

Sedimentology and sequence stratigraphy of the Middle–Upper Jurassic Krossfjord and Fensfjord formations, Troll Field, northern North Sea

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ABSTRACT: The Middle–Upper Jurassic Krossfjord and Fensfjord formations are secondary reservoir targets in the super-giant Troll oil and gas field, Horda Platform, offshore Norway. The formations comprise sandstones (c. 195 m thick) sourced from the Norwegian mainland to the east, that pinch out basinwards into offshore shales of the Heather Formation to the west. Sedimentological analysis of cores from the Troll Field has identified six facies associations, which represent wave- and tide-dominated deltaic, shoreline and shelf depositional environments. Resulting depositional models highlight the complex distribution of depositional environments, and reflect spatial and temporal variations in physical processes at the shoreline, rate of sediment supply and accommodation development. These models are further complicated by the absence of coastal plain facies, which implies that the Troll Field was fully subaqueous during deposition, that shoreline regression was forced by falling sea level or that coastal plain deposits were removed by transgression. Genetic sequences bounded by major flooding surfaces (‘series’) exhibit laterally uniform thicknesses, implying no major tectonic influence on sedimentation. The recognition of pronounced variability in facies character and stratigraphical architecture emphasize the need for a robust depositional model of the formations in order to drive future exploration in these, and coeval, reservoirs.

INTRODUCTION

The super-giant Troll oil and gas field is located on the Horda Platform on the eastern margin of the Viking Graben, northern North Sea (Fig. 1a), and has produced 220.7 million Sm³ (1.39 billion barrels) of oil and 391.8 billion Sm³ (13.84 trillion cubic feet) of gas during 21 years of production since 1990 (NPD 2011). The Troll Field is divided into the Troll West and Troll East accumulations, although pressure communication has been proven between the two accumulations (NPD 2011). Rotated fault blocks define the traps for both accumulations (Fig. 1c) and the reservoir consists of shallow-marine sandstones; production to date has been from the Sognefjord Formation (Oxfordian–Kimmeridgian/Volgian) (Fig. 2). The underlying Fensfjord Formation (Callovian) forms part of the reservoir and has a proven oil column of 6–9 m in the northern part of Troll East (NPD 2011). The Fensfjord Formation also forms a significant reservoir in the Brage Field (Callovian–Oxfordian), which lies 20 km to the SW of Troll (Fig. 1a). The Sognefjord and Fensfjord formations, together with the underlying Krossfjord Formation (Bathonian), form part of the Viking Group, which is situated above the prolific Brent Group (Fig. 2).

The sedimentology of the Krossfjord and Fensfjord formations is poorly understood as they have not been the focus of previous published work, despite the formations containing potentially large reserves. The formations comprise sandstones

principally sourced from the Norwegian mainland to the east and pinch out basinwards into the offshore shales of the Heather Formation to the west towards the North Viking Graben (Stewart *et al.* 1995). The development of a detailed sedimentological and sequence stratigraphical model for the Krossfjord and Fensfjord formations is complicated by two factors. First, the sedimentological character, distribution and stratigraphical architecture of shallow-marine sandstones are strongly controlled by spatial and temporal variation in physical processes at and near the shoreline (e.g. wave- v. tide- v. fluvial-dominated processes) (e.g. Gani & Bhattacharya 2007; Ainsworth *et al.* 2011). Second, the geographical partitioning and the relative importance of physical processes can be further complicated in rifts due to fault-block rotation, uplift and subsidence; the sedimentology and stratigraphical architecture of both the Krossfjord and Fensfjord formations may, thus, be anticipated to be complex because they were deposited during the Middle–Late Jurassic rift event (Ravnås & Bondevik 1997).

The aims of this paper are twofold: (1) to produce a high-resolution sedimentological and sequence stratigraphical model for the Krossfjord and Fensfjord formations in the Troll Field; and (2) to determine the dominant shoreline processes and genetic stratigraphical relationships within and between these formations. The work reported herein will improve our understanding of syn-rift sandstone distribution in the northern North Sea, and guide future exploration and production from Krossfjord and Fensfjord reservoirs.

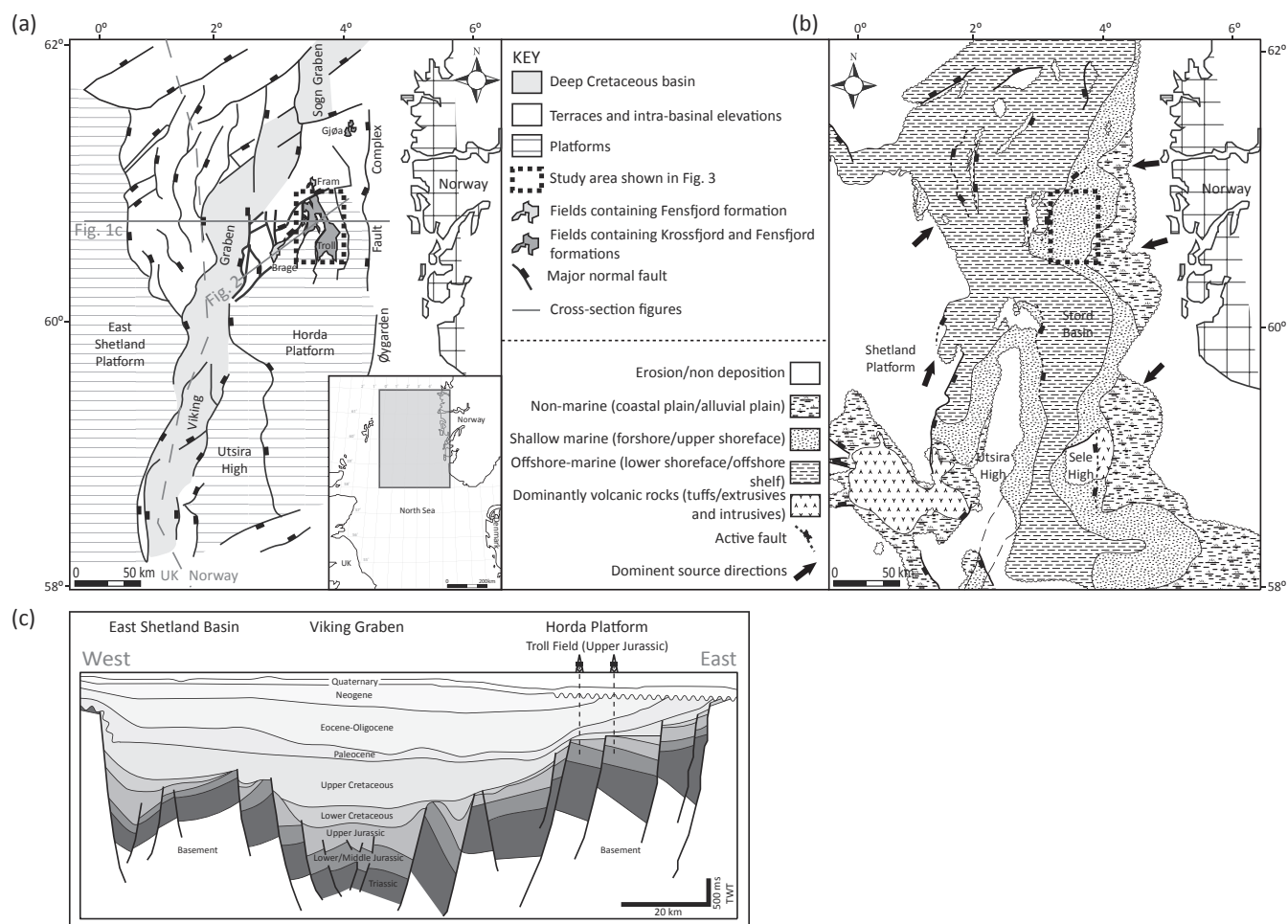


Fig. 1. (a) Simplified map of the north Viking Graben highlighting the Horda Platform, and the Troll, Brage, Fram and Gjøa fields, which host Krossfjord and Fensfjord reservoirs (modified after Færseth 1996; Ravnås & Bondevik 1997; Fraser *et al.* 2002). (b) Simplified palaeoenvironmental map of the northern North Sea during the mid- to late Callovian and deposition of the Fensfjord Formation in the Troll Field (modified after Husmo *et al.* 2002). (c) Geoseismic profile illustrating the major fault blocks from west to east across the Viking Graben (modified after Husmo *et al.* 2002). Cross-sections (c and Fig. 2) and maps (Fig. 3) are located in (a).

GEOLOGICAL SETTING AND PREVIOUS WORK

Regional tectonic context

The Troll Field is located on the Horda Platform, on the eastern flank of the North Viking Graben. The northern part of the North Sea rift basin is a fault-bounded depocentre that is 170–200 km wide, and is flanked by the Shetland Platform to the west and the Norwegian mainland to the east. It is the northern arm of the North Sea trilete rift system, which was initially developed during the Triassic as a continental rift system, and was reactivated and significantly expanded during the Late Jurassic as a marine rift system (Roberts *et al.* 1990a; Davies *et al.* 2001). It is characterized by normal faults that strike north, NE or NW, and which bound rotated fault blocks that are 15–50 km wide (Færseth & Ravnås 1998). The fault blocks are arranged around a central low, known as the Viking Graben (Færseth & Ravnås 1998). The North Viking Graben is located in the North Sea between 59° and 61°N, and represents one arm of the trilete failed rift system (Fig. 1a).

The basin underwent a complex tectonic evolution; initial phase of extension occurred during the Permo-Triassic, and multiple phases of extension occurred in the Middle-Late Jurassic (Bajocian–Volgian). The Permo-Triassic and Middle-Late Jurassic

phases of rifting are separated by a post-rift interval, in which two regional tectonic uplift events are identified in the Hettangian and late Toarcian–Aalenian (Steel 1993; Færseth 1996; Færseth & Ravnås 1998). During the Early Jurassic the basin was characterized by tectonic quiescence and spatially uniform subsidence. The Toarcian–Aalenian event interrupted this period of quiescence and formed the North Sea thermal dome, which provided clastic sediment for the northwards progradation and subsequent southwards retreat of the Middle Jurassic ‘Brent Delta’ (Ziegler 1990; Underhill & Partington 1993). The subsequent Middle-Late Jurassic depositional systems, rather than being sourced from the North Sea dome, were sourced from the Norwegian mainland to the east and prograded to the west. These systems were deposited across a series of north-south-trending fault blocks that formed during the Middle-Late Jurassic rift event (Rattee & Hayward 1993).

The trilete Middle-Late Jurassic rift system formed in response to the deflation of the North Sea thermal dome (Ziegler 1990; Underhill & Partington 1993). Both the initiation and cessation of rifting was diachronous across the basin; in the northern North Sea, rifting initiated in the Bajocian (Johannessen *et al.* 1995; Hesthammer *et al.* 1999). The rate of extension and fault-controlled subsidence generally increased through the Jurassic, and were greatest in the Late Oxfordian–Kimmeridgian

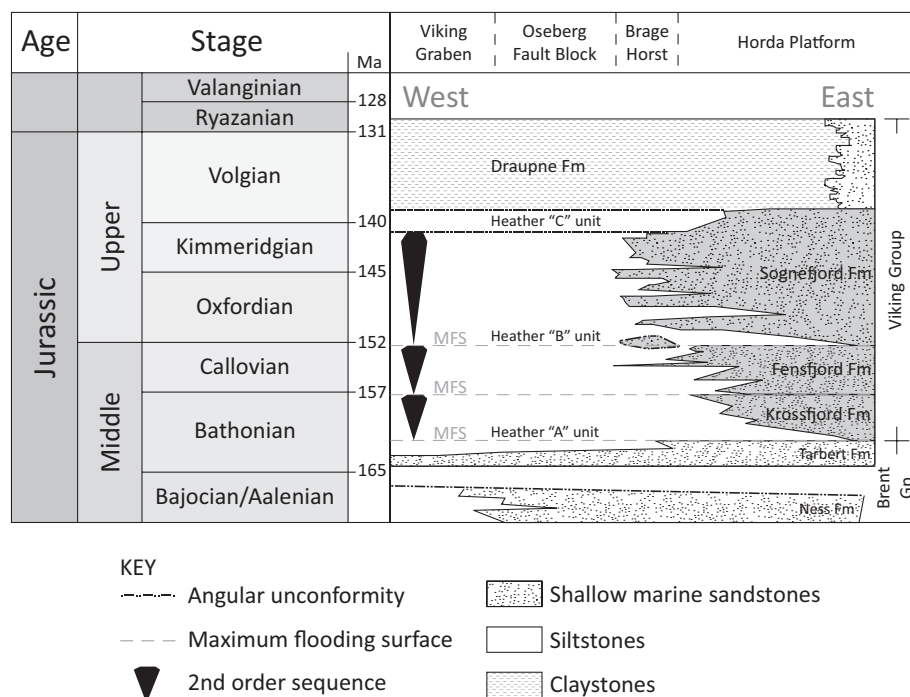


Fig. 2. Middle–Upper Jurassic chronostratigraphical framework for a SW–NE-orientated cross-section through the North Viking Graben and Horda Platform (Fig. 1a) (modified after Partington *et al.* 1993; Stewart *et al.* 1995; Fraser *et al.* 2002).

(Færseth & Ravnås 1998). However, in detail, the Middle–Late Jurassic rift event can be divided into several discrete phases of basin-wide rifting and fault-related subsidence; these phases are discussed further below, so that our detailed sedimentological and stratigraphical analysis can be placed in a robust, regional, tectonostratigraphical framework.

Tectonic–stratigraphical evolution of Horda Platform and Troll Field

The Troll Field and surrounding area contains three major sandstone tongues of Middle–Late Jurassic age. These are the Krossfjord, Fensfjord and Sognefjord formations of the Viking Group (Vollset & Doré 1984) (Fig. 2), which are each 100–200 m thick near the rift margin and which pinch-out westwards into fine-grained Heather Formation deposits in the North Viking Graben (Ravnås & Bondevik 1997). The sandstone tongues were deposited in several transgressive–regressive cycles at the margins of a shallow sea that covered the Horda Platform (Stewart *et al.* 1995). The combined thickness of the sandstone tongues, and associated Heather Formation siltstones and mudstones, is up to 400 m (Husmo *et al.* 2002). The Heather Formation is informally split into three parts on the Horda Platform to describe its stratigraphical relationship to the three major sandstone tongues: the Heather ‘A’ unit lies above the Brent Group and beneath the Krossfjord Formation (Bathonian); the Heather ‘B’ unit overlies the Fensfjord Formation and underlies the Sognefjord Formation (Callovian); and the Heather ‘C’ unit overlies the Sognefjord Formation (Oxfordian and Kimmeridgian) (Stewart *et al.* 1995). The Sognefjord Formation is locally directly overlain by the Draupne Formation and the Heather ‘C’ unit is absent; in these locations the contact between the Sognefjord and Draupne formations is an angular unconformity (Stewart *et al.* 1995).

