology – retrogradational part

The Tarbert Formation represents the retreating part of the 'Brent delta' and shows a variation in depositional environments along the coast (east–west; Fig. 12B, C and D) in the Middle–Late Bajocian. The Tarbert Formation shows wave reworking in well 34/8-1 as spit environment (see also Ravnås *et al.*, 1997; Figs 12D and 13), transforming to stacked bay-head deltas capped by beach-barrier complexes in 34/10-A-11 (Figs 12C and 13) that pass laterally into a wave-dominated estuary in 34/7-22 (Figs 12B and 13; expressed as fluvial-tidal channel; cf. Davis *et al.*, 2000). In light of the argued influence of fault activity in the Ness and Tarbert formations, the facies distribution pattern described above for the Tarbert Formation can best be explained by rotation of the Permo–Triassic fault-blocks giving an asymmetric subsidence pattern along the coastline. In this way the estuary development represents high-subsidence and accommodation space creation in the hangingwall part (well 34/7-22) and the wave-reworked area as the lesser subsidence (with low accommodation-space creation) in the footwall part of the Permo–Triassic fault block (34/8-1; Fig. 13). It is typical for rift basins to show this kind of variability in sediment infill patterns and facies types along the coast (Gawthorpe & Leeder, 2000), as observed here for the Tarbert Formation. Rift or fault activity within the Tarbert Formation, with some impact on the lateral facies variation, has been reported by several authors (Fält *et al.*, 1989; Fjellanger *et al.*, 1996; Ravnås *et al.*, 1997; Davies *et al.*, 2000; Ravnås *et al.*, 2000).

DISCUSSION

This study has demonstrated that Early Bajocian fault-activation led to wedge-shaped stratal development in the Ness and Tarbert formations in the Tampen area. In terms of displacement and strain, these fault movements are subordinate but sufficiently large to have influenced the distribution

