The distribution of Cretaceous and Paleocene deep-water reservoirs in the Norwegian Sea basins

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ABSTRACT: Facies maps for selected Cretaceous and Paleocene deep-water sandstone reservoirs in the Norwegian Sea constitute an exploration tool and allow description of the basin infill in relation to tectonic phases. Sequences K40 (middle–late Albian) and K60 (middle–late Cenomanian) formed in an immature basin where most of the fan systems and slumps were derived from local highs. Sequence K80 (Coniacian–late Santonian) contains sandstones interpreted to be slumped deposits in parts of the Halten and Dønna terraces (Lysing Formation), but with fans of widespread extent in the Vøring and northern Møre Basin. The K85–K90 sequence set (early Santonian–late Campanian) contains sandstones equivalent to the Nise Formation that are the main potential reservoirs in the Vøring Basin; they were fed by multiple entry points and developed into areally extensive basin floor thicks. Sequence Pg10 (Danian–Selandian: 'Egga' Member) is interpreted to comprise a basin floor fan in the Ormen Lange discovery. During this cycle the Halten Terrace rotated eastwards exposing Upper Cretaceous mudstones. Vast amounts of sediment were deposited in the western Møre and Vøring Basin around new exposed areas.

KEYWORDS: *Norwegian Sea, stratigraphy, sedimentation, deep water, sandstone reservoir, oil and gas exploration*

INTRODUCTION

Most of the drilling activity in the Norwegian Sea and adjacent areas has been concentrated on the Halten Terrace, the Trøndelag Platform and the Møre Margin, with only limited, recent drilling of structures in the frontier, deep-water Møre and Vøring basins (Fig. 1). As most of the early wells targeted Jurassic reservoirs, the stratigraphy of the Cretaceous and Tertiary has received less exhaustive study. With the recent trend of exploration of the Møre and Vøring basins targeting Cretaceous and Tertiary deep-water reservoirs, a greater understanding of these depositional systems is necessary.

Two of the major risks to be considered when evaluating prospects in this area are the presence and quality of Cretaceous and Tertiary reservoirs. These are difficult to assess for several reasons: the lack of wells, the variable seismic quality or poor acoustic response of the sandstone intervals and the complexity of deep-water depositional systems. This paper describes the study of the Cretaceous and Paleocene facies of the Norwegian Sea carried out for the 16th Licensing Round, which closed in January 2000.

Most of the previous publications on the regional geology of the Norwegian Sea covering the Cretaceous–Paleocene have proposed several kinds of tectonic models (see overview in Gabrielsen & Doré 1995), have addressed structure and paleogeography (e.g. Hinz *et al.* 1993; Bjørnseth *et al.* 1997; Lundin & Doré 1997; Roberts *et al.* 1997; Brekke *et al.* 1999; Gabrielsen *et al.* 1999; Larsen *et al.* 1999; Martinsen *et al.* 1999), regional sedimentation (Shanmugan *et al.* 1994; Morton & Grant 1998) and hydrocarbon exploration (e.g. Koch & Heum 1995; Doré *et al.* 1997; Aram 1999; Kittilsen *et al.* 1999; Sánchez-Ferrer *et al.* 1999). More recent contributions following on after the completion of our investigation include Brekke (2000), Skogseid *et al.* (2000) and Mogensen *et al.* (2000). Very few publications, however, have proposed regional sequence stratigraphic or depositional models (Swiecicki *et al.* 1998), or have shown well correlations of Cretaceous strata.