Deposition of the Krossfjord, Fensfjord and Sognefjord formations was driven by the supply of coarse clastic material from the eastern flank of the developing North Sea rift system as a result of uplift of the Norwegian hinterland (Stewart *et al.* 1995; Ravnås & Bondevik 1997). Each of the three formations has been interpreted as a second-order genetic sequence (*sensu*

Galloway 1989), which is bounded by major flooding surfaces (Fig. 2) (Stewart *et al.* 1995). Deposition in a range of shelf-to-shoreface environments, with varying degrees of tidal and/or fluvial influence, has been interpreted for the formations (Ravnås & Bondevik 1997; Dreyer *et al.* 2005).

The tectonostratigraphical evolution of the Horda Platform and the North Sea rift system resulted in the development of three structural provinces: (1) the relatively stable Horda Platform in the east; (2) a number of tilted half grabens that host the Brage, Oseberg, Troll and Fram fields (Stewart *et al.* 1995); and (3) the deep, fault-bounded, North Viking Graben in the west (Fig. 1). Rifting during the Middle–Late Jurassic can be subdivided into three periods (Fig. 2) (Fraser *et al.* 2002).

(i) **Bathonian–latest Callovian.** During the initial Bathonian–latest Callovian period of rifting, a series of faulted terraces developed between the Viking Graben and the Horda Platform. Rotation of the normal fault blocks, which define the traps of the Oseberg and Brage fields, caused local reworking of the upper Ness and Tarbert formations (Brent Group) on the Horda Platform (Husmo *et al.* 2002). It was during this period of rifting that the Krossfjord and Fensfjord formations were deposited (Vollset & Doré 1984; Steel 1993). In the Troll Field, the Krossfjord Formation is characterized by progradation of a sand-rich delta during relatively low rates of normal faulting and fault-block rotation (Ravnås *et al.* 2000) (Fig. 2). The Fensfjord Formation consists of regressively stacked, fine-grained sandstones, which accumulated during a period of tectonic quiescence during the Middle Callovian, when the sediment supply rate was higher than the basin subsidence rate (Steel 1993; Stewart *et al.* 1995; Ravnås & Bondevik 1997; Fraser *et al.* 2002). At the point of maximum regression during the Late Callovian, the Fensfjord Delta covered the entire Horda Platform and extended into the distal sub-basins that now host the Brage and Oseberg fields (Fig. 2) (Husmo *et al.* 2002). It has been speculated that turbidites, which were presumably sourced from the collapse of the Fensfjord Delta front, were deposited westwards of the Fensfjord Delta at this time (Ravnås

et al. 2000). Landwards migration of the Fensfjord Delta is attributed to fault-related subsidence outpacing sediment supply, which was coeval with footwall uplift of the western and NW boundary faults of the Horda Platform. Fault-controlled uplift in the Brage area resulted in the creation of footwall islands, which represented an important intrabasinal sediment source (Ravnås *et al.* 2000; Husmo *et al.* 2002). A marine transgression occurred in the Late Callovian and resulted in deposition of fine-grained sediments of the Heather 'B' unit (Steel 1993).

- (ii) **Oxfordian–Kimmeridgian.** During this period the Sognefjord Formation was deposited and rifting reached its climax, creating the major structural divide between the Viking Graben and the Horda Platform (Stewart *et al.* 1995). Increased extension caused uplift and tilting of fault blocks, resulting in fault-block footwalls rising above sea level at the margins of the Horda Platform. Erosion occurred on these footwall crests, allowing older sediment of the Sognefjord Formation to be reworked and deposited (Fraser *et al.* 2002).
- (iii) **Early–Middle Volgian.** The final stage of rifting caused extensive faulting in the west of the Viking Graben and mild reactivation of faults on the Horda Platform; this resulted in uplift and eastwards tilting of normal fault blocks (Fossen *et al.* 2003). Consequently, many fault blocks suffered local erosion and collapse, which resulted in Lower and Middle Jurassic strata being truncated beneath Upper Jurassic strata in several locations on the Horda Platform (Husmo *et al.* 2002). Deposition of the Sognefjord Formation was terminated by marine flooding, which led to deposition of deep-marine mudstones of the Draupne Formation (Fraser *et al.* 2002).

Previous depositional models for the Viking Group

Several depositional models have been published for the sandstones of the Viking Group, with a particular focus on the Sognefjord Formation. An early model interpreted the Sognefjord Formation sandstones as offshore bars, and proposed that transgressive erosion was the main control on facies distribution (Whitaker 1984; Hellem *et al.* 1986; Osborne & Evans 1987). Eustatic sea-level rise was interpreted to have been the major controlling factor on sedimentation. Subsequent models interpreted the sandstone tongues of the Viking Group to represent regressive–transgressive deltaic units containing a variety of shallow-marine shelf to shoreface environments (e.g. Steel 1993; Stewart *et al.* 1995). A greater tectonic influence on sedimentation was also suggested due to the recognition of variations in stratal thickness identified on seismic reflection data. The most recent model for the Oxfordian part of the Sognefjord Formation interprets the delta to have been mixed influence, with a wave-dominated spit deflecting fluvially supplied sediment towards the SW (Dreyer *et al.* 2005). The spit is interpreted to have been attached to the coast in the north and bordered to the east by a tidal backbasin. These various depositional models have different implications for predicted facies distributions across the Troll Field and elsewhere on the Horda Platform and North Viking Graben.

DATASET

Thirty-two wells in the Troll Field penetrate the Fensfjord Formation, and 22 of these wells also penetrate the underlying Krossfjord Formation (NPD 2011). Nine of these wells contain core within the interval of interest, giving a total core length of 893 m, all of which has been logged at a scale of 1:50 (Fig. 3, Table 1). In most wells, only the upper part of the Fensfjord

Formation is cored. Only one well, 31/2-4R, has complete core recovery of the Fensfjord Formation. Wells 31/5-5 and 31/2-4R have partial core recovery from the Krossfjord Formation (Table 1). Sedimentological facies analysis included describing grain size and shape, sorting, sedimentary structures, diagenetic features and the nature of bedding contacts. In addition, trace and body fossils were documented, including their orientation, size, cross-cutting relationships and intensity of bioturbation (cf. Bockelie & Howard 1984; MacEachern & Bann 2008). A biostratigraphical framework for the Fensfjord Formation was established by Whitaker (1984) in the Brage Field. This framework has recently been extended to five cored wells in the Troll Field, through analysis of quantitative palynology and kerogen counts (GeoStrat 2011). Wireline-log data have been used to identify facies in uncored wells. Borehole image and dipmeter data are not available for the studied wells, thus palaeocurrent directions could not be reconstructed from cored or uncored sections of the wells.

Two regional three-dimensional (3D) seismic reflection data sets that cover the Troll Field have been interpreted (North Sea exploration blocks 31/2, 31/3, 31/5 and 31/6). Troll West contains seismic survey 'NH0301', which has a coverage of approximately 800 km², line spacing of 18.75 m in inline (NE–SW) and 12.5 m in crossline (NW–SE) directions, and which images to a depth of about 3000 ms (millisecond) two-way time (ms TWT). Troll East contains seismic survey 'SG9202', which has a coverage of around 900 km², line spacing of 25 m in both inline (east–west) and crossline (north–south) directions, and which images to a depth of approximately 2400 ms TWT. The surveys overlap in the centre of the Troll Field. Based on seismic velocity and frequency data, the seismic resolution in the interval of interest is estimated to be about 15–25 m. Attribute data were used to understand the gross stratigraphical architecture of the intervals of interest. However, detailed analysis is complicated by the occurrence of closely spaced gas–oil and oil–water contacts that combine to produce a prominent 'flat spot', which obscures and distorts seismically resolved stratal architectures. Detailed seismic analysis is beyond the scope of this paper, and is the subject of ongoing work.

FACIES ANALYSIS AND WIRELINE-LOG CALIBRATION

Eleven different facies (A–J) are identified in the Krossfjord and Fensfjord formations (Table 2, Fig. 4). These facies are grouped into six facies associations, which are described and interpreted below. Representative sedimentary logs of each facies association are displayed in Figures 5–7, and cross-plots, which illustrate the quantitative wireline-log character of the facies associations, are shown in Figure 8.

Facies Association 1: Offshore

Facies Association 1 (FA1) is predominantly composed of Facies A1 and A2, with minor proportions of Facies I (Table 2), and is cored primarily within the Heather 'B' unit (Fig. 5b). Whereas Facies A2 is identified in all cored wells across the study area, Facies A1 is absent in wells located in the eastern part of the Troll Field.

Description. Facies A1 is a very-fine-grained siltstone with *Belemnites* and *Terebellina* burrows. Facies A2 is a fine-grained siltstone with *Planolites*, *Terebellina* and *Chondrites* burrows (Fig. 5b). Bioturbation intensity is high (5–6 on the qualitative scale of MacEachern & Bann 2008). Facies A1 and A2 are distinguished from one another using the prevailing

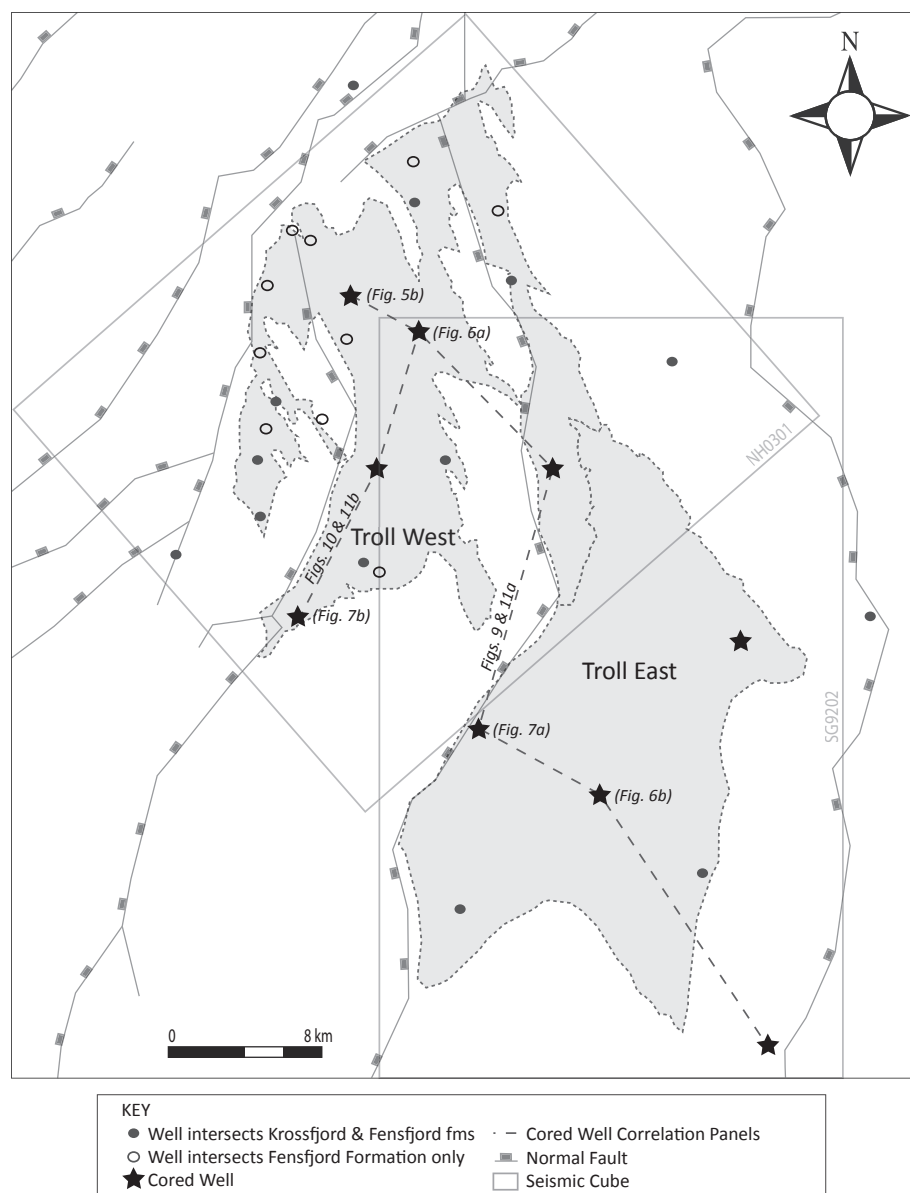


Fig. 3. Simplified map of the Troll Field (Fig. 1a) illustrating the distribution of wells available to this study, major faults and well correlation panels (modified after Færseth 1996; Ravnås & Bondevik 1997; Fraser *et al.* 2002; NPD 2011).

Table 1. Inventory of core data from the lower Viking Group in the Troll Field. Unit thickness is shown in metres and the percentage of core recovered is shown in brackets

Field	Well No.	Heather 'B' unit (m)	Fensfjord Fm (m)	Krossfjord Fm (m)	Length of core logged (m)
Troll West	31/2-1	63 (100%)	147 (46%)	138 (0%)	102.7
	31/2-3	53 (100%)	116 (73%)	78 (0%)	116.44
	31/2-4R	60 (100%)	105 (100%)	85 (45%)	202.8
	31/3-1	19 (100%)	152 (62%)	111 (0%)	109.96
	31/5-5	65 (100%)	130 (24%)	>75 (<72%)	114.86
Troll East	31/6-1	30 (100%)	202 (43%)	56 (0%)	107.5
	31/6-3	20 (100%)	87 (32%)	176 (0%)	28.1
	31/6-5	25 (100%)	235 (8%)	35 (0%)	42.65
	31/6-6	13 (100%)	228 (23%)	29 (0%)	28.15

ichnotaxa and grain size. Contacts between the two facies are gradational over 5–10 m and FA1 can occur in units that are up to 60 m thick. Very-coarse- to medium-grained sandstone beds occur locally in FA1 (Facies I). Beds of Facies I have sharp bases and gradational tops, and vary in thickness from a few centimetres to 1 m (e.g. at 1484 m in Fig. 5b). Palynofacies analysis indicates an aerobic environment with relatively

high salinity, high marine species diversity and low energy (GeoStrat 2011).