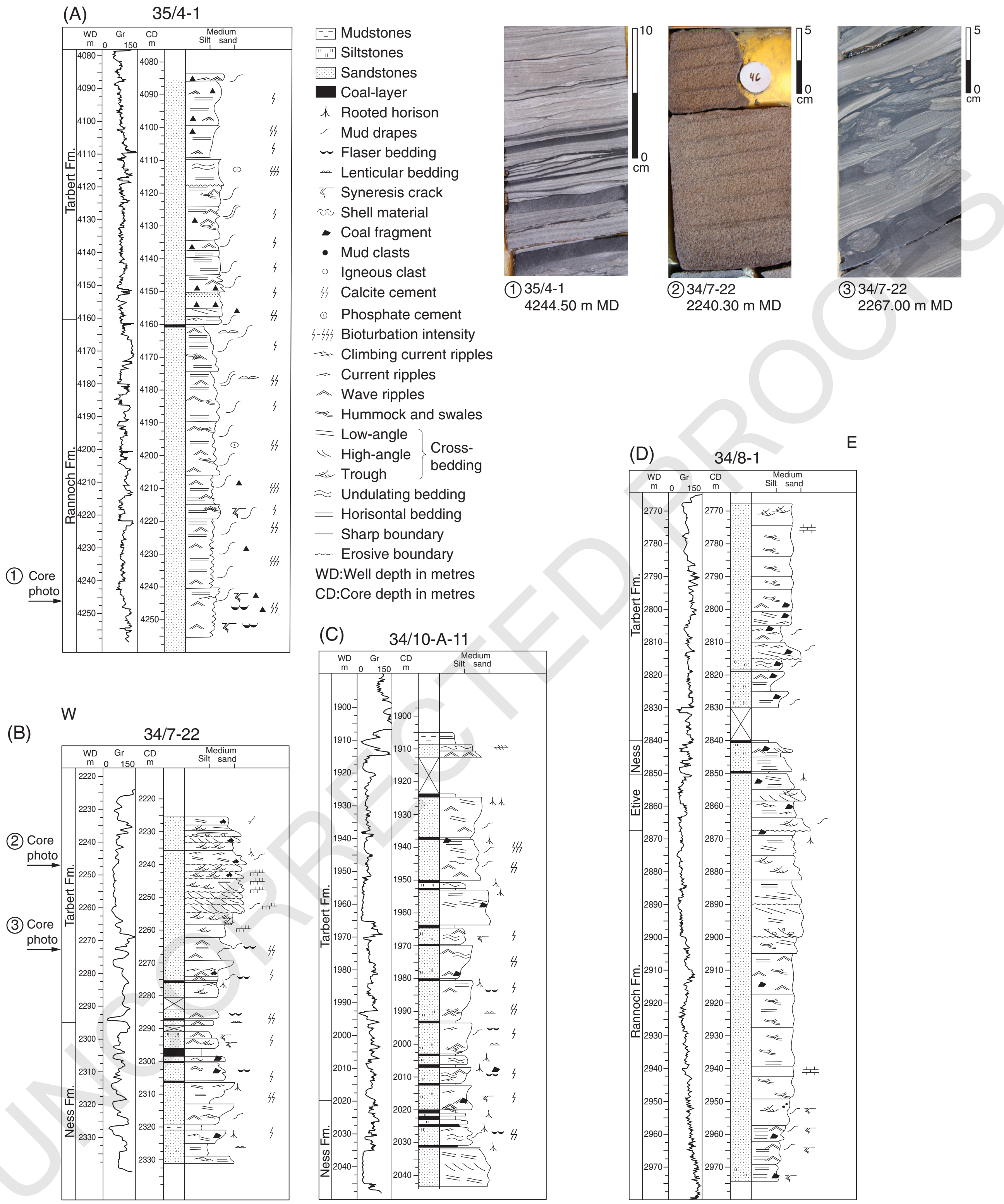

Fig. 12. Log of the Brent Group in (A) well 35/4-1, note the 90 m thick aggrading unit Rannoch Formation. Palynological data indicate a trend upwards from freshwater condition becoming progressively more brackish in the upper part; see Fig. 11 for location; (B) well 34/7-22. Note the cross-bedded sandstone interval in the middle part of the Tarbert Formation; (C) well 34/10-A-11; (D) well 34/8-1, the location of this well is important in Figs 11 and 13.

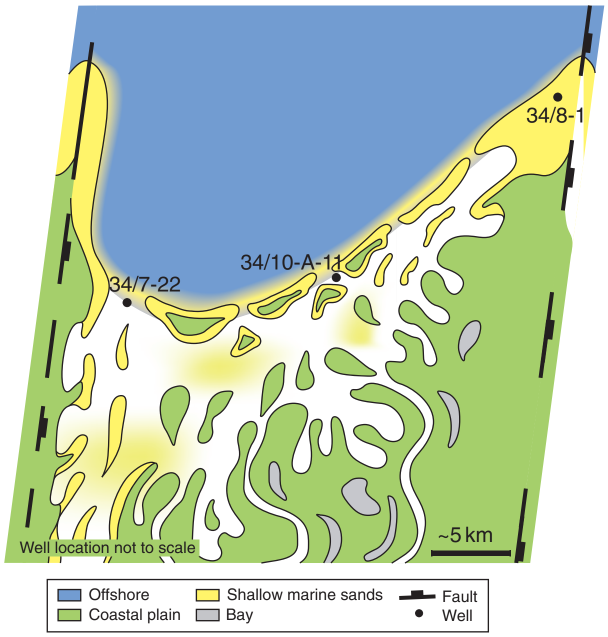

Fig. 13. Schematic illustration of the variation in depositional environments of the Ness and Tarbert formations (during transgressive) in wells 34/7-22, 34/10-A11 and 34/8-1 and their relationship with the faults. Well position not to scale. Here, the shoreline at the footwall area extends further into the basin, whereas the hangingwall area experienced transgression (see Gawthorpe & Leeder, 2000).

and lithological partitioning (net to gross ratio) of Middle Jurassic strata at the scale of 100s of metres. In this section, we discuss how our findings add to the understanding of Jurassic rift-initiation in this part of the North Sea rift system.

Rift initiation

The period between the Late Permian–Middle Triassic and Middle–Late Jurassic rift episodes is traditionally characterized as a post-rift period (i.e. a period of tectonic quiescence). By contrast, there is evidence of fault activity at various stages during this time interval that suggests this period is better described as an inter-rift period during which minor fault-slip accumulated due to subsidence and compaction. It has also been speculated that fault-slippage during this period was caused by pulses of mild extension (Ravnås *et al.*, 2000). For the most part, these inter-rift fault movements occurred on Permo–Triassic faults that propagated upward during deposition of the inter-rift sedimentary sequence. Such faults include the Statfjord East fault (Fig. 4) and the Ninian-Hutton-Dunlin fault, both of which are reported to have been active throughout the Jurassic period (Hampson, *et al.*, 2004).