In this paper we attempt to map the distribution of deep-water sandstones in the Møre and Vøring basins and to describe the basin sedimentary infill in relation to tectonic events. A simplified sequence stratigraphic framework for these successions is described, aimed at correlating the wells of the Halten Terrace and Trøndelag Platform with those drilled in basinal areas. The maps illustrate the potential presence of sandy areas but do not necessarily imply commercial sandstone reservoirs. The predictive value of the facies maps for hydrocarbon exploration is the main contribution of this paper. However, they also provide an insight to the evolution during

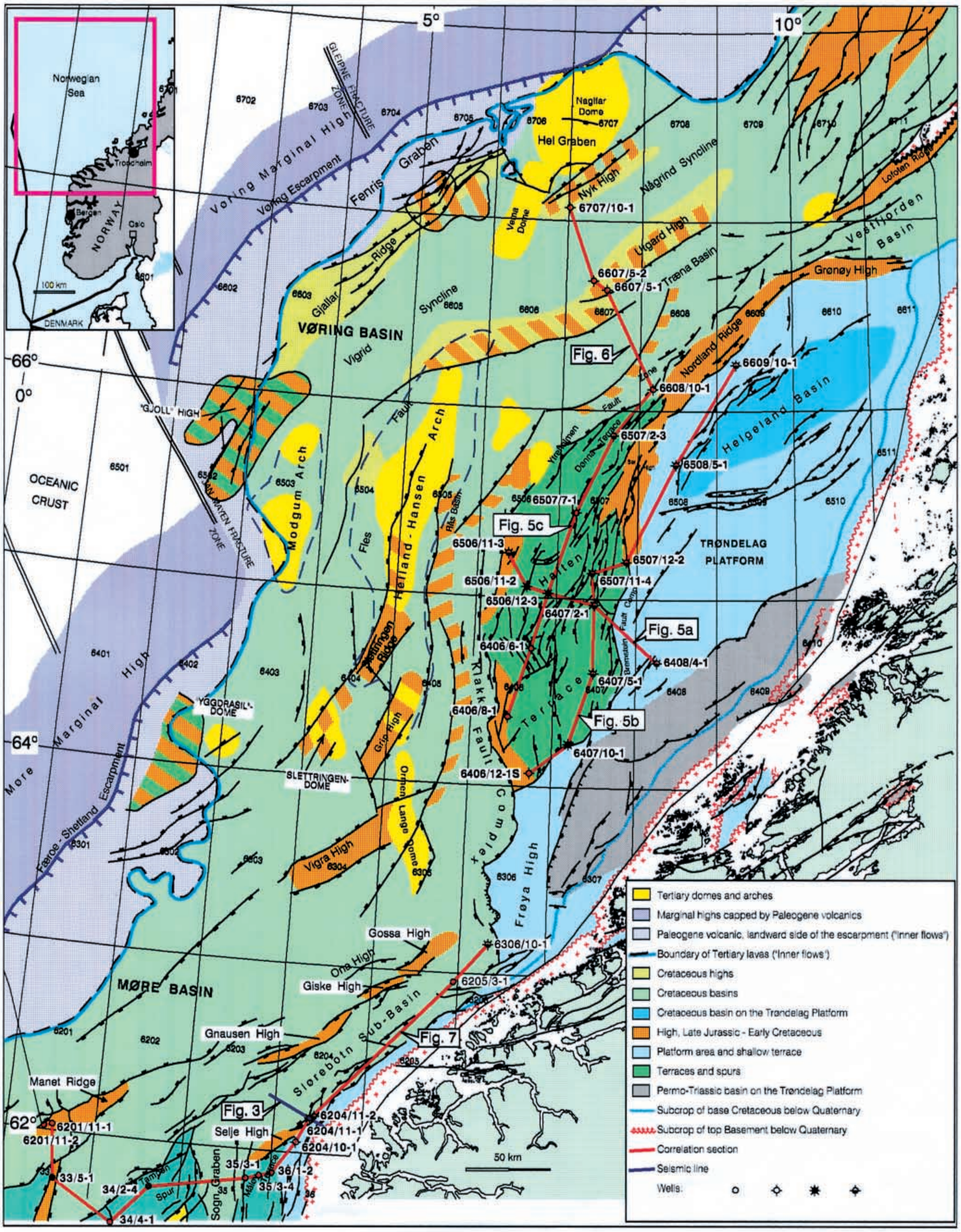

Fig. 1. Structural elements of the Norwegian Sea (modified after Blystad *et al.* 1995). See location of correlation sections (Figs 4 and 5) and of the seismic line of Figure 3.