Wireline-log signature. Facies Association 1 is typified by high gamma-ray values, reflecting its high clay content (Figs 5b and 8a). Facies A2 has lower gamma-ray values than Facies A1 due to its slightly coarser grain size. Calcite cemented horizons are easily

Table 2. Summary of facies (A–J) in the Krossfjord and Fensfjord formations. Core photographs for facies A, C, D, F, G, H, I and J are presented in Figure 4

Facies	Description	Thickness in core (m)	Bioturbation and ichnotaxa	Wireline-log character	Interpretation
A1	Very-fine-grained, dark grey–very dark green–grey siltstone. Moderately well sorted with subrounded to subangular grains. Packages of increased siltstone content are identified in discrete coarsening-upwards or fining-upwards sections (<0.5 m). Mica and carbonaceous fragments common throughout. Pyrite and glauconite are rare. Bedding is absent	1–10	BI=5–6 (<i>Skolithos</i> , <i>Terebellina</i>)	GR=58–80 API DT=60–140 µs/ ft NPHI=0.30– 0.56 p.u. RHOB=2.2– 2.6 g cm ⁻³	Deposition from suspension in an oxygenated environment
A2	Fine-grained, dark grey–medium grey/brown siltstone with rare fine-grained sandstone. Moderately well sorted with subrounded to subangular grains. Occasional coal fragments (1–2 mm) and glauconite. Nodular calcite cement is rare and siderite nodules are occasionally present. Bedding is largely absent due to bioturbation, apart from rare parallel laminations	2–15	BI=5–6 (<i>Terebellina</i> , <i>Planolites</i> , <i>Chondrites</i>)	GR=48–76 API DT=85–150 µs/ ft NPHI=0.11– 0.39 p.u. RHOB=2.1– 2.4 g cm ⁻³	Deposition from suspension in a well-oxygenated environment with very rare sedimentation from storm processes
B	Very-fine- to medium-grained, medium–dark grey/brown sandstone. Siltstone content is highly variable. Moderately well sorted with subrounded to subangular grains. Mica and carbonaceous fragments are common. Siderite is occasional and pyrite is rare. Nodular calcite cement (<50 cm thick), wood and carbonaceous material are rare. Bedding is largely absent due to bioturbation, with very rare cm-scale low-angle cross-laminations	1–15	BI=5 (<i>Ophiomorpha</i> , <i>Skolithos</i> , <i>Chondrites</i> , <i>Planolites</i>)	GR=65–70 API DT=75–160 µs/ ft NPHI=0.35– 0.56 p.u. RHOB=2.2– 2.7 g cm ⁻³	Settling from hypopycnal plume or fair-weather suspension deposition (bioturbated deposits) alternating with rare combined flow storm currents (laminated deposits)
C	Coarsening-upwards very-fine- to coarse-grained, heterolithic, dark–medium grey sandstone. Moderately sorted with subrounded to subangular grains. Calcite cement is occasionally present in thin beds (<50 cm). Parallel-laminated lamina sets bounded by low-angle truncation surfaces are identified as hummocky cross-stratification. Abundant mica and carbonaceous fragments identified along laminae. Laminated bed sets are 0.1–0.5 m thick with sharp, planar to hummocky tops. Bed sets are interbedded with bioturbated, shaly sandstone. Occasional shell fragments are organized in a chaotic manner but are rarely fully disarticulated, in thin beds (<10 cm)	1–5	BI=2–4 (<i>Ophiomorpha</i> , <i>Skolithos</i> , <i>Chondrites</i> , <i>Planolites</i>)	GR=40–100 API DT=50–120 µs/ ft NPHI=0.08– 0.42 p.u. RHOB=2.0– 2.4 g cm ⁻³	Storm-generated combined flow currents (laminated deposits) alternating with rare fair-weather suspension deposition (bioturbated deposits)
D	Medium- to coarse-grained, medium–light grey, planar laminated to trough and tabular cross-laminated sandstone. Quartz grains are typically clear to milky, occasionally pinkish. Well sorted but may occasionally be poorly sorted in thin beds (<15 cm) with subangular to subrounded grains. Rare mica and carbonaceous fragments. Rare calcite nodules. Shell fragments are common throughout. Occasionally, entire shells are preserved, usually in convex-up position	1–6	BI=0–1	GR=45–150 API DT=60–150 µs/ ft NPHI=0.14– 0.50 p.u. RHOB=2.1– 2.8 g cm ⁻³	Deposition under high hydrodynamic energy alternating from lower flow regime (dune-scale trough and tabular cross-laminated sandstone) to upper flow regime (planar laminated sandstone) in a marine setting
E	Medium- to coarse-grained, medium–light grey sandstone. Moderately well sorted. Quartz grains are translucent but occasionally smoky. Carbonaceous fragments and pyrite are rare. Thin (<5 cm) calcite nodules are occasionally present. Unit is structureless with very rare low-angle planar lamination. Broken shell material is common throughout	2–7	BI=0–1	GR=40–130 API DT=50–130 µs/ ft NPHI=0.04– 0.35 p.u. RHOB=1.9– 2.5 g cm ⁻³	Deposition dominated by fair-weather wave swash activity
F	Fine- to medium-grained, medium grey sandstone. Well sorted with subrounded grains. Mica and siltstone appear draped along laminae highlighting planar to trough –cross-stratified sandstone beds. Paired drapes are evident. Dip directions are commonly bidirectional. Thin shelled bivalves are present	1–3	BI=1–5 (<i>Palaeophycus</i> , <i>Planolites</i> , <i>Skolithos</i>)	GR=80–110 API DT=80–140 µs/ ft NPHI=0.12– 0.30 p.u. RHOB=2.2– 2.6 g cm ⁻³	Deposition with relatively high hydrodynamic energy under the influence of tidal currents
G	Sharp-based, fining-upwards, fine- to coarse-grained, medium grey, moderately- to poorly-sorted sandstone. Base may contain very coarse-grained sandstone with rounded grains. Abundant mica and carbonaceous fragments, along with intense bioturbation towards the top. Very rare high-angle cross-lamination to parallel lamination in thin beds (<0.1 m thick) particularly near the top. Only associated with Facies F	0.5–1	BI=4–5 (<i>Palaeophycus</i> , <i>Planolites</i> , <i>Skolithos</i>)	GR=40–100 API DT=60–130 µs/ ft NPHI=0.25– 0.36 p.u. RHOB=1.9– 2.4 g cm ⁻³	Waning current deposit in a tidal setting, as suggested by association with Facies F

Table 2. (Continued)

Facies	Description	Thickness in core (m)	Bioturbation and ichnotaxa	Wireline-log character	Interpretation
H	Fine-grained, grey sandstone interspersed throughout with lenses of siltstone and mudstone. Well-sorted with subrounded to subangular grains. Mica and carbonaceous material are common. Internal structures include ripple cross-lamination, isolated ripple sets and discontinuous laminae, which are evident in ripple troughs (mm scale). In siltstone-rich parts, lenticular and flaser bedding are evident. Wavy bedding is also present. Planar-laminated fine-grained sandstone beds occur rarely. Micro-faults are common. Body and trace fossils are typically absent	2–3	BI=0	GR=60–150 API DT=60–120 μ s/ ft NPHI=0.16– 0.48 p.u. RHOB=2.2– 2.5 g cm ⁻³	Rhythmically fluctuating tidal current activity in a protected setting
I	Sharp-based, fining-upwards, granular- to fine-grained, light grey, well-sorted sandstone. Grains are subrounded to subangular, and quartz is very common. Carbonaceous material is occasional with very rare mica. Generally appears structureless with rare planar-parallel laminations defined by higher siltstone content. Body fossils are absent. Bioturbation is variable with fine-grained sandstone being slightly bioturbated and coarse-grained sandstones being apparently structureless	0.1–4	BI=0–3	GR=30–80 API DT=60–110 μ s/ ft NPHI=0.12– 0.40 p.u. RHOB=2.1– 2.4 g cm ⁻³	Storm generated 'event' bed in a suspension-dominated setting, as suggested by association with Facies A or a thick waning flow deposit
J	Dark green to grey, poorly sorted, matrix-supported, medium- to coarse-grained sandstone. Beds are sharp based and occasionally calcite cemented. Blue- to smoky- to rose-quartz grains. Matrix contains granules and pebbles, glauconite, carbonaceous material and high concentrations of bioclastic fragments and intact shells. Beds are internally chaotic and structureless. Grain size typically fines upwards at the cm scale. Occurs at a distinct stratigraphical position marked by shifts from proximal to distal facies associations	0.1–1	BI=0	GR=60–70 API DT=100–140 μ s/ ft NPHI=0.32– 0.40 p.u. RHOB=2.1– 2.3 g cm ⁻³	Transgressive lag deposit as indicated by the stratigraphical position at shifts from proximal to distal facies associations

BI, bioturbation index; GR, gamma ray; DT, sonic travel time; NPHI, neutron porosity; RHOB, bulk density.

identified and are represented by high-value 'spikes' in the density log and low-value 'spikes' in the neutron porosity log. Beds of Facies I within siltstone-dominated successions of Facies A2 are marked by pronounced decreases in neutron porosity and sonic values, increased resistivity values and a slight decrease in gamma-ray values. The wireline-log signature of Facies I is clear where thick beds of this facies are developed; in thinner beds, however, the response is weaker, and only smaller spikes in the neutron porosity and sonic logs are observed (e.g. at 1484 m in Fig. 5b).

Interpretation. Facies A is characterized by highly bioturbated, very-fine-grained sediments, suggesting deposition of fine material from suspension fall-out (Howard & Reineck 1981; Collinson & Thompson 1989). The high concentration of siltstone and the lack of primary bedding structures suggests offshore deposits were subject to extensive bioturbation below storm wave base (MacEachern & Bann 2008), probably in a middle–outer shelf environment. The very dark colour of Facies A1 indicates a high organic content, which, when combined with the high bioturbation index, implies deposition in an environment ideal for benthic fauna with high nutrient and oxygen levels, and normal marine salinity. This interpretation is reinforced by palynofacies analysis. Facies A1 has a higher siltstone content compared to Facies A2, which may be indicative of a deeper water environment for the former, which is reinforced by the ichnotaxa present (Pemberton *et al.* 1992). Facies A1 coarsens upwards into Facies A2, signifying a shallowing of water depth.

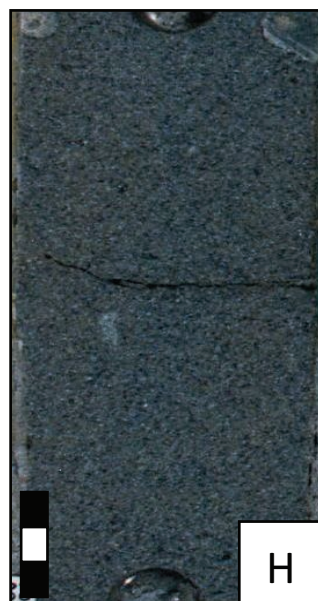
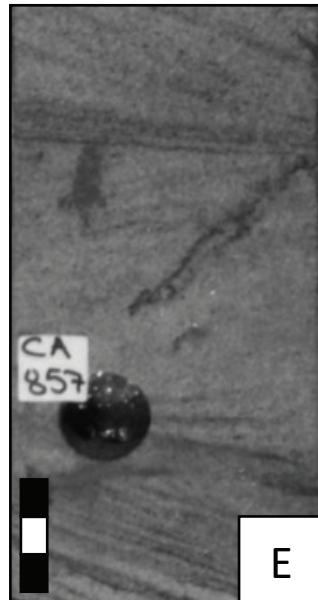
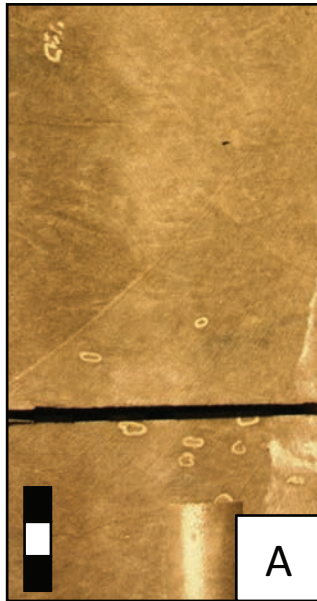
The isolated, sharp-based, very-coarse- to medium-grained sandstone beds (Facies I) are interpreted to be the product of high-energy events that were able to transport coarse-grained material into a relatively distal environment. A number of mechanisms have

been proposed for the origin of such deposits, including offshore sediment transport by major storms, floods, rip currents, river-fed hyperpycnal flows and tsunamis (Kumar & Sanders 1976; Gruszczynski *et al.* 1993; Mulder *et al.* 2003). Similar interpretations have been proposed for comparable beds in the Sognefjord Formation (Dreyer *et al.* 2005). Wells that contain thicker event beds are located in the northern part of Troll West, closer to the sediment source inferred for the Sognefjord Formation (Dreyer *et al.* 2005).

Facies Association 2: wave-dominated lower shoreface

Facies Association 2 (FA2) is identified throughout the Fensfjord Formation in the Troll Field (e.g. Fig. 6a) and in the Krossfjord Formation in Troll West (Fig. 3).

Description. FA2 is composed of 5–15 m-thick, upwards-coarsening successions of Facies B and C. Bioturbated, very-fine- to medium-grained sandstone that contain rare low-angle laminations (Facies B) at the base of the association pass gradationally upwards into very-fine- to medium-grained sandstone that contains rhythmically interbedded, hummocky cross-stratified and bioturbated intervals (Facies C). Sharp-based, poorly sorted, structureless beds of granular- to fine-grained, light grey sandstone (Facies I), which are 0.2–0.5 m thick, occur within Facies B and C. The dominant ichnotaxa recognized in FA2 are *Skolithos* and *Ophiomorpha*. *Planolites* and *Chondrites* are also evident, in addition to rare, fully disarticulated shell fragments. Bioturbation decreases in intensity from the base to the top of the association. Palynofacies analyses indicates an aerobic environment with relatively high salinity, low marine species diversity and low energy (GeoStrat 2011).



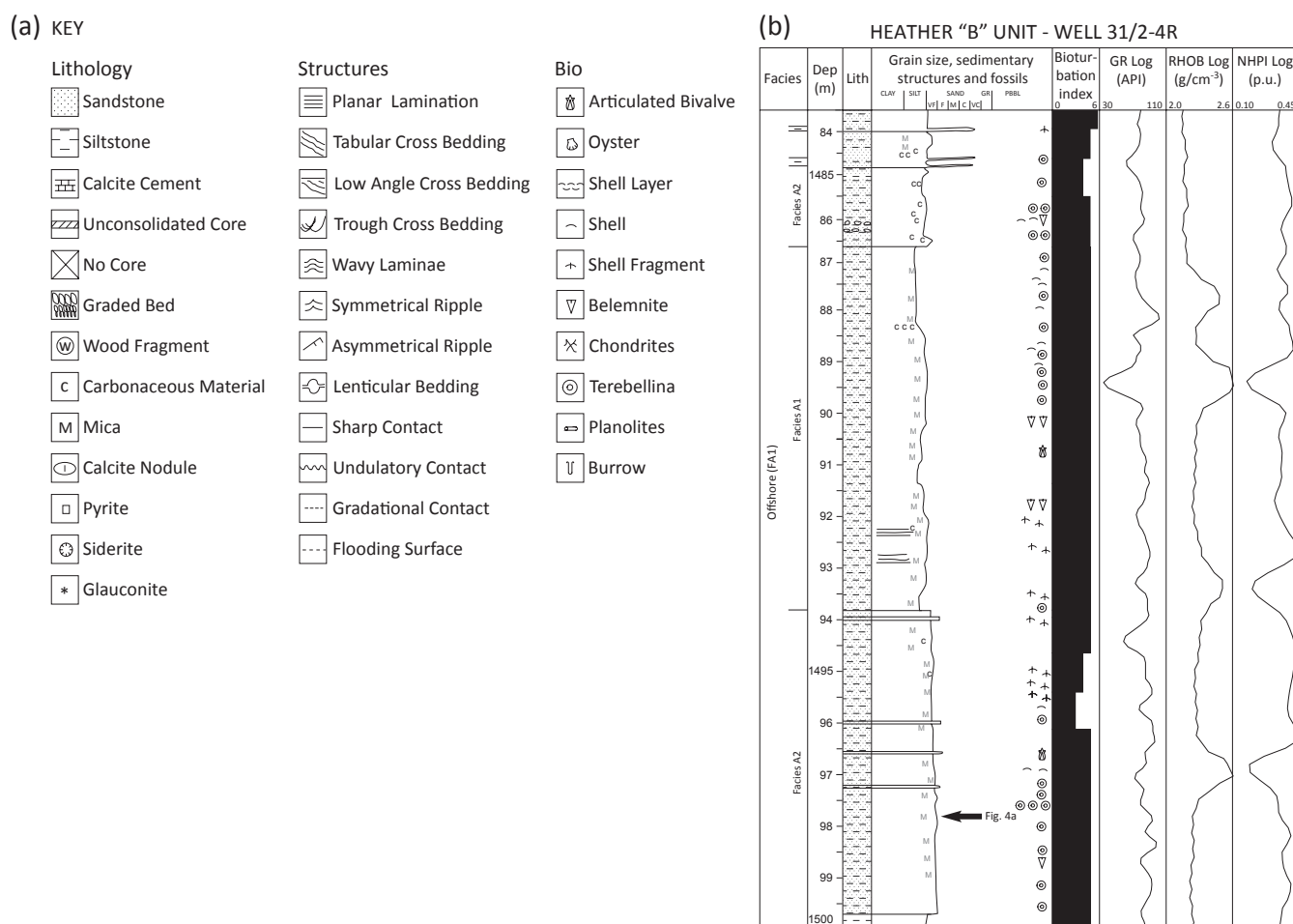


Fig. 5. (a) Key to facies association sedimentary logs and (b) sedimentary log through offshore facies association from well 31/2-4R. The well location is shown in Figure 3.