There are at least two end-member models that can explain such fault activity during the inter-rift period. One is that extension continued more or less continuously at a very low rate, activating faults at different locations in the basin at different times. The other is that the basin experienced a number of short-lived (some millions of years) pulses of extension, as advocated by Ravnås *et al.* (2000). At present the resolution of available data makes it difficult to discriminate between these two models.

The suggested time of initiation for the main Middle–Late Jurassic rift phase varies from study to study, ranging from Late Bajocian (Helland-Hansen *et al.*, 1992; Mitchener *et al.*, 1992, Johannessen *et al.*, 1995) to Kimmeridgian (Badley *et al.*, 1988). This wide range may indicate that rift-initiation was not synchronous throughout the basin (Ravnås & Bondevik, 1997) because wedge-shaped stratal packages (with internal stratal thinning or expansion) in a depositional strike section are taken to indicate syn-depositional fault-block rotation (i.e. syn-rift deposition; e.g. Yielding *et al.*, 1992; Ravnås & Steel, 1998). Considering the data presented in this study, we suggest that the Jurassic rift episodes of the northern North Sea rift system initiated in the Early Bajocian within the central part of the basin, marked by the base of the wedge-shaped Ness and Tarbert formations in the Gullfaks-Kvitebjørn area (Figs 4 and 6).This would correspond approximately at the base of the Early Bajocian. Work by Graue *et al.* (1987) and Fält *et al.* (1989) suggests that the Ness Formation shows evidence of syn-sedimentary faulting along major structural lineaments that most likely represent Permo–Triassic faults. Rifting first occurred in the proto-Viking Graben and the adjacent areas and then expanded to affect the lateral platform-areas at a later stage to cause the syn-rift activity reflected in the Tarbert Formation in the East Shetland Platform (Davies *et al.*, 2000) and the Horda Platform (Ravnås *et al.*, 1997).

The initial rift stage (Early Bajocian) was probably characterised by a combination of increased movement of the Permo–Triassic faults as well as the development of a new Jurassic fault-population at the base of the large-scale Ness and Tarbert stratal wedge (Fig. 4) that created scattered local depocentres (see also Fig. 3; Gawthorpe & Leeder, 2000; Sharp *et al.*, 2000; Davies *et al.*, 2000). We refer to the anomalously thick sandstone units, which formed in the fault-induced local depocentres, as the 'base Ness sandstone unit' (Figs 8, 9A, 9C and 10D). Davies *et al.* (2000) found fault-induced local depocentres at the rift-initiation level within the Tarbert Formation on the East Shetland Platform which appears to be analogous to the 'base Ness sandstone unit'. In other locations with limited sand supply either further landward or offshore, these local depocentres may have had a different sedimentological expression than seen in Fig. 9A and C.

The base Ness sandstone unit in well 34/10-23 (Fig. 9A) has earlier been interpreted earlier as the result of rapid sea-level rise, with a step-up of the shoreline with cross-bedded sandstones representing shoreface (Bullimore & Helland-Hansen, 2009). Such a rapid sea-level rise is not indicated in any of the laterally adjacent wells (see Figs 4 and 8). In the UK sector, a similar unit with tens of metres of cross-bedded sandstones has been interpreted as incised-valley fills (Morris *et al.*, 2003; Hampson *et al.*, 2004). This latter interpretation explains the aggradational style and isolated occurrence of the sandstones but is at odds with the lack of a time-equivalent seaward shoreline detached sedimentary wedge, at least in the Norwegian sector of the 'Brent delta' (Graue *et al.*, 1987; Helland-Hansen *et al.*, 1992; Fjellanger *et al.*, 1996; Bullimore & Helland-Hansen, 2009; Mjøs, 2009).

The transition from the rift-initiation stage to a phase of increased fault movement has been correlated to a sharp increase in the rate of basin-wide subsidence early in the rift event (e.g. Steckler *et al.*, 1988). Gupta *et al.* (1998) suggested that the transition from rift-initiation to syn-rift occurs as fault activity becomes localized into linked arrays (Table 2 and Fig. 3). With a decline in the number of active faults, the rate of fault displacement increased; hence, the rate of tectonic subsidence increased. Observations from the East Shetland Basin (Dawers & Underhill, 2000; McLeod *et al.*, 2000; Hampson *et al.*, 2004), the Tampen Spur area (Bruaset *et al.*, 1999; Ravnås *et al.*, 2000) and the Horda Platform (Fjellanger *et al.*, 1996; Færseth *et al.*, 1997; Ravnås *et al.*, 1997) are in general agreement with the predictions of the model described by Gupta *et al.* (1998). For the Gullfaks–Kvitebjørn mega-block, we have demonstrated an earlier rift-initiation than has been reported from the basin flanks. At least two possible explanations can account for this. Either the position of the Kvitebjørn area, as part of a major step-over of the Viking Graben (ramp and horst, according to Fossen *et al.*, 2010), had reduced subsidence rates in that location, or increased subsidence rates occurred more or less synchronously across the Gullfaks–Kvitebjørn Permo–Triassic mega-block.