Cretaceous to Paleocene times of the Mid-Norwegian shelf by furnishing an overall semi-detailed sedimentation history (Fig. 1).

TECTONIC SETTING

The major tectonic elements of the Norwegian Sea are illustrated in Figure 1, modified from Blystad *et al.* (1995), who defined them with reference to the Base Cretaceous unconformity (BCU). Elements such as the Fles Fault Complex, Gjallar Ridge, Naglfar Dome and Nyk and Utgard highs are important to the current depositional models. Other structures such as the informally termed 'Gjoll' High or 'Yggrasil' Dome have been mapped (Fig. 1). The deep basins are composed of greatly expanded Cretaceous successions, over 7 km thick in the Møre Basin, up to 8 km in the Southern Vøring Basin west of the Fles Fault Complex, over 7 km in the Rås and Træna basins and up to 6 km in the Någrind Syncline.

The eastern North-Atlantic continental margin, including the Norwegian Sea, has undergone multiple rift events throughout its evolution since the Carboniferous, (e.g. Ziegler 1990; Hinz *et al.* 1993; Brekke *et al.* 1999, and references therein). A late Middle Jurassic to Early Cretaceous extensional event is responsible for the formation of many tectonic elements of the Norwegian Sea (Blystad *et al.* 1995). According to Doré *et al.* (1997) major rifting occurred during the Late Jurassic and was followed by Cretaceous post-rift thermal subsidence with intermittent extensional phases. Upper Cretaceous sandstones (Cenomanian to Coniacian) were deposited as a result of tectonic activity along the Nordland Ridge (Lundin & Doré 1997). An important uplift event over wide areas of the North Atlantic Ocean, linked to thermal doming of the Iceland plume occurred during the Maastrichtian–Danian (e.g. Knott *et al.* 1993; Nadin & Kusznir 1995), but there is no consensus about the precise timing of its onset. A recent paper by Skogseid *et al.* (2000) discussed in detail the emplacement of the plume body beneath the lithosphere.

The Paleocene–Eocene break-up of the continental crust marked the beginning of crustal separation between Greenland and Eurasia (Ziegler 1990), causing increased volcanism coupled with plateau lavas, which peaked during the Eocene. Major Tertiary compressional events related to broad-scale inversion of depocentres (datings differ among authors: compare, for example, Bjørnseth *et al.* 1997 with Doré *et al.* 1997) are manifested as huge domes along the NE Atlantic margin. These events are linked to plate motion changes where the NW–SE transfer zones such as the Jan Mayen fracture zone in the Norwegian Sea (Fig. 1) have played an important role (Doré & Lundin 1996).

The Scandinavian landmass was a main sediment source for the Cretaceous reservoirs to the east. The Jan Mayen Microcontinent west of the study area might have been emergent already by Cretaceous times (e.g. Brekke *et al.* 1999), supplying with sediment the western Møre and Vøring basins. However, the conventional hypothesis is that east Greenland delivered sediments into these basins (e.g. Ziegler 1990; Kuvaas & Kodaira 1997; Larsen *et al.* 1999). This is now a matter of considerable debate that we do not intend to resolve here.

METHODS

Facies maps for key intervals considered important for hydrocarbon exploration were constructed using wells, 2D/3D seismic data, regional isochore-time maps, seismic amplitude maps and, to a lesser extent, seismic facies maps, depending on the information available for each particular area. The connection