FA2 typically overlies other coarsening-upwards successions within the Fensfjord and Krossfjord formations (e.g. at 1618 m in Fig. 6a). The lower and upper boundaries of FA2 are sharp; the upper boundary is occasionally overlain by a dark green-grey, poorly sorted, matrix supported, medium- to coarse-grained sandstone (Facies J).

Wireline-log signature. The upwards transition from Facies B to C is represented on wireline logs by an upwards decrease in gamma-ray and density-log values, and an upwards increase in neutron porosity and sonic log values (e.g. from 1618 to 1612 m in Fig. 6a). The abundance of mica in Facies B and C results in FA2 having overall high gamma-ray values (Serra & Serra 2003) (e.g. at 1615 m in Fig. 6a; see also Fig. 8b).

Interpretation. FA2 is defined by the alternations between fair-weather suspension settling and more energetic hydrodynamic conditions. Facies B is composed of interbedded sandstone and

siltstone, which is indicative of fluctuating energy levels (Bourgeois 1980; Dott & Bourgeois 1982; Duke 1985). Siltstone is deposited via fair-weather suspension settling, whilst sandstone is deposited through waning, storm-generated suspension currents (Brenchley 1985). The high bioturbation index of siltstones in Facies B suggests that they record prolonged fair-weather periods that allowed biogenic reworking of the sediment. These characteristics are typical of the 'transition zone', which is above storm wave base but below fair-weather wave base (Reineck & Singh 1973), and which is referred to here as the 'distal lower shore-face' (*sensu* Van Wagoner *et al.* 1990). This zone was only disturbed by large, infrequent storm events. The low-angle, inclined lamina sets and beds identified in Facies C are interpreted as hummocky cross-stratification (HCS) (e.g. at 1612.5 m in Fig. 6a). HCS is the result of combined flow that is formed by a unidirectional current generated by a storm, which carries sand out from the coast under the influence of high-amplitude waves. The waves then disperse the sand through oscillatory motion, depositing

Fig. 4. Core photographs illustrating selected facies of the Krossfjord and Fensfjord formations: (a) Facies A, a fine-grained siltstone with *Terebellina* trace fossils (31/2-4R at 1498 m); (b) Facies C, a fine-grained sandstone with hummocky cross-stratification (31/6-1 at 1529 m) (NPD 2011); (c) Facies D, a tabular cross-stratified medium- to coarse-grained sandstone (31/5-5 at 1887 m); (d) Facies F, a cross-stratified sandstone with paired mud-draped laminations (31/6-6 at 1723 m); (e) Facies F, a cross-stratified sandstone with bidirectional mud-draped laminations (31/6-6 at 1770 m) (NPD 2011); (f) Facies G, a sharp-based, fining-upwards medium-grained sandstone (31/6-5 at 1714 m); (g) Facies H, a fine-grained sandstone with lenticular bedding and evidence of micro-faulting (31/6-1 at 1604.5 m); (h) Facies I, a well-sorted, graded, coarse-grained to granular sandstone (31/5-5 at 1866 m) (NPD 2011); and (i) Facies J, a very poorly sorted coarse-grained to granular sandstone with a sharp base (31/2-1 at 1658 m). Photographs are located in the successions illustrated in Figures 5–7, where possible. The black and white scale bar represents 3 cm.

it as hummocks (Bourgeois 1980; Dott & Bourgeois 1982; Duke 1985). Similar low-angle, inclined lamina sets and beds are interpreted as HCS in the Sognefjord Formation in the Troll Field (Stewart *et al.* 1995; Dreyer *et al.* 2005). The rhythmic interbedding of bioturbated sandstone and hummocky cross-stratified sandstone reflects the alternation between fair-weather deposition and storm deposition, in water depths that lie between fair-weather wave base and storm-wave base (Walker 1984; Brechley 1985). The prevalence of HCS in Facies C indicates a more proximal lower shoreface location (*sensu* Van Wagoner *et al.* 1990) compared to Facies B (Dott & Bourgeois 1982). Thin (<10 cm), structureless beds of Facies I are interpreted to have been deposited by gravity-driven or storm-related flows (cf. Dreyer *et al.* 2005).

Facies Association 3: wave-dominated upper shoreface and foreshore

Facies Association 3 (FA3) is identified in the Fensfjord Formation throughout the Troll Field (Fig. 6a), except in the upper part of the formation in Troll East. It is also present in the Krossfjord Formation.

Description. FA3 is 2–15 m thick, and is comprised of Facies D and E. Medium- to coarse-grained, well-sorted, planar laminated to trough and tabular cross-bedded sandstone (Facies D) is typically interbedded with and/or coarsens upwards into medium- to coarse-grained, apparently structureless, sandstone (Facies E). Broken shell material is common within FA3, although articulated shells are occasionally present, especially in Facies E (e.g. at 1618 m in Fig. 6a). Overall, FA3 is poorly bioturbated. FA3 always overlies FA2 in upwards-coarsening successions. Palynofacies analyses indicate an aerobic environment with relatively high salinity, low marine species diversity and high energy (GeoStrat 2011).

Well-log signature. Gamma-ray values in FA3 are usually low owing to the lack of clay and mica (Fig. 8c). Density values are also lower than for FA2, reflecting greater porosity in FA3 (Fig. 8c). Variability in the log signature of FA3 is principally due to patchy calcite cementation (e.g. at 1625.5 m in Fig. 6a).

Interpretation. Facies D lacks bioturbation, and contains an abundance of planar lamination and trough cross-bedding. The well-sorted character of the sandstone indicates extensive reworking, probably in a high-energy marine environment above fair-weather wave base (i.e. the upper shoreface: *sensu* Van Wagoner *et al.* 1990; see also Walker 1984). The facies lacks evidence of a tidal influence (e.g. reactivation surfaces, bidirectional current ripples: Nio & Yang 1991). Alternation of trough cross-bedding and planar lamination can be explained by the migration of longshore bars and troughs (e.g. Nielsen & Johannessen 2001). The bars were dominated by unidirectional currents, which winnowed out finer-grained material. Migration of the bars and superimposed 3D dunes resulted in the deposition of trough cross-bedded intervals. The parallel laminations, however, formed due to the passage of weaker currents through the inter-dune trough areas, which accounts for the overall finer grain sizes (cf. Gani & Bhattacharya 2007).

Facies E is common in the upper part of upwards-coarsening successions of FA3. The coarse-grained, very-well-sorted character of the sandstone in Facies E suggests constant wave action, which winnowed out finer grains (Hart & Plint 1995). The structureless appearance and rare parallel laminations is consistent with deposition in a foreshore environment characterized by swash processes, although similar structures have also been documented on the crest of bar forms (Hunter *et al.* 1979).

The vertical stacking of FA2 and FA3 to form overall upwards-coarsening successions is interpreted to represent progradation of a wave-dominated shoreface (Fig. 6a).

Facies Association 4: wave-dominated, tide-influenced upper shoreface

Facies Association 4 (FA4) is identified in the upper part of the Fensfjord Formation in Troll East only (Fig. 6b).

Description. FA4 comprises fine- to medium-grained, planar- to trough-cross stratified sandstone (Facies F). Cross-beds in Facies F appear bidirectional (e.g. Fig. 4e) and siltstone drapes are identified along cross-bed foresets (e.g. at 1710 m in Fig. 6b). These sandstones are interbedded with units of sharp-based, fining-upwards, fine- to coarse-grained sandstone, which are stacked to form upwards-fining units that are 0.5 m thick (Facies G). Facies G also contains abundant mica and carbonaceous fragments, and very rare parallel laminations are identified in thin beds (<0.1 m). The dominant ichnotaxa in FA4 are *Palaeophycus*, *Planolites* and *Skolithos*. Shell fragments occur sporadically throughout this facies association. Palynofacies analyses indicate an aerobic to dysaerobic environment with relatively low salinity, low marine species diversity and relatively low energy (GeoStrat 2011).

Successions of FA4 are 5–10 m thick and typically overlie lower shoreface deposits of FA2. FA2, in this context, is intensely bioturbated (e.g. at 1720 m in Fig. 6b). FA4 also occurs in association with FA5 in Troll East (Fig. 7a).

Well-log signature. The upwards transition from Facies F to Facies G is represented by a decrease in gamma-ray and neutron porosity values, and an increase in density values. This is due to the coarser grain size and lower mica content of Facies G compared to Facies F. The variable grain size in beds of Facies F and G gives FA4 an overall serrated appearance on wireline logs (e.g. at 1712 m in Fig. 6b).

Interpretation. The well-sorted character and abundance of planar- to trough-cross stratified beds in Facies F suggest a relatively high-energy depositional environment above fair-weather wave base (upper shoreface: *sensu* Van Wagoner *et al.* 1990). The occurrence of apparently opposed cross-bed orientations implies episodic reversals in flow direction. Sandstone laminae are also draped with silt, occasionally displaying rhythmical silt-layer couplets (cf. Visser 1980). The deposition of silt may have occurred during slack water periods associated with tidal currents (Nio & Yang 1991). This facies is therefore interpreted as being deposited in an upper shoreface environment where fair-weather wave-driven processes were modulated by tidal influence (cf. Vakarelov *et al.* 2012). Facies G consists of sharp-based, coarse-grained, fining-upwards sandstone beds, occasionally with a basal lag (e.g. at 1714.5 m in Fig. 6b), suggesting deposition by an energetic process that was able to erode into the underlying deposits. The units are thin (0.3–1 m) and commonly have bioturbated tops, implying that Facies G was deposited under waning flow conditions. Whilst such deposits can be formed by a number of processes (e.g. storm-generated rip currents or gravity flows generated by river floods), the position of this facies within tide-influenced deposits suggests they could be remnants of tidal channels (cf. Israel *et al.* 1987).

FA4 overlies lower shoreface deposits of FA2. In this context, Facies B appears highly bioturbated, which could reflect increased sediment colonization by burrowing organisms, promoted by tidal current action (Dashtgard *et al.* 2012). However,

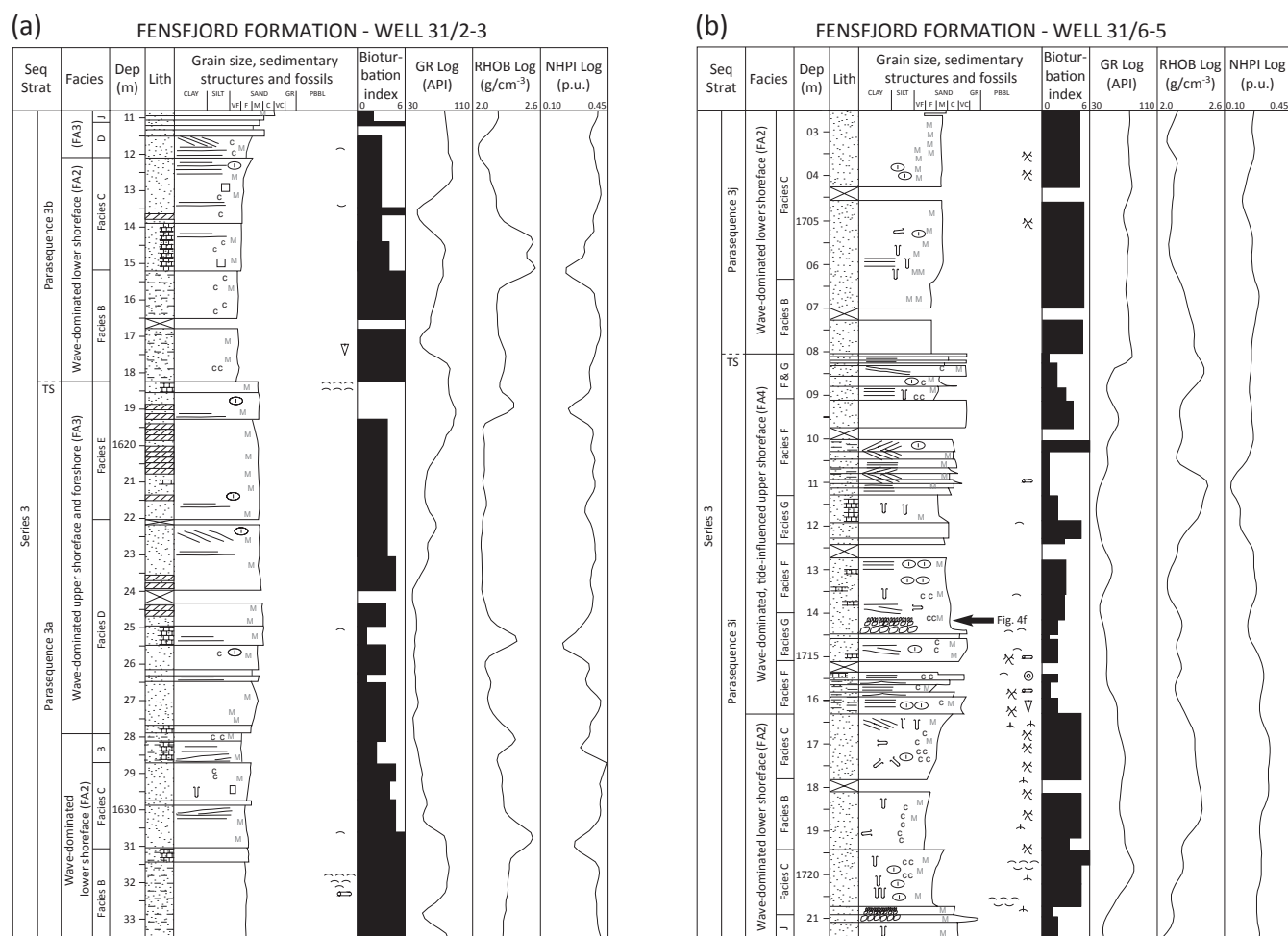


Fig. 6. (a) Sedimentary log through wave-dominated lower shoreface, and upper shoreface and foreshore facies associations from well 31/2-3 and (b) sedimentary log through wave-dominated, tide-influenced upper shoreface facies association from well 31/6-5, indicating parasequences bounded by local transgressive surfaces (TS). The well locations are shown in Figure 3.

there is no direct evidence to support a wave-dominated, tide-influenced lower shoreface succession, despite Facies B and C occurring beneath wave-dominated, tide-influenced upper shoreface deposits.