The asymmetrical Ness and Tarbert wedge, recognized here from the Kvitebjørn area, places the onset of initial rifting within the Ness Formation (Fig. 6). The incipient faulting that influenced the depositional patterns of the Ness Formation indicates that the footwall part of the Gullfaks–Kvitebjørn mega-block (Fig. 4) underwent extension at this time. Ravnås and Steel (1998) described a similar setting with segmentation of the footwall collapse and Sharp *et al.* (2000) showed footwall flexing with development of half-grabens during block-rotation. These two examples illustrate similarities to the development of the faulted Kvitebjørn Field from the Ness Formation (Early Bajocian) and onwards in terms of stratigraphy.

As the population of small faults within the Gullfaks–Kvitebjørn mega-block accumulated strain, they propagated and linked, with some developing into major faults through fault linkage processes (e.g. see Cowie, 1998; Dawers & Underhill, 2000). At this stage, other Permo–Triassic faults were active, including the major Snorre and Gullfaks faults (Fig. 1). The well correlations of the Brent Group in this study show that this occurred at the last stages of Brent Group deposition or during submergence of the Brent Group. The large fault-blocks outlined by a few Permo–Triassic faults were active in the Early–Middle Jurassic (Fig. 3), a collection of minor faults during deposition of the Ness–Tarbert formations (Fig. 3) that gradually developed into the well-known Late Jurassic fault population. The exact reason for the selective reactivation of Permo–Triassic faults is unclear but it is likely to relate to variations in frictional strength, geometric restrictions, fault interaction and/or orientation relative to the regional stress field.

Early syn-rift

The Ness Formation shows a general aggradational stacking of facies, with a balance between sediment supply and accommodation space creation (Fig. 4). The transition from the progradational style of the advancing 'Brent delta' (Rannoch, Etive and lower Ness formations) to an aggradational style was explained by Ravnås *et al.* (1997) to be the result of increased rate of fault-related subsidence and thus added rate of accommodation space creation – a model that is supported by the findings of the present study of the Gullfaks–Kvitebjørn mega-block. A 'Mid-Ness-Shale' unit within the wedge-shaped Ness–Tarbert is described by Fjellanger *et al.* (1996) in the western part of block 34/10 (north of Fig. 4) as an organic-rich lagoonal mudstone. This observation adds to the picture of a westward rotation of the Kvitebjørn-Gullfaks Permo–Triassic mega-block, where the formation of this thick lagoonal mudstone unit is indicative of rapid subsidence. Hampson *et al.* (2004) also reports the occurrence of a wedge-shaped 'Mid-Ness-Shale' unit (lagoonal mudstone) on the UK side, which thickens toward the Ninian-Hutton fault. These 'Mid-Ness-Shale' units are associated with the hanging wall depocentres of Permo–Triassic faults and, together with the lithologic distribution within the Ness Formation (Fig. 4), show a net to gross reduction westward, with preservation of thicker mudstone intervals between the sandstone units as the river-supplied muds became trapped and preserved in the high-accommodation setting of the hangingwall area. The hangingwall area probably experienced transgressive events (see timelines in Fig. 4) that reached farther inland than the footwall area and with more immature and laterally restricted coal-layer accumulations in the hangingwall than the footwall area. The occurrence of isolated fluvial channels in the