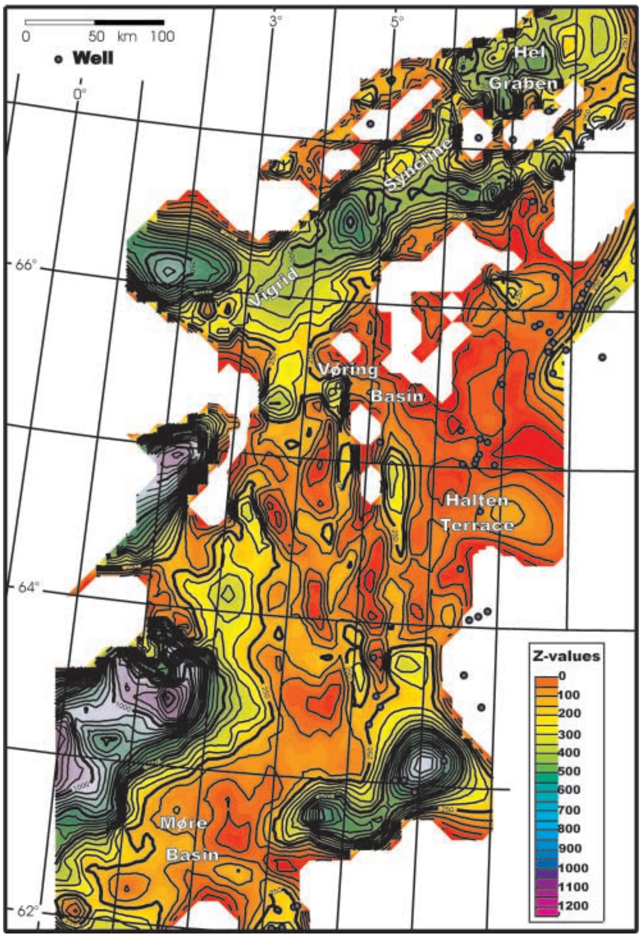

Fig. 2. Regional base to top Paleocene isochore map. Z-values correspond to isochores in time (ms). Note depocentres in the Møre Basin, Vigrid Syncline and Hel Graben. White patches are zones where the Paleocene succession is thin or absent. For interpretation see text.

between isochores with known thicknesses from wells and seismic information was essential. Thick areas where well control indicates they are sandy were interpreted basinwards into undrilled regions as sand-prone areas. Producing multiple isochore maps for a single interval by varying the colour patterns of the vertical thickness scale allowed selection of the most likely isochore to delimit sand-prone areas. On the selected isochore one can readily recognize geometries with evident geological significance, since their outline closely resemble fan lobes with a common sediment fairway as sketched in several turbidite fan models (e.g. Richards 1996). This was particularly evident in the Slettringen Ridge area (Fig. 1). Regional isochore maps reveal depocentres (troughs), thins (swells) or areas with no section (emerged or eroded), and allow one to infer the sediment dispersal patterns. The Paleocene isochore-time map is shown as an example in Figure 2; it was used as the basis for the facies map of the Lower Paleocene sequence, discussed later.

The main reservoirs in the area usually have a seismic expression of higher amplitude reflectors (Fig. 3) that can be traced and mapped compared with the remainder of the succession which is considered dominantly argillaceous. An excellent example of this can be seen in Kittilsen *et al.* (1999, fig. 2), where the Nise equivalent sandstones penetrated in the Nyk High well (6707/10-1) have a conspicuous seismic expression. Many sequences of different orders can be identified in various