Facies Association 5: tide-dominated, wave-influenced embayment

Facies Association 5 (FA5) is identified in the middle of the Fensfjord Formation in Troll East (31/6-1; Fig. 7a).

Description. FA5 consists of fine-grained, well-sorted sandstone that contains lenses of siltstone or mudstone (Facies H). The facies association contains ripple cross-lamination, isolated ripple sets and discontinuous laminae, which occur on a mm scale (e.g. at 1605 m in Fig. 7a). The lenses of mudstone (> 1 cm thick) appear either laminated or structureless. Wavy-bedded lamina sets show regular reversals in the direction of ripple forest dip between beds. Planar-laminated fine-grained sandstone beds occur rarely in this facies association. Wavy bedding dominates Facies H but lenticular bedding and flaser bedding also occur. Interbedded sandstone and siltstone occur at the decimetre (dm) scale as the facies fines upwards. Syn-sedimentary micro-faults are also evident. Synaeresis cracks are not identified. Bioturbation and body fossils are absent. Palynological analyses indicate brackish conditions with relatively low energy (GeoStrat 2011).

The facies association is only identified in association with FA4; thin (<3 m) successions of FA5 are typically intercalated with thicker (5–10 m) successions of FA4. Contacts between these facies association are sharp.

Well-log signature. Gamma-ray, density and neutron porosity values are nearly uniform within FA5 (Figs 7a and 8e). Gamma-ray and neutron porosity values appear high and density values appear low compared to other facies associations. The only variability in these logs is due to the localized occurrence of calcite cement. In these cases, the gamma-ray and neutron porosity decreases and the density increases.

Interpretation. The interbedded rippled sandstone and mudstone layers suggest periodic fluctuations in hydrodynamic conditions, from high current velocity, capable of moving sand grains to form ripples, to slack water conditions, which allowed silt, mud and mica to settle out of suspension (Reineck & Wunderlich 1968). The planar-laminated sandstone beds are interpreted as event beds deposited from upper flow-regime conditions, most probably during storms based on the well-sorted, fine-grained character of the sandstones and the overall facies context. The upwards-fining trend seen in Facies H suggests that the overall hydrodynamic energy of the system was decreasing. The low bioturbation index may result from a narrow colonization window that is related to high rates of sedimentation (e.g. Gani

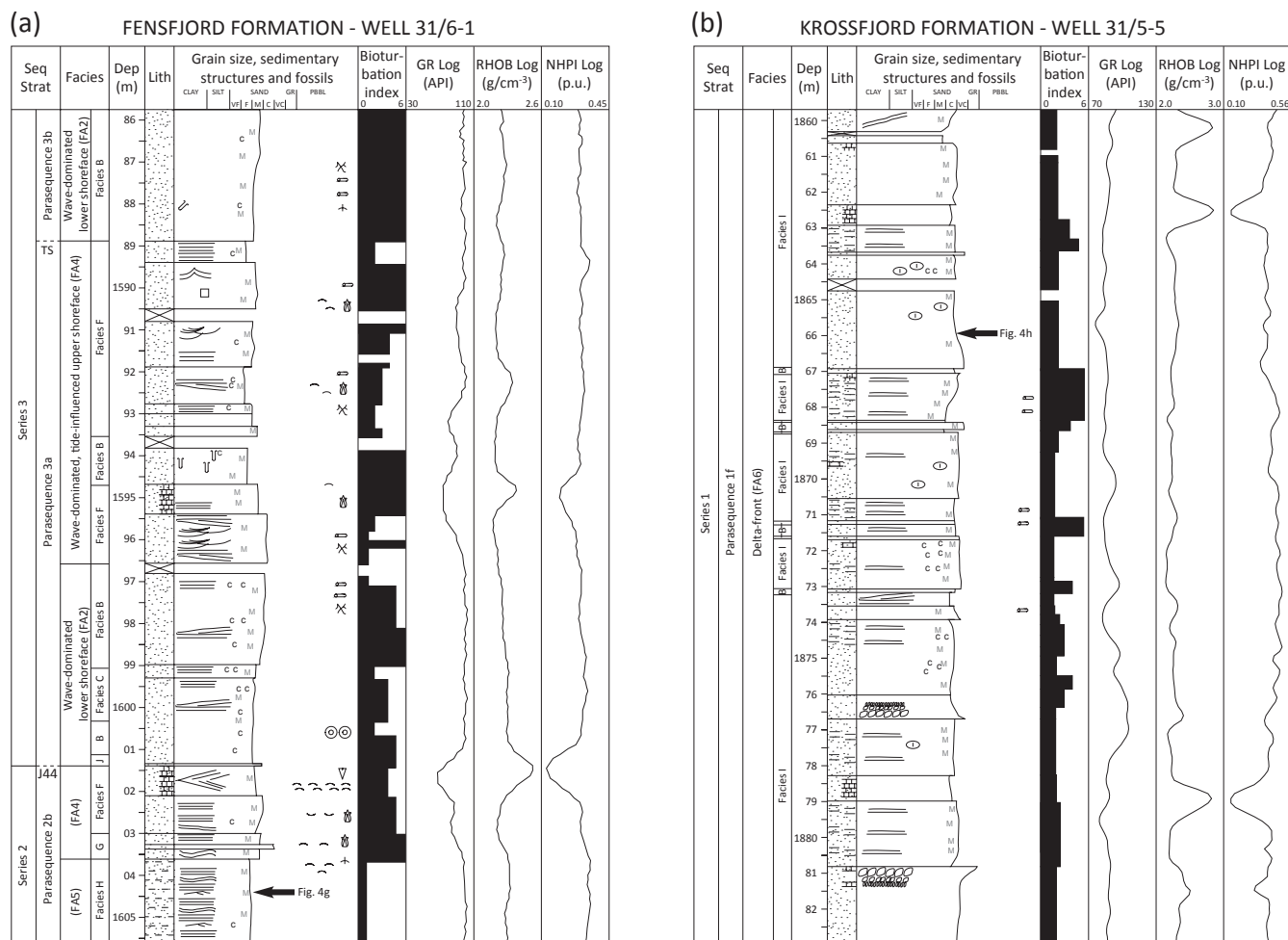


Fig. 7. (a) Tide-dominated, wave-influenced embayment facies association sedimentary log from well 31/6-1 and (b) delta-front facies association sedimentary log from well 31/5-5 with parasequences bounded by local transgressive surfaces (TS) and basic sequences (Series 1, 2 and 3) bounded by maximum flooding surfaces (J-). The well locations are shown in Figure 3.

et al. 2005) and/or brackish water conditions, and/or fluctuating salinities.

Periodic alternation of hydrodynamic energy is common to a number of tidal and estuarine environments such as subtidal flats, tidal channels and intertidal flats (e.g. Reineck & Wunderlich 1968). Flaser and wavy bedding have also been recognized in fluvial (Martin 2000) and lacustrine environments (Ainsworth *et al.* 2012). Furthermore, the thin, structureless mudstone lenses could represent fluid-mud deposits, which have been identified in tidal–fluvial channel successions, mouth-bar and terminal distributary channel successions, and delta-front successions (Ichaso & Dalrymple 2009). However, FA5 is only identified in association with FA4, which is interpreted as a wave-dominated, tide-influenced shoreface; this argues against a fluvial or lacustrine environment of deposition. FA5 is therefore interpreted to document tidally dominated deposition in a sheltered environment, such as an embayment. There is no evidence of subaerial exposure, implying deposition in a subtidal setting. The facies association is commonly associated with FA4, which suggests it represents shallow-water deposition above a wave-dominated, tide-influenced upper shoreface.

Facies Association 6: delta front

Facies Association 6 (FA6) is only identified in the Krossfjord Formation (well 31/5-5; Fig. 7b).

Description. FA6 is identified in one well only and is 30 m thick. This facies association is characterized by sharp-based, fining-upwards, well-sorted beds of medium- to coarse-grained sandstone (Facies I). These beds, which amalgamate to form units that are 2–4 m thick, are typically structureless, although rare planar lamination is observed. Rare (< 1 m thick) intervals of Facies I are calcite cemented. The tops of the fining-upwards units consist of 0.2–0.3 m-thick intervals of bioturbated, fine- to medium-grained sandstone (Facies B). Bioturbation is restricted to the top of the upwards-fining sandstone beds. No palynofacies analyses were conducted on the Krossfjord Formation.

Well-log signature. FA6 is characterized by uniformly high neutron porosity values, and uniformly low density and gamma-ray values (Figs 7b and 8f). Thin intervals of calcite cement (< 1 m) cause a decrease in neutron porosity values and an increase in density values (e.g. at 1862.5 m in Fig. 7b). Gamma-ray values are locally increased by high concentrations of carbonaceous debris (e.g. at 1875 m in Fig. 7b).

Interpretation. We interpret that the fining-upwards beds of structureless and parallel-laminated sandstone were deposited from high-energy, high-concentration submarine gravity flows, which were characterized by a high rate of deposition (Lowe 1982; Middleton 1993). The stacked, amalgamated nature of the beds implies repeated gravity flows (e.g. at 1875 m in Fig. 7b). Three

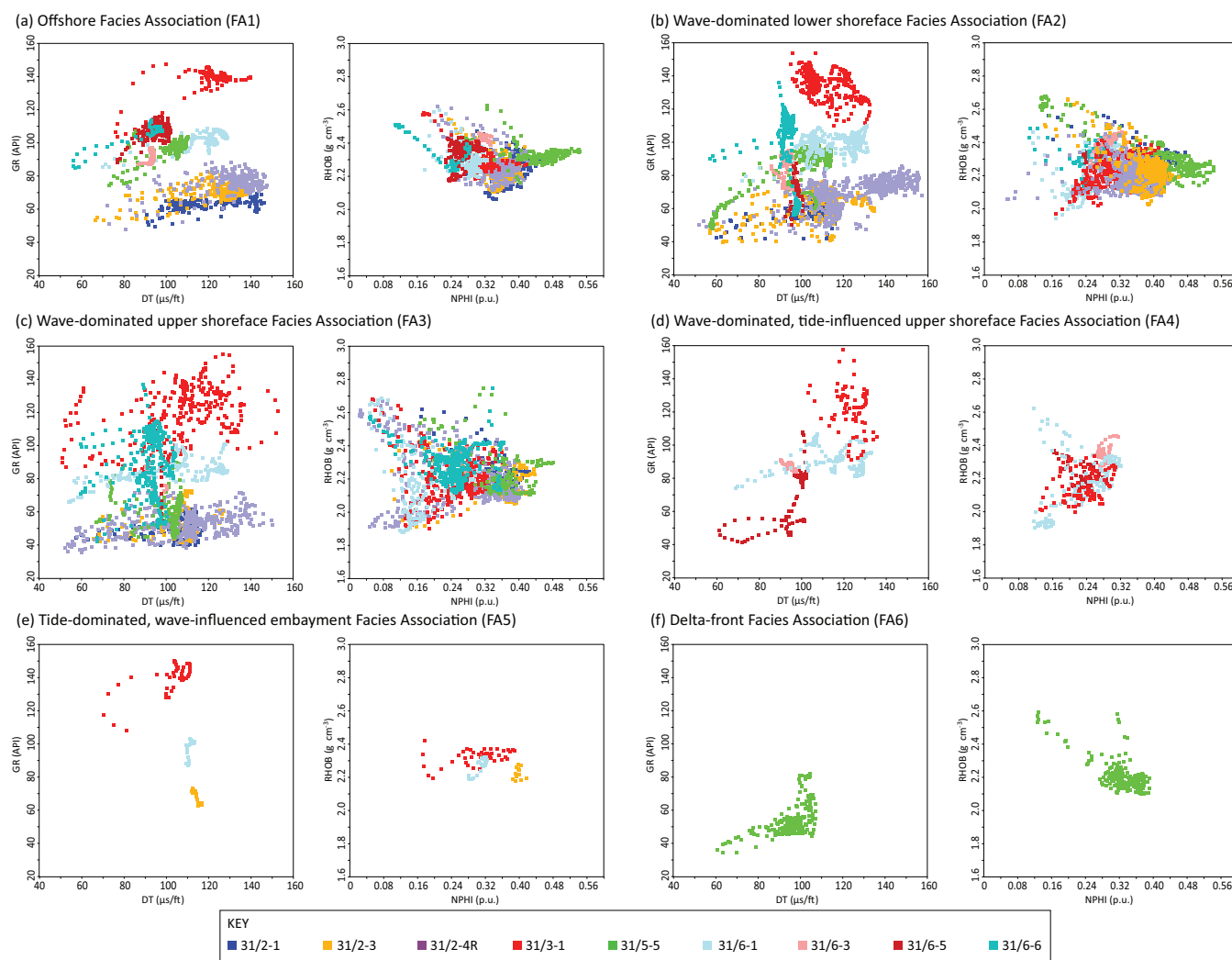


Fig. 8. Wireline-log cross-plots of gamma-ray (GR) v. sonic (DT) data, and density (RHOB) v. neutron porosity (NHPI) data. The cross-plots illustrate the quantitative log character of the facies associations identified in the Krossfjord and Fensfjord formations: (a) offshore; (b) wave-dominated lower shoreface; (c) wave-dominated upper shoreface and foreshore; (d) wave-dominated, tide-influenced upper shoreface; (e) tide-dominated, wave-influenced embayment; and (f) delta front. The cross-plots are compiled with data from logged core intervals. The cross-plots illustrate the absence of clear differences in quantitative log character between many facies associations, which limits their identification in uncored wells. The wireline logs were, therefore, only used to distinguish sandstone-rich facies associations from mudstone-rich facies associations.

mechanisms may plausibly produce the sediment gravity flows that deposited the thick-bedded, structureless sandstone of FA6. First, sustained hyperpycnal flows could be generated by the introduction of dense, sediment-laden water from rivers into the basin (Mulder *et al.* 2003; Plink-Björklund & Steel 2004). Second, repeated, retrogressive failure of sand-rich, shallow-marine mouth bars could generate turbidity currents (Olariu *et al.* 2010). Third, 'sediment breaching' (i.e. gradual retrogression of steep, subaqueous, sand-rich slopes) may generate sustained turbidity currents (Van Den Berg *et al.* 2002). The high-density character of the interpreted gravity flows favours a hyperpycnal flow or sediment-breaching origin. Based on the coarse grain size and the thickness of amalgamated beds in FA6, in combination with its close proximity to the sediment source at the palaeoshoreline, we interpret that FA6 was deposited in a proximal delta-front environment (cf. Mutti *et al.* 2000; Olariu *et al.* 2010).