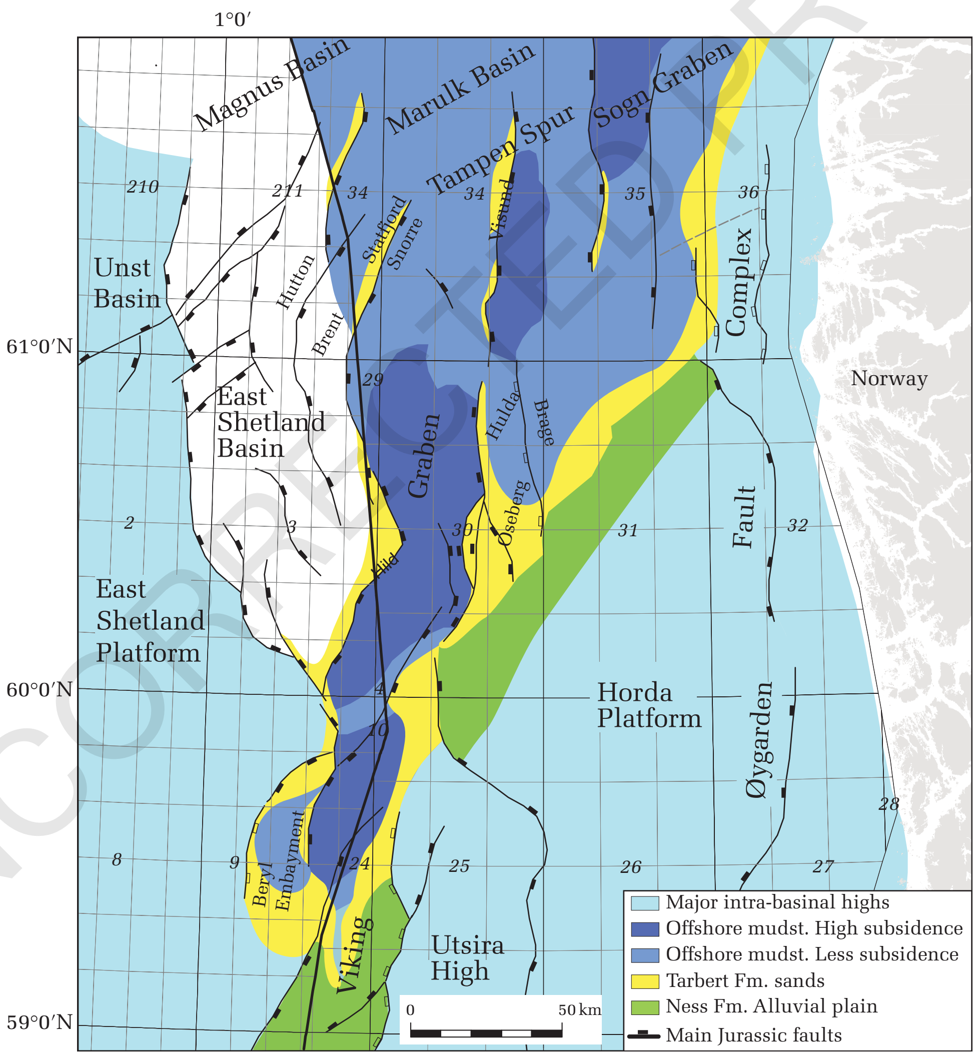

Fig. 14. Schematic illustration of the transgressed northern Viking Graben with the footwall islands in the early part of the Late Jurassic Epoch.

hangingwall area is the result of axial drainage being attracted into the subsiding areas.

The Brent Group forms a continuum from the rapidly advancing deltaic Rannoch-Etive formations, without recordable tectonic influence, to the delta pinch-out in Early Bajocian time where the initiation of fault movements created an irregular delta front (Fig. 11). This can be seen as the precursor to the retreating Tarbert Formation (Rønning & Steel, 1987). The timelines in Fig. 4 demonstrate that the hangingwall area was transgressed earlier than the footwall area of the Gullfaks–Kvitebjørn Permo–Triassic mega-block, which made the footwall area of this block a (temporary) footwall island. The ongoing block rotations created estuaries with amplified tidal currents in the hangingwall and spits/shoreface at the footwall highs (Figs 13 and 14).

Under such transgressive conditions the net sediment transport is directed landward (van der Molen & van Dijck, 2000), where barrier-inlets (as shown in Fig. 13) will act as grain size-filters (Oost, 1995). Finer-grained sediments pass through the inlets whilst coarser-grained sediments will be kept within or outside the inlets. These observations can explain why the back-barrier area of the Tarbert Formation has finer-grained sediments (Figs 9A, 9B, 12B and C) and may also explain the origin of the enigmatic ‘silk sand’ (Bruaset *et al.*, 1999; named after its textural properties) found in the Gullfaks Field. The ‘silk sand’ unit is structureless and trough cross-bedded, medium grained, 30 m to 54 m thick and about 1.5 km wide (E–W), tidally influenced sandstone with high permeability (Bruaset *et al.*, 1999). Its tidal character and the uniform grain-size trend, typical of the back-barrier area (Oost, 1995), indicate that the ‘silk sand’ may represent a tidal-bar complex or a flood-tidal delta. A full analysis is beyond the scope of the present study but it is interesting to note its presence in our study area as a consequence of the transgression caused by the rotation of the Permo–Triassic megablock.