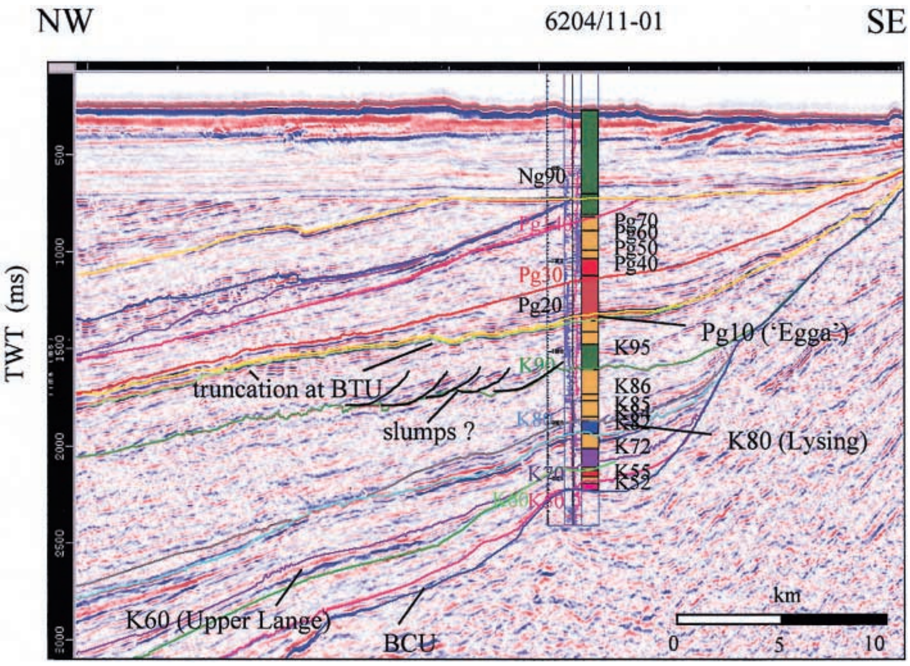

Fig. 3. Example of seismic line with well, Møre Basin, showing the Cretaceous–Tertiary succession. Note the higher frequency of sequences in the well compared to the seismic events, and high seismic amplitudes in sandstone-bearing sequences Pg10–20, K80, K60. Seismic data courtesy of TGS-NOPEC Geophysical Company. See Figure 1 for location.

wells, but those lacking seismic expression and not representing regional reservoirs were ranked of secondary importance. Sand-prone areas could also be interpreted from amplitude maps in specific areas, especially with 3D seismic coverage. The extension of high amplitude sheet-like reflectors on 2D seismic data was mapped with confidence when it showed a consistent picture (e.g. sequence K80 around the Slettringen Dome area) but, in general, discretion was practised when interpreting varying seismic amplitudes, especially when derived from different surveys.

Most of the palaeobathymetry and chronology adopted is based on a non-exclusive study of 51 wells in the area carried out in 1999 by Robertson Research International (RRI) for RWE-DEA Norge. Additionally, a detailed palynological study of 69 samples of Nyk High well 6707/10-1 was conducted by RWE-DEA's laboratory in Wietze (Germany). Well correlations along relevant sections are presented here as chronostratigraphic diagrams. The palaeobathymetry given by the microfaunal assemblages was complemented by studies of core data and flexural backstripping in the case of sequence K80 on the Halten Terrace. The paleogeographic maps for the Møre Basin are modified from a non-exclusive PGS study released in 1999.

SEQUENCE STRATIGRAPHY AND REGIONAL SEISMIC INTERPRETATION

This section describes the stratigraphic framework used during this evaluation. Lithostratigraphy is based on the scheme of Dalland *et al.* (1988). Other terms (i.e. Nise equivalent, 'Egga' Member, Upper Lange sandstones) are used informally. In the south of the Norwegian Sea, i.e. south of 63°N, the lithostratigraphy is considered to be more like that of the Northern North Sea (Isaksen & Tonstad 1989).

The Cretaceous–Tertiary succession has been divided into numerous sequences (Fig. 4), all of which will not be described here. Some sequence boundaries are correlative to those of Swiecicki *et al.* (1998) for the Norwegian Sea and Oakman & Partington (1998) for the North Sea (Fig. 4). As described earlier, regional reservoir intervals can manifest themselves as mappable seismic events. The position of the sequence boundary, which actually occurs at the base of the massive sandstone packages, can be inferred in seismic data, whilst the maximum flooding surfaces display no obvious seismic expression in the studied lines. Therefore, we adopt here the classical concepts of sequence stratigraphy as conveyed by van Wagoner *et al.* (1990).

The following sections describe aspects of sequences, composition, timing, occurrence in relevant wells and seismic interpretation, whereas the distribution of their facies and the relationship to tectonic phases will be discussed later. Sequences K10 to K30 (Fig. 4) were deposited during the Ryazanian to Albian, accommodated mainly in inherited Jurassic structural lows, and have seldom been drilled. Their hydrocarbon prospectivity is poor as they occur at depths of up to 9 and 11 km in the Vøring and Møre basins, respectively.