SEQUENCE STRATIGRAPHICAL FRAMEWORK

A sequence stratigraphical framework has been created for the Krossfjord and Fensfjord formations in the Troll Field, using the

procedure outlined below. In each cored interval, facies associations are stacked vertically into upwards-shallowing successions bounded by transgressive surfaces, which are marked by landward facies shifts (e.g. FA3 overlain by FA2) (Figs 6 and 7). These upwards-shallowing successions are equivalent to parasequences (*sensu* Van Wagoner *et al.* 1990). Core observations indicate that parasequences typically have a wave-dominated (FA2 and FA3), mixed wave- and tide-influenced (FA2, FA4 and FA5) or a fluvial-dominated character (FA6). However, the various sandstone-prone facies associations have a similar wireline-log character (Fig. 8). As a result, parasequences can be recognized in uncored intervals and wells by vertical trends in wireline logs (e.g. intervals of upwards-decreasing gamma-ray values bounded by sharp increases in gamma-ray values) but their internal facies character cannot be confidently interpreted in the absence of core.

Correlation of groups of parasequences between wells has been constrained by field-wide mapping of major seismic reflectors and by biostratigraphical data (Figs 9 and 10). A high-resolution biostratigraphical scheme for the Fensfjord Formation in the Troll Field has identified 13 bioevents and six palynofacies associations (GeoStrat 2011). Major flooding surfaces, marked

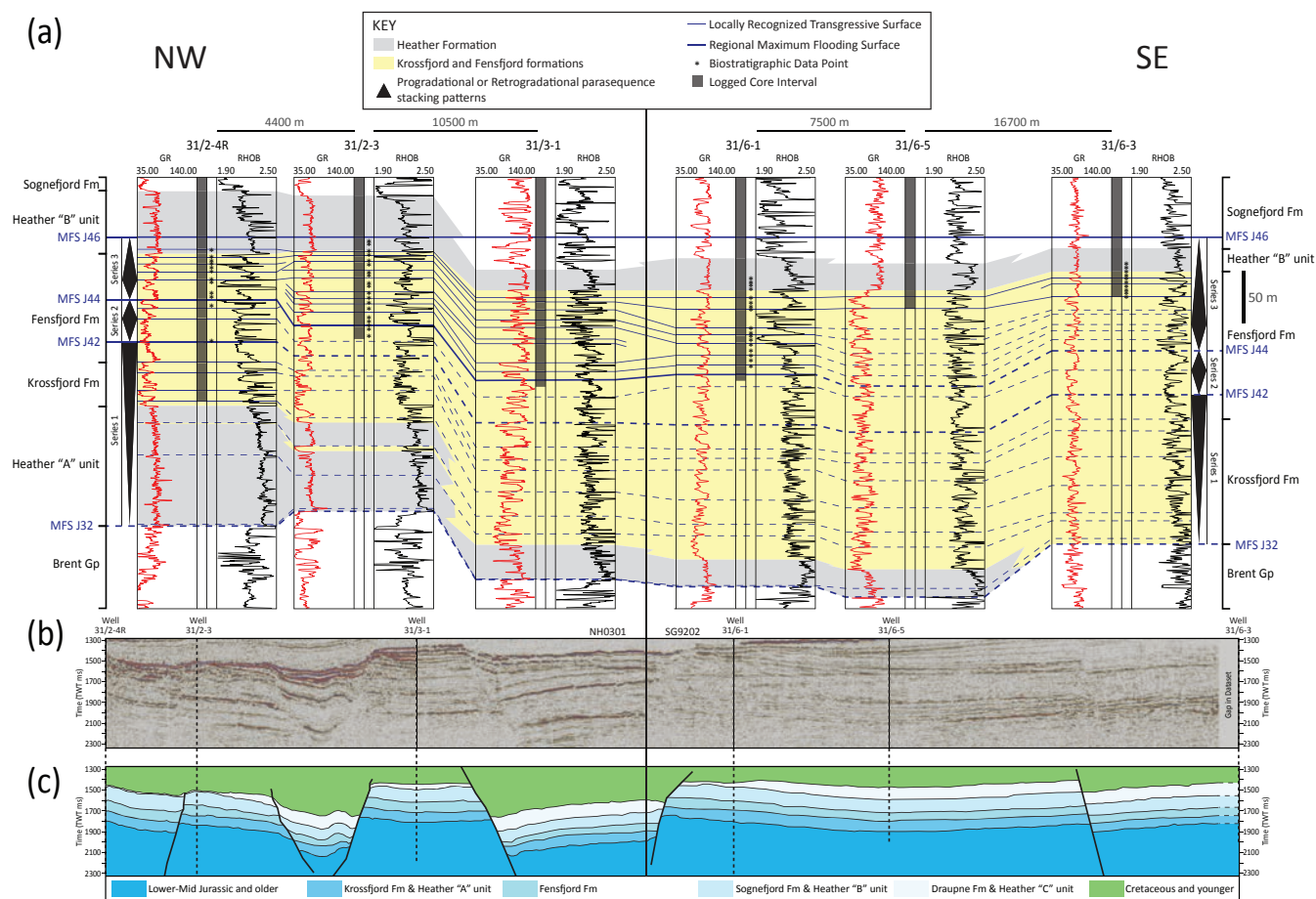


Fig. 9. (a) NW-SE-orientated (depositional strike-orientated) well-log correlation panel across Troll Field (see Fig. 3 for the location), using the MFS J46 as a flattened datum surface, (b) corresponding, uninterpreted composite seismic section and (c) geoseismic interpretation along the well-log correlation panel.

by pronounced landwards facies shifts in vertical successions, have been calibrated using biostratigraphical data to identify the maximum flooding surfaces interpreted throughout the northern North Sea in the widely used stratigraphical scheme of Partington *et al.* (1993) (so-called 'J surfaces'). In addition, and where data permit, minor transgressive surfaces recognized in core and wireline-log data have been correlated using the Troll Field biostratigraphical scheme described above. These have not been extended or correlated to other studies beyond the Troll Field. Biostratigraphical control is absent in uncored intervals, which broadly correspond to the lower Fensfjord Formation and Krossfjord Formation.

Sequence boundaries (*sensu* Van Wagoner *et al.* 1990) have not been interpreted because no surfaces marked by fluvial incision or subaerial exposure have been identified in core and wireline-log data. Furthermore, palynological analysis has not conclusively identified a non-marine or marginal-marine assemblage that defines a regionally developed surface (i.e. sequence boundary) that can be correlated across the Troll Field (GeoStrat 2011). As a consequence, the groups of parasequences (i.e. parasequence sets: *sensu* Van Wagoner *et al.* 1990) that are correlated between regional maximum flooding surfaces ('J surfaces') correspond to 'genetic sequences' (*sensu* Galloway 1989). Each of the parasequence groups that are bound by regional maximum flooding surfaces is designated as a numbered 'series' (or 'basic sequence'), following the established convention used to describe stratigraphical architecture in the Sognefjord Formation reservoir of the Troll Field (e.g. Dreyer *et al.* 2005). 'Series 1'

is bounded by the J32 and J42 maximum flooding surfaces at its base and top, respectively, and consists of the Heather 'A' unit, the Krossfjord Formation and the lowermost Fensfjord Formation (Figs 9a and 10a). Series 1 contains eight parasequences, which are stacked to form a single progradational parasequence set. 'Series 2' is bounded by the J42 and J44 maximum flooding surfaces at its base and top, respectively, and consists of the lower-middle Fensfjord Formation (Figs 9a and 10a). Series 2 contains three parasequences, the lowest of which constitutes a progradational parasequence set. The upper two parasequences are stacked within a retrogradational parasequence set, although not all parasequences can be distinguished in each well. 'Series 3' is bounded by the J44 and J46 maximum flooding surfaces at its base and top, respectively, and consists of the upper Fensfjord Formation and the lower Heather 'B' unit (Figs 9a and 10a). Series 3 contains a maximum of 10 parasequences. The lower five parasequences are stacked to form a progradational parasequence set, although not all five parasequences can be distinguished in each well, and the upper five parasequences constitute a retrogradational parasequence set. The vertical stacking of parasequences defines an overall progradational architecture in 'Series 1', and a progradational-retrogradational architecture in 'Series 2' and 'Series 3' (Figs 9a, 10a and 11).

Although major and minor flooding surfaces have been identified, systems-tract terminology has not been employed since no sequence boundaries have been confidently identified, as discussed above. The lack of evidence for a sequence boundary detailed above may reflect type-2 sequences where rapid subsidence

Krossfjord and Fensfjord formations, Troll Field

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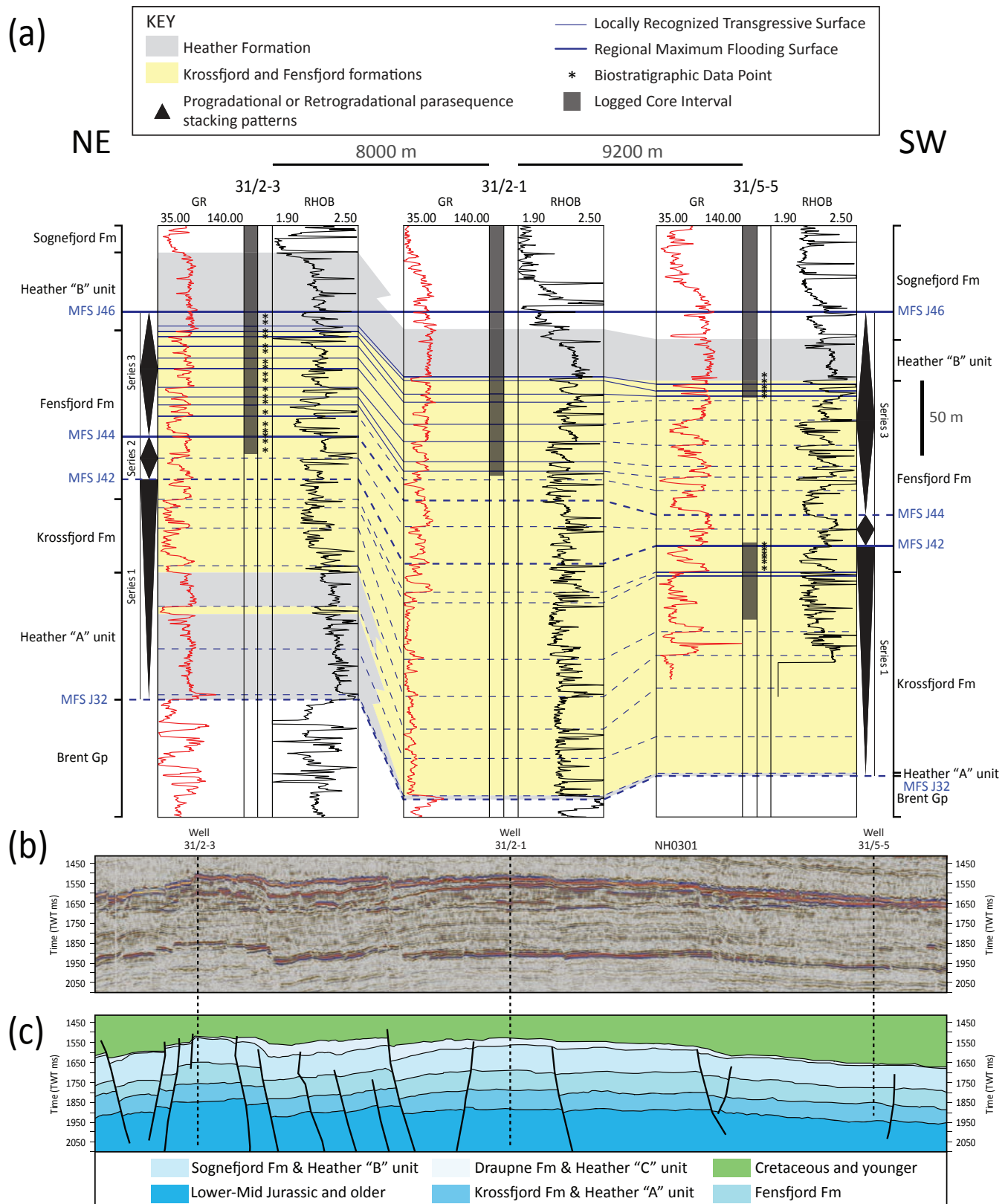


Fig. 10. (a) NE-SW-orientated (depositional dip-orientated) well-log correlation panel across Troll West Field (see Fig. 3 for the location), using the MFS J46 as a flattened datum surface, (b) corresponding, uninterpreted composite seismic section and (c) geoseismic interpretation along the well-log correlation panel.

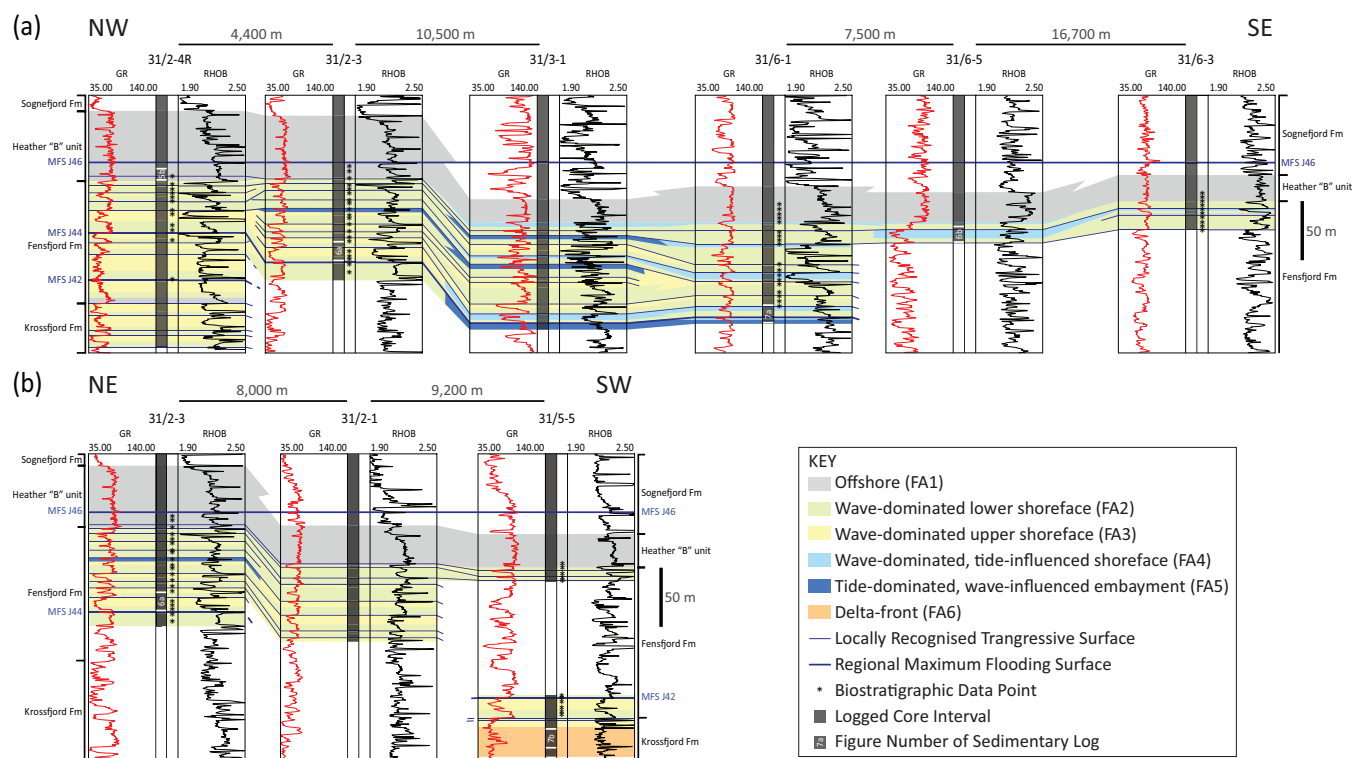


Fig. 11. (a) NW–SE-orientated (depositional strike-orientated) and (b) NE–SW-orientated (depositional dip-orientated) core-log correlation panels across Troll Field (see Fig. 3 for the location), using MFS J46 as a flattened datum surface.

exceeds the rate of sea-level fall preventing sub-aerial exposure (Posamentier & Vail 1988). Previous studies focusing on sequence stratigraphy in extensional rift basins have therefore placed the sequence boundary between the highstand and transgressive systems tracts (e.g. Posamentier & Allen 1993a, b; Howell & Flint 1996). However, without a detailed understanding of local variations in sediment supply and timing of activity on different fault segments, it is inappropriate to use systems-tract terminology for stratigraphical sequences deposited during rifting (e.g. Gawthorpe *et al.* 1994). Furthermore, we are unable to explicitly relate the observed stratal stacking patterns to discrete portions of the eustatic sea-level curve; in the context of the rift setting studied here, it is likely that stacking patterns are driven by tectonics (i.e. relative sea-level changes) rather than eustasy.