The Late Bajocian transgression of the Brent Group with block-faulting along the pre-existing Permo–Triassic fault lineaments has been documented by several authors (Fält *et al.*, 1989; Helland-Hansen *et al.*, 1992; Fjellanger *et al.*, 1996). This phase correlates directly to rifting, convincingly, as the syn-sedimentary tectonic signs stand out (on seismic data). The earlier stage of rifting is more difficult to discern (Davies *et al.*, 2000). However, as demonstrated in this study, the sedimentary responses to early stages of rifting can be identified.

CONCLUSIONS

Seismic, well and core data from the northern North Sea have been integrated in an attempt to constrain when and how Jurassic rifting affected the Jurassic succession in the Tampen area; in particular with respect to the depositional environments of the Brent Group. We conclude that:

1. The Gullfaks–Kvitebjørn mega-block shows fault-displacement on the East Statfjord fault during the Jurassic period in a manner similar to the Ninian–Hutton–Dunlin fault (Hampson *et al.*, 2004). These faults originated in the Permo–Triassic and produced mega-blocks that either continued to be active throughout the Triassic and Jurassic or were reactivated in the Late Triassic–Early Jurassic. We suggest a model wherein a few weak and favourably oriented Permo–Triassic faults remained active throughout the Jurassic and where the onset of the Middle–Late Jurassic rift phase populated the early mega-blocks with smaller faults that developed into mature Late Jurassic fault populations over time.
2. The onset of Middle–Late Jurassic rifting in the northern Viking Graben is reflected by the wedge-shaped Ness–Tarbert formations by means of regional well-correlations (Fig. 4) across the Kvitebjørn Field (Fig. 6), where rifting appears to have initiated during deposition of the lowermost part of the Ness Formation at that location. This interpretation agrees with a model where ‘base Ness sandstone units’ were deposited within local depocentres formed by normal faults in the early rift phase. This pattern of normal faults and their associated local depocentres developed into a more mature fault population, as some of the small faults linked up to form larger faults that took over much of the fault activity. The early fault population caused the added accommodation space which, in sum, created the wedge-shaped Ness and Tarbert formations, in accordance with general models of rift-initiation (Gawthorpe & Leeder, 2000; Sharp *et al.*, 2000; Davies *et al.*, 2000).
3. These data indicate that fault activity in the Gullfaks-Kvitebjørn transect area (Figs. 4 and

6) was initiated earlier than faulting in the East Shetland Platform and Horda Platform, where a similar development has been reported for the Tarbert Formation. The location of the Kvitebjørn footwall with respect to the Viking Graben step-over (Fossen *et al.* 2010) can explain the early faulting (footwall flexure and collapse).

4. The wedge-shaped Ness-Tarbert formations (Figs 4 and 6) show internal trends in the form of low net-to-gross ratios and the trapping of landward-supplied sediments toward the hangingwall area. Footwall areas have higher net to gross ratios and poorer preservation of strata. These trends are the result of the variable depositional pattern that occurs along the strike of a rotating fault-block.
5. The advancement of the 'Brent delta' was halted due to several factors: northward increasing water depth; over-extension of the delta-front that exhausted its sediment supply budget; and, probably most importantly, increased rates of fault movements, leading to increased subsidence. This fault initiation caused irregular delta-front morphology at the northern extension of the 'Brent delta' (Fig. 11). Footwall areas were prone to progradational facies-stacking patterns while the hangingwall areas developed more aggradational stacking patterns. This fault-influenced irregular delta front became increasingly irregular, with increased tectonic topography, as the faults moved and the coastline retreated southwards. This led to the development of an estuarine environment in the hangingwall area and spit/shoreface-development in the footwall area (Fig. 14). Originally weak tidal currents operating at the delta front were enhanced into strong tidal currents due to the funnel-shaped coastal morphology created by the flooded hangingwall of the fault-blocks. This motif of a complex shoreline morphology shifted southwards with time into the South Viking Graben due to the southward extension of the rift-activity in the Late Jurassic.

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