Sequence K40 (middle–late Albian)

Sequence K40 correlates to part of the Agat Formation (Gulbrandsen 1987), where sandstones of this sequence are a proven reservoir. The best developments of K40 sandstones occur in wells 35/3-1 and 35/3-4, where they attain thicknesses of 274 and 233 m, respectively. Sequence K40 marks a major period of onlapping and overstepping of pre-existing highs, particularly on the Halten Terrace (e.g. 6407/1-2, 6506/11-2), the Dønna Terrace and the Trøndelag Platform. This sequence is generally composed of upper bathyal to outer neritic mudstones, but sandstones are encountered in several wells, e.g. 6305/12-1, although these are generally thin. Where the K40 sequence boundary has been mapped it shows the same general trends as the BCU, but continuous flooding of palaeohighs has smoothed the overall sea floor topography.

Sequence K60 (middle–late Cenomanian)

Sequence K60 is dominated by varicoloured mudstones, but sandstones occur much more frequently in key wells, e.g. 6305/12-1, 6506/11-3 and 6507/7-1. The K60 sequence equates to part of the upper section of the Lange Formation, the informally named Upper Lange sandstones. It is a potential

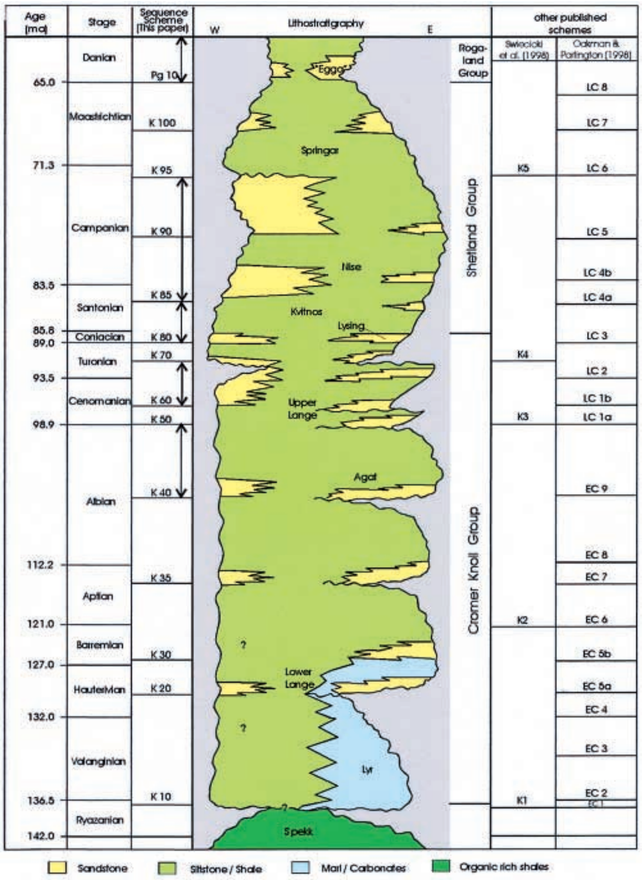

Fig. 4. Stratigraphic summary of Cretaceous sequences and formations with equivalencies to other schemes. Time-scale after Gradstein & Ogg (1996); stratigraphy of east portion based mostly on Dalland *et al.* (1988) and of west portion on data from Brekke *et al.* (1999), except position of the Nise equivalent sandstones, which is based on our own results from the Nyk High well.

reservoir in many parts of the study area, very well developed on the eastern flank of the Gossa High, particularly in well 6305/12-01, where a sandstone unit with oil shows attains a gross thickness of 129 m.

The K60 sequence and most of the Cenomanian stage is absent over wide areas, e.g. in the Smørbukk area (6506/12-3,8, 6407/2-1, 6406/3-3,4,1; Fig. 5a), Halten Terrace (6507/3-1, 6506/12-4), on the Frøya High (6407/10-3 and 6306/6-1), on the Trøndelag Platform (6408/4-1; Fig. 5a), and in other areas such as the Dønna Terrace and in the southern Halten Terrace. It is still preserved in other wells with thicknesses from about 14 m (6506/11-3) to 30 m thick (6507/2-1, -2). All this is ascribed to an erosional event whose timing was probably late Cenomanian since erosion cut down into lower Cenomanian rocks which are overlain by the lower Turonian (Fig. 5a). Lundin & Doré (1997) mentioned a Cenomanian event that was later discussed and dated mid-Cenomanian by Gradstein *et al.* (1999).