Well correlation panels

The sequence stratigraphical framework and corresponding facies association distributions are illustrated in three well correlation panels (Figs 9–11). Figures 9 and 10 illustrate wireline-log-based well correlations of the entire lower Viking Group (i.e. Heather ‘A’ unit, Krossfjord Formation, Fensfjord Formation and Heather ‘B’ unit). Figure 11 illustrates core-log-based well correlations of the upper part of the Fensfjord Formation only. The following subsections describe the sequence stratigraphical features of each stratigraphical unit.

Heather ‘A’ unit and the Krossfjord Formation. The Heather ‘A’ unit and the Krossfjord Formation are latest Bajocian in age (165 Ma) and lie above a regionally extensive transgressive surface that caps the Brent Group (MFS J32) (Partington *et al.* 1993). The top of the Krossfjord Formation does not correspond to a regional maximum flooding surface but is a minor transgressive surface (Figs 9 and 10). Wells, cores and wireline logs indicate that the Krossfjord Formation is coarser grained and has a higher sandstone content than the Fensfjord Formation.

The Krossfjord Formation and the Heather ‘A’ unit have been subdivided into seven parasequences that are approximately 5–25 m thick. None of the transgressive surfaces that bound these parasequences have been correlated to regional maximum flooding surfaces (cf. Partington *et al.* 1993) owing to a lack of robust biostratigraphical age constraints.

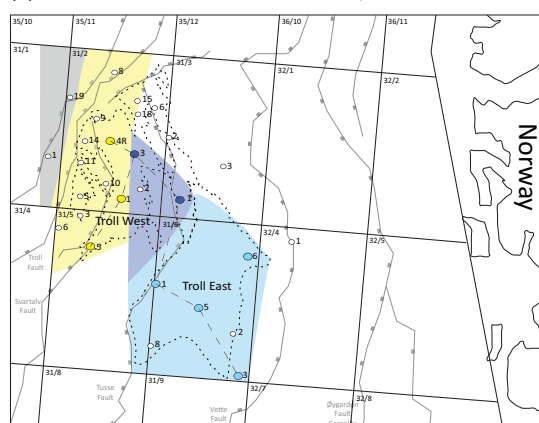
Well correlations show thickening of offshore mudstone (Heather ‘A’ unit) towards the north, (Figs 9a and 10a). This trend corresponds to thinning of the overlying Krossfjord Formation towards the north of the study area. Seismic data show no thickening of the Krossfjord–Heather ‘A’ interval towards or across faults (Figs 9b, c and 10b, c).

Overall, the Krossfjord Formation contains relatively thin parasequences (c. 5 m thick) at its base, thicker parasequences (c. 25 m thick) towards its middle of the formation and thinner parasequences (c. 10 m thick) towards its top (Figs 9a and 10a). Two distinct facies associations are identified in core in the upper part of the Krossfjord Formation; well 31/5-5 contains coarse-grained, delta-front deposits (FA6; Fig. 11b), whereas the most northerly well studied, 31/2-4R, contains three wave-dominated shoreface parasequences (each c. 15 m thick) bounded by local transgressive surfaces (FA2 and FA3; Fig. 11a).

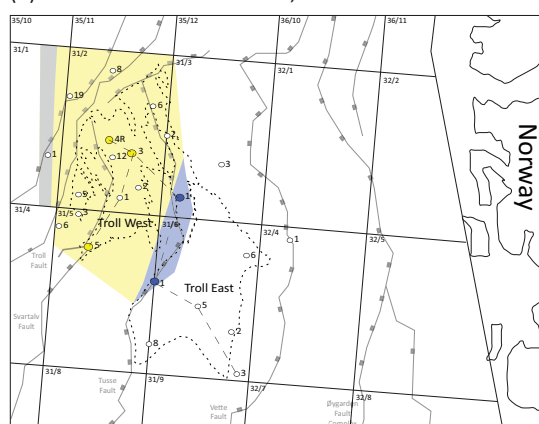
Fensfjord Formation. The base of the Fensfjord Formation is defined by a minor transgressive surface that is locally associated with an approximately 1 m-thick transgressive lag, which is rich in bioclastic material and is calcite cemented (wells 31/2-4R and 31/5-5 in Fig. 11). West of the Troll Field, towards the basin centre, a tongue of Heather Formation mudstones associated with this transgressive surface separates the Krossfjord and Fensfjord formations (Husmo *et al.* 2002). The top of the Fensfjord Formation does not correspond to a regional maximum flooding surface, and biostratigraphical data suggest that this lithostratigraphical boundary is diachronous (Fig. 9a).

Biostratigraphical data indicate that two regionally significant maximum flooding surfaces, the J42 (Early Callovian, 155.5 Ma)

(a) Series 3 - Middle to Late Callovian, below MFS J46



(b) Series 2 - Middle Callovian, below MFS J44



(c) Series 1 - Late Bathonian to Early Callovian, below MFS J42

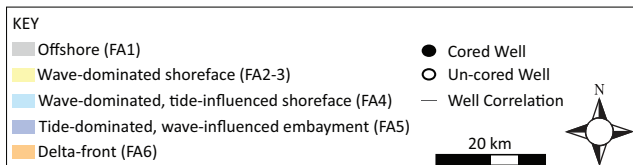
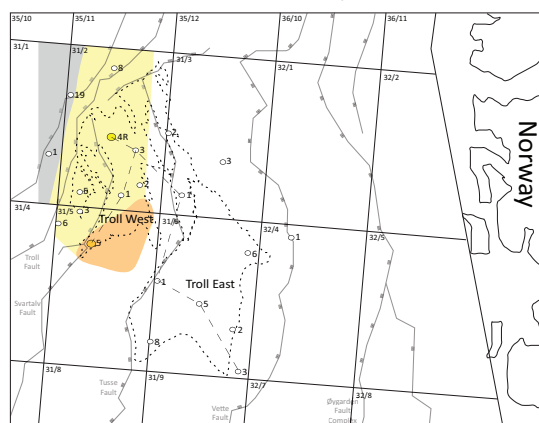


Fig. 12. Facies-association belt extents at maximum regression in the Troll Field as suggested by the well correlation panels (Figs 9a, 10a and 11) during (a) Middle–Late Callovian times (between MFS J44 and MFS J46), (b) Middle Callovian (between MFS J42 and MFS J44) and (c) Late Bathonian–Early Callovian (below MFS J42).

and J44 (Middle Callovian, 154Ma) surfaces, are developed within the Fensfjord Formation; these surfaces can be correlated across the Troll Field (Figs 9a and 10a). Regional maximum flooding surface J46 (Late Callovian, 152Ma) has not been

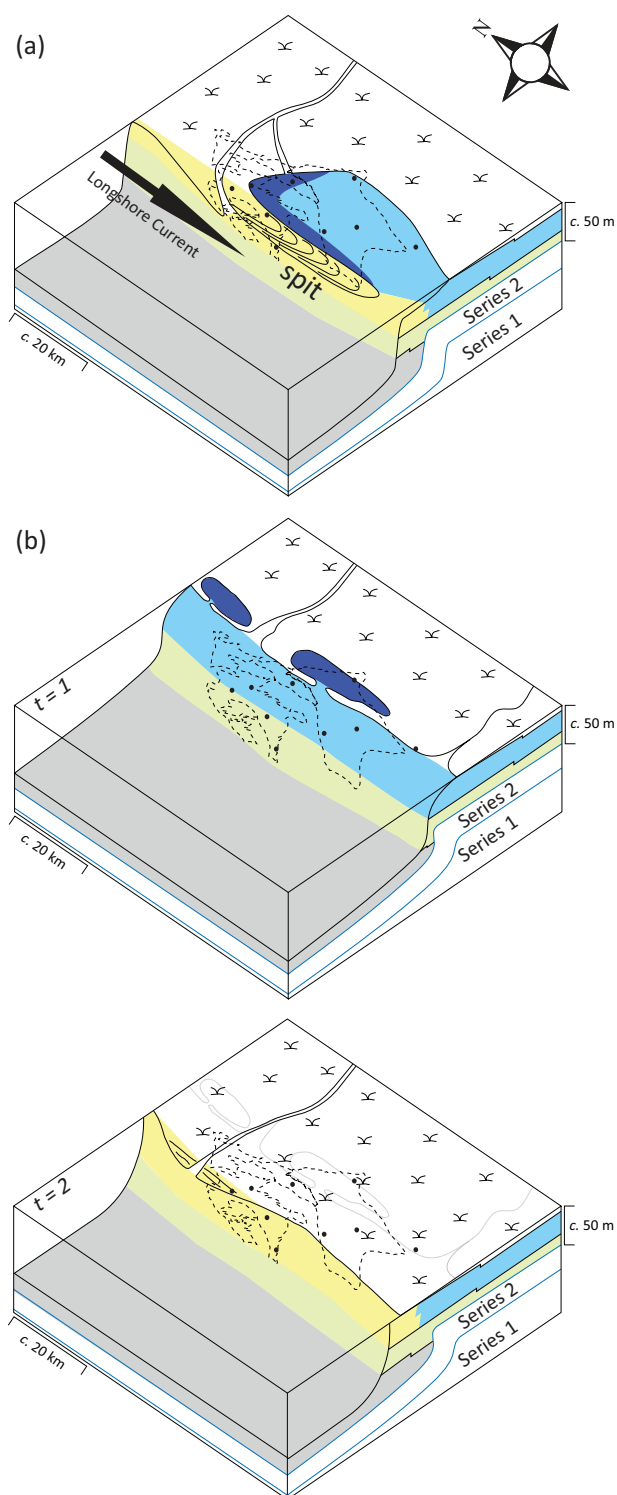
identified within the Fensfjord Formation but occurs in the overlying Heather ‘B’ unit or lowermost part of the Sognefjord Formation (S. Patruno pers. comm. 2011). The Fensfjord Formation can be further subdivided into 13 parasequences, each 10–40m thick, which are correlated across the Troll Field. The parasequences are of relatively uniform thickness laterally, and well and seismic data indicate that the Fensfjord Formation itself is isopachous (Figs 9 and 10). In Troll West, the parasequences typically comprise wave-dominated shoreface deposits (FA2 and FA3) (wells 31/2-4R, 31/2-1 and 31/5-5 in Fig. 11). Above maximum flooding surface J44, in an interval that contains abundant core control, wave-dominated shoreface parasequences commonly pass laterally, towards the east, into mixed, wave- and tide-influenced parasequences (FA2, FA4 and FA5) (wells 31/2-3, 31/3-1, 31/6-1, 31/6-5 and 31/6-3 in Fig. 11); the significance of this observation is discussed below.

Palaeogeographical reconstructions

Three palaeogeographical maps have been reconstructed from core and wireline-log data (Fig. 12). The maps illustrate the limit of facies belts at maximum regression within the ‘series’ that are bounded by regional maximum flooding surfaces (Figs 9a, 10a and 11). Because there are fewer well penetrations and fewer cored wells, the palaeogeographical reconstructions for the older stratigraphical intervals are less well constrained. Well data indicate no large-scale thickening across faults during the deposition of the Krossfjord and Fensfjord formations (Figs 9b, c and 10b, c), and as a result no active structures are indicated in the reconstructions. Because no fluvial deposits have been identified in core, no fluvial point source(s) of sediment input are shown in the reconstructions. Likewise, evidence for subaerial exposure (e.g. roots, pedogenic alteration) is also lacking in core, and therefore a subaerially exposed coastal plain is not shown in the reconstructions (Fig. 12).

Series 1: maximum regression Late Bathonian–Early Callovian, below MFS J42. A palaeogeographical reconstruction for maximum regression of the Krossfjord Formation, below the regional maximum flooding surface J42, has been compiled using core data from five wells and wireline-log data from 19 wells (Fig. 12c). Deposits of three environments have been recognized for this time period. Wave-dominated shoreface deposits (FA2 and FA3) are present in the NW part of Troll West (well 31/2-4R in Fig. 12c), and fluvial-dominated delta-front deposits (FA5) occur in the western part of Troll West (well 31/5-5 in Fig. 12c). Facies associations occur as linear belts orientated NNE–SSW across the study area, as constrained by the occurrence of offshore deposits (FA1) in uncored wells west of the Troll Field (Figs 9a and 10a).

Series 2: maximum regression Middle Callovian, below MFS J44. A palaeogeographical reconstruction for maximum regression of the lower Fensfjord Formation, below the regional maximum flooding surface J44, has been compiled using core data from five wells and wireline-log data from 18 wells (Fig. 12b). Wave-dominated shoreface deposits (FA2 and FA3) are identified in three cored wells in Troll West (wells 31/2-3, 31/2-4R and 31/5-5 in Fig. 12b), and these define a facies-association belt that extends across the Troll West Field and into the previously offshore area to the NW of the Troll Field. The facies belt is, therefore, wider than its equivalent in the previous time period (Fig. 12c; see also Figs 9a and 10a). To the east of this facies-association belt, tide-dominated, wave-influenced embayment deposits (FA5) are recognized in two cored wells in the centre of the Troll Field (wells 31/2-3 and 31/6-1 in Fig. 12b).



The lateral extent of this facies-association belt further to the east is not interpreted owing to the absence of core data. Facies-association belts are, again, orientated north–south.

Series 3: maximum regression Middle–Late Callovian, below MFS J46. A palaeogeographical reconstruction for maximum regression of the uppermost Fensfjord Formation, above the regional maximum flooding surface J44, has been compiled using core data from nine wells and wireline-log data from 18 wells (Fig. 12a). Wave-dominated shoreface deposits (FA2 and FA3) are restricted to the western half of Troll West (wells 31/2-1, 31/2-4R and 31/5-5 in Fig. 12a). Tide-dominated, wave-influenced embayment deposits (FA5) extend east across the centre of the Troll Field (wells 31/2-3 and 31/3-1 in Fig. 12a). Wave-dominated, tide-influenced shoreface deposits (FA4) occupy the entirety of Troll East (wells 31/6-1, 31/6-3, 31/6-5 and 31/6-6 in Fig. 12a). Offshore deposits (FA1) are identified to the west of the Troll Field in uncored wells (Figs 9a and 10a). Facies-association belts are, again, orientated broadly north–south but there are lateral variations in both thickness and facies distribution (e.g. the tide-dominated, wave-influenced embayment facies-association belt thins and pinches out towards the south) (Fig. 12a).

The palaeogeographical reconstructions highlight temporal and spatial variations in a depositional process regime (e.g. the dominance of wave, tide and fluvial processes) during deposition of the Krossfjord and Fensfjord formations. The western part of each reconstruction consistently shows that wave-dominated shoreface deposits (FA2 and FA3) form the outer part of the sandstone tongues that pinch-out towards the west and pass basinwards into offshore deposits. The eastern part of each reconstruction indicates a more variable process regime, with significant tidal and fluvial influence. The importance of a tidal influence appears to increase through time, becoming progressively more prominent from the Krossfjord Formation to the upper Fensfjord Formation (Figs 11 and 12), although it should be noted that core data from Troll East is only available to constrain the youngest reconstruction (Fig. 12a). In addition, the following features occur throughout deposition of the Krossfjord and Fensfjord formations: (1) no subaerially exposed coastal plain deposits are identified in the study area; (2) facies-association belts are orientated NNE–SSW; and (3) facies-association belts are of similar width across the study area. These various features are addressed by depositional models presented below.

DISCUSSION: DEPOSITIONAL MODEL FOR THE KROSSFJORD AND FENSFJORD FORMATIONS

The well correlations and palaeogeographical reconstructions presented above (Figs 11 and 12) highlight the complex spatial and temporal distributions of facies-association belts within the Krossfjord and Fensfjord formations of the Troll Field, albeit

Fig. 13. Block diagrams of depositional models illustrating the lateral change from mixed wave- and tide-influenced deposits to wave-dominated shoreface deposits from east to west across the Troll Field. Two end-member models are proposed: (a) spatial variation in depositional environments with a wave-driven spit system fronting a tide-influenced back basin; and (b) temporal variation in depositional environments with an early tide-dominated, wave-influenced embayment and shoreface developed on the inner–middle shelf ($t = 1$), evolving into a wave-dominated shoreface as it progrades to the outer shelf ($t = 2$). Coastal plain deposits are absent in the core, implying that they were either not deposited due to development of a broad subaqueous delta platform or they were removed by later transgressive erosion; the latter is implied in the block diagrams.

within a broadly similar range of shallow-marine environments. The facies associations and stratigraphical components recognized in the Krossfjord and Fensfjord formations are similar to those of the overlying Sognefjord Formation (Dreyer *et al.* 2005), suggesting that the same depositional model(s) may potentially be applicable to all three sandstone-prone formations in the Viking Group. In the following subsections the following three key aspects of the sedimentology and stratigraphical architecture of the Krossfjord and Fensfjord formations are discussed: (1) the east to west variation in depositional environments across the Troll Field; (2) the vertical increase in abundance of tide-influenced deposits; and (3) the absence of coastal plain deposits.

East to west change from mixed wave- and tide-influenced deposits to wave-dominated deposits in the upper Fensfjord Formation

Series 3, the upper part of the Fensfjord Formation (MFS J44–MFS J46), is characterized by pronounced partitioning between wave-dominated shoreface deposits in the west of the Troll Field and a mixed wave- and tide-influenced environment in the east of the field (Figs 11a and 12a). The change can be explained by spatial variation in the depositional process regime (Fig. 13a), temporal variation in the process regime (Fig. 13b) or a combination of the two (Fig. 13). In each model, the source(s) of fluvial sediment input to the shoreline is inferred to have been situated to the north of the Troll Field; this is consistent with previous interpretations (Fraser *et al.* 2002; Husmo *et al.* 2002; Dreyer *et al.* 2005) and is supported by the absence of fluvial deposits in core. The shoreline position is interpreted to have been consistently north–south orientated, in agreement with the linear arrangement of facies-association belts (Fig. 12).

The first depositional model (Fig. 13a) illustrates spatial variation in coeval environments. Sediment was supplied from a fluvio-deltaic source in the north, and redistributed through wave-generated, southward-directed longshore currents to form a spit in Troll West. The seawards face of the spit consists of a wave-dominated shoreface. The spit protects landwards areas from wave energy, which therefore appear to contain relatively stronger, and perhaps locally amplified, tidal energy in a tide-dominated embayment and back-basin setting in Troll East. Similar models have been proposed for the Sognefjord Formation of the Troll Field (Dreyer *et al.* 2005) and the Cretaceous Frewens Delta, US Western Interior (Willis *et al.* 1999), both in the context of asymmetrical delta systems (Bhattacharya & Giosan 2003). The Holocene Maguelone shoreline, SE France (Raynal *et al.* 2009), which is starved of fluvial sediment input, also displays a similar shoreline morphology, with sand spits fronting lagoons. However, the area immediately landwards of the spit barrier is typically composed of terrestrial vegetation and peat deposits (e.g. Nielsen & Johannessen 2001), neither of which is identified in cored successions in the Troll Field. Furthermore, foreshore deposits in spit systems commonly contain roots (e.g. Nielsen & Johannessen 2008), which are also lacking.

The second depositional model (Fig. 13b) illustrates temporal variation in environments, with early progradation of a tide-dominated, embayed shoreline to later progradation of a mixed wave- and tide-influenced shoreface, and finally progradation of a wave-dominated shoreface. A wave-dominated, tide-influenced environment is interpreted to exist during early progradation due to the wide-shelfal platform in front of the shoreline, which increases tidal resonance and decreases the effect of wave energy through friction (Hubbard *et al.* 1979; Pugh 1987; Ainsworth *et al.* 2011). Tidal embayments are created through topographical restrictions such as barrier islands (e.g. Oertel 1985). It has also been suggested that inner-shelf deltaic shorelines are irregular

and contain abundant topographical restrictions, which may locally amplify tidal range (Plink-Björklund 2012). With continued progradation, the width of the shelfal platform is decreased and wave processes become increasingly dominant, as illustrated for late progradation (Fig. 13b). The gradual change in the depositional process regime was driven by progradation of the shallow-marine depositional system, which reflects the interplay between sediment supply, accommodation and basin physiography (Ainsworth *et al.* 2008). Similar depositional models have been proposed for the Holocene Mekong River Delta (Ta *et al.* 2002) and the Holocene Song Hong (Red River) Delta (Tanabe *et al.* 2006).

Vertical increase in abundance of tide-influenced deposits

Well correlations of cored wells in the Troll Field highlight an increasing prevalence of tide-influenced deposits vertically through the Krossfjord and Fensfjord formations (Fig. 11), although it should be noted that the dataset is biased towards ‘Series 3’ in the upper part of the Fensfjord Formation (MFS J44–MFS J46). The pattern of upwards-increasing tidal influence could record the progressive progradation in ‘Series 1’ of parasequences (Fig. 9a) that are constructed via the mechanisms depicted in either depositional model (Fig. 13). However, the same architecture cannot be invoked for ‘Series 2’ and ‘Series 3’, which each exhibit progradational–retrogradational stacking of parasequences (Figs 9a, 10a and 11). More likely, the upwards increase in tidal influence reflects the change from progradational to retrogradational stacking in ‘Series 2’ and ‘Series 3’ (Figs 9a, 10a and 11), and from progradational to retrogradational stacking of the three ‘series’ (as noted by Steel 1993; Stewart *et al.* 1995; Husmo *et al.* 2002). Numerous studies document the preferential development and preservation of tidally influenced deposits in net-transgressive strata (e.g. Nio & Yang 1991; Sixsmith *et al.* 2008; Kieft *et al.* 2011).

Absence of coastal plain deposits

Coastal plain deposits are absent in cores from the Krossfjord and Fensfjord formations because either: (1) palaeosols were originally developed in each parasequence and then removed by transgressive erosion (i.e. ravinement); (2) palaeosols were not developed due to forced regression during relative sea-level fall; or (3) palaeosols were not developed due to construction of a broad, shallow, subaqueous platform during each parasequence-scale progradational episode.

Transgressive surfaces are identified at parasequence boundaries in both formations (Figs 9a, 10a and 11) and many are associated with lags that record erosional winnowing of the substrate (e.g. Fig. 4i). Transgressive erosion can remove up to 20 m of the substrate (Demarest & Kraft 1987) with such deep erosion being generally associated with channelized tidal scour. Forced regression during falling relative sea level results in the accumulation of thin, attenuated coastal plain deposits that are more readily removed by transgressive erosion than the thicker coastal plain intervals accumulated during normal regression (e.g. Posamentier & Morris 2000). However, the product of such deep erosion related to channelized tidal scour is a high-relief erosional surface lined by large angular shale clasts (Cattaneo & Steel 2003). Such features are not identified in core data and therefore argue against this explanation for the absence of coastal plain deposits.

Forced regression during falling sea level can also result in a complete absence of coastal plain facies. Three of the eight criteria used to identify forced regressive deposits by Posamentier & Morris (2000) are recognized in the Krossfjord and Fensfjord formations:

(1) the absence of fluvial or coastal plain facies capping regressive successions; (2) increased average grain size in regressive deposits in a proximal to distal direction due to the cannibalization and redistribution of older, proximal highstand sediments; and (3) the long distance of regression and anomalously thin character of parasequences due to decreased accommodation during lowering of relative sea level. Steel (1993) previously used the first and third of these criteria to propose forced regression for the development of parasequences in the Viking Group. However, two criteria identified by Posamentier & Morris (2000) are absent: (1) sharp-based shoreface deposits indicative of erosion of shelf deposits due to the lowering of wave base during falling relative sea level; and (2) a zone of shallow-marine sediment bypass as a result of sea-level fall, sometimes expressed as the detachment of lowstand shoreface deposits from their highstand precursor shorefaces. Furthermore, three criteria identified by Posamentier & Morris (2000) are indeterminable and therefore require further detailed analysis of seismic data including: (1) the progressive reduction in relief of clinoforms going from proximal to distal due to progradation into progressively shallower water; (2) seawards-dipping bounding surfaces on the top of parasequences due to the lowering of sea level; and (3) the presence of 'foreshortened' stratigraphical sections where the decompacted thickness of a coarsening-upwards sequence is less than the palaeowater depth. Therefore, conclusive evidence of forced regression appears to be absent but this may reflect the sparse distribution of core and well data in the Troll Field and surrounding area, and the limited analysis to date of clinoform trajectories in seismic data.

An alternative interpretation is that palaeosols were never developed during each progradational episode. This interpretation implies that the area of the Troll Field was subaqueous throughout deposition of the Krossfjord and Fensfjord formations, and that a broad, shallow, subaqueous platform was repeatedly constructed during each parasequence-scale progradational episode. The drowning of a broad, shallow platform during subsequent transgression may also have promoted the development of tidal embayments behind retreating barrier islands and spits. The development of broad subaqueous platforms is common in many modern deltas that are subject to significant wave and tidal action (e.g. Swenson *et al.* 2005; Plink-Björklund 2012), such as the Yangtze Delta, East China Sea (Hori *et al.* 2002). The development of broad, subaqueous platforms have also been interpreted in a handful of ancient examples, including the Cretaceous Wise Gulch, Berry Gulch and Morapos sandstones, US Western Interior (Hampson *et al.* 2008). Furthermore, through the detailed examination of clinoforms imaged in seismic data from the Troll Field, the development of a fully subaqueous deltaic system is proposed to explain the lack of coastal plain facies in the stratigraphically younger Sognefjord Formation (S. Patruno pers. comm. 2012).

CONCLUSIONS

The Middle–Upper Jurassic Krossfjord and Fensfjord formations are two shallow-marine sandstone tongues that form important secondary reservoirs in the super-giant Troll Field, and are prospective in surrounding areas of the Horda Platform on the eastern margin of the Viking Graben, northern North Sea. Regionally, both formations thin and pinch out into offshore shales of the Heather Formation towards the west, beyond the limit of the Horda Platform. This paper presents the first detailed sedimentological and stratigraphical analysis of the two formations in the Troll Field, as an aid to predicting reservoir distribution and character. The main conclusions of this core- and wireline-log-based analysis of the Krossfjord and Fensfjord formations in the Troll Field are summarized below.

1. Core observations indicate that mixed-influenced deltaic, shoreline and shelf environments were in existence during the Middle Jurassic in the area of the Troll Field. Palaeogeographical reconstructions of maximum regression show facies-association belts of similar width, orientation and distribution. A wide (10–20 km) belt of north–south-trending, wave-dominated shoreface deposits is present in the western part of the Troll Field. The eastern part of the field contains more irregular (0–20 km wide), north–south-trending belts of mixed wave- and tide-influenced shoreface, tide-dominated embayment, and/or fluvial-dominated delta-front deposits. The change from tide-influenced deposits in the east to wave-dominated deposits in the west can be attributed either to spatial variation in the depositional process regime within an asymmetrical delta fronted by a spit, or to temporal variation in the depositional process regime as the system prograded from a sheltered, inner-shelf location in the east to an exposed, outer-shelf location in the west.
2. Correlation between wells is constrained by field-wide mapping of major seismic reflectors at base-Heather 'A', top-Krossfjord and top-Fensfjord levels, combined with recognition of biostratigraphically distinctive, regional maximum flooding surfaces (J32, J42, J44 and J46) in cored wells. This framework allows recognition of three 'series' bounded by the regional maximum flooding surfaces. Analysis of the entire stratigraphical interval, its constituent 'series' and their component parasequences indicate relatively uniform thicknesses across the extent of the Troll Field, implying the absence of any major structural control on sedimentation during the Middle Jurassic in this area.
3. Coastal plain deposits are not identified in the Krossfjord and Fensfjord formations in the Troll Field. The absence may be attributed to the development of a broad, shallow, subaqueous platform across the Troll Field during repeated parasequence-scale regressions, to transgressive erosion at the top of each parasequence or to forced regression during falling sea level for each parasequence-scale regression. Forced regression is consistent with the thin, laterally extensive character of parasequences in the Viking Group over the Horda Platform and areas adjacent areas to the west.

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