Sequence K60 may be interpreted with confidence where it is constrained by well data from the Halten and Dønna terraces, Trøndelag Platform and eastern margins of the Møre Basin. In the deeper-water areas of the Møre and Southern Vøring basins, the sequence becomes extremely condensed and it is picked at the base of a distinctive low amplitude seismic event. The K60 sequence is today at depths of 7.5 and 6.5 km in the Møre Basin depocentres, and 5.5 km and 7.5 km in the Vigrid and Någrind synclines, respectively.

Sequence K80 (Coniacian–late Santonian)

Sequence K80 is characterized by well developed sandstones (lower Coniacian) at its base, belonging to the Lysing Formation, although most of the sequence is dominantly mudstones and equates to the lower part of the Kvitnos Formation (Fig. 4). This sequence may be seismically interpreted with confidence where it is constrained by well data and where the sequence boundary is marked by an extensive development of the lower Coniacian sandstone. The K80 sequence occurs at depths of 5 to 6 km in the Møre Basin depocentres, and more than 5 and 7 km in the Vigrid and Någrind synclines, respectively. The K80 depth structural map shows the same general trends as the K60 depth map, with transgression of remaining palaeohighs, such as the Grip High, to further smoothen the overall topography.

Sequences K85 to K90 (early Santonian–late Campanian)

Sequences K85 and K90 equate to the upper part of the Kvitnos Formation (K85), the entire Nise Formation (i.e. part of K85 and part of K90) and the lowermost part of the Springar Formation (i.e. part of K90) (Fig. 4). Two thick sandstone units separated by hemipelagic shales were penetrated by well 6707/10-1 on the Nyk High (Kittilsen *et al.* 1999); they attain 1288 m and correlate to sequences K85 and K90. Our chronology indicates that the base reservoir level (K85 sequence boundary, 4240 m) is late Santonian (lower part) and the top reservoir level (K95 sequence boundary, 2952 m) is late Campanian (see Figs. 4, 6). The reservoir is topped by mudstones of the K95 sequence (seal). The 300 m of sandstones of sequence K85 in well 6707/10-1 extend towards the Utgard High to the southeast and are represented there by a 140 m thick sandstone package (well 6607/5-2), reduced to only 17 m thick in well 6607/5-1. The younger sandstone unit belongs to sequence K90. It is about 850 m thick in 6707/10-1, only about 20 m thick in 6607/5-2 and is absent in 6607/5-1 (Fig. 6), as the Utgard High was uplifted and eroded during the Maastrichtian.

The K85 sequence occurs at depths of 4.5 to 5 km in the Møre Basin depocentres and almost 5 and 6 km in the Vigrid and Någrind synclines, respectively. The top of the sequence set (e.g. K95 sequence boundary) appears to be an erosional unconformity in the western part of the study area: Slettringen, 'Yggdrasil' domes, and Gjallar Ridge (see also Swiecicki *et al.* 1998, fig. 12, sequence K5). This discordance is probably associated with a compressional event towards the end of the Campanian. It is placed at the top of the thick massive sandstone (Nise Formation equivalent) in well 6710/10-1, where it becomes a correlative conformity that can be traced confidently into the Naglfar Dome and onto the Gjallar Ridge. Furthermore, the sequence has been truncated by early Paleocene erosion across parts of the Trøndelag Platform.

Pg10 (Danian–Selandian)

Sequence Pg10 represents the initial deposits of the Paleocene corresponding to the informal 'Egga Member' of the Våle Formation (e.g. 6305/5-1) or the basal part of the Tang Formation. The former is the main reservoir in the Ormen Lange gas discovery (Gjelberg *et al.* 1999). This Member was penetrated by several wells in the Slørebotn Sub-Basin and other localities along the southern portion of the Møre Basin margin. Across much of the Halten Terrace and Frøya High the sequence is absent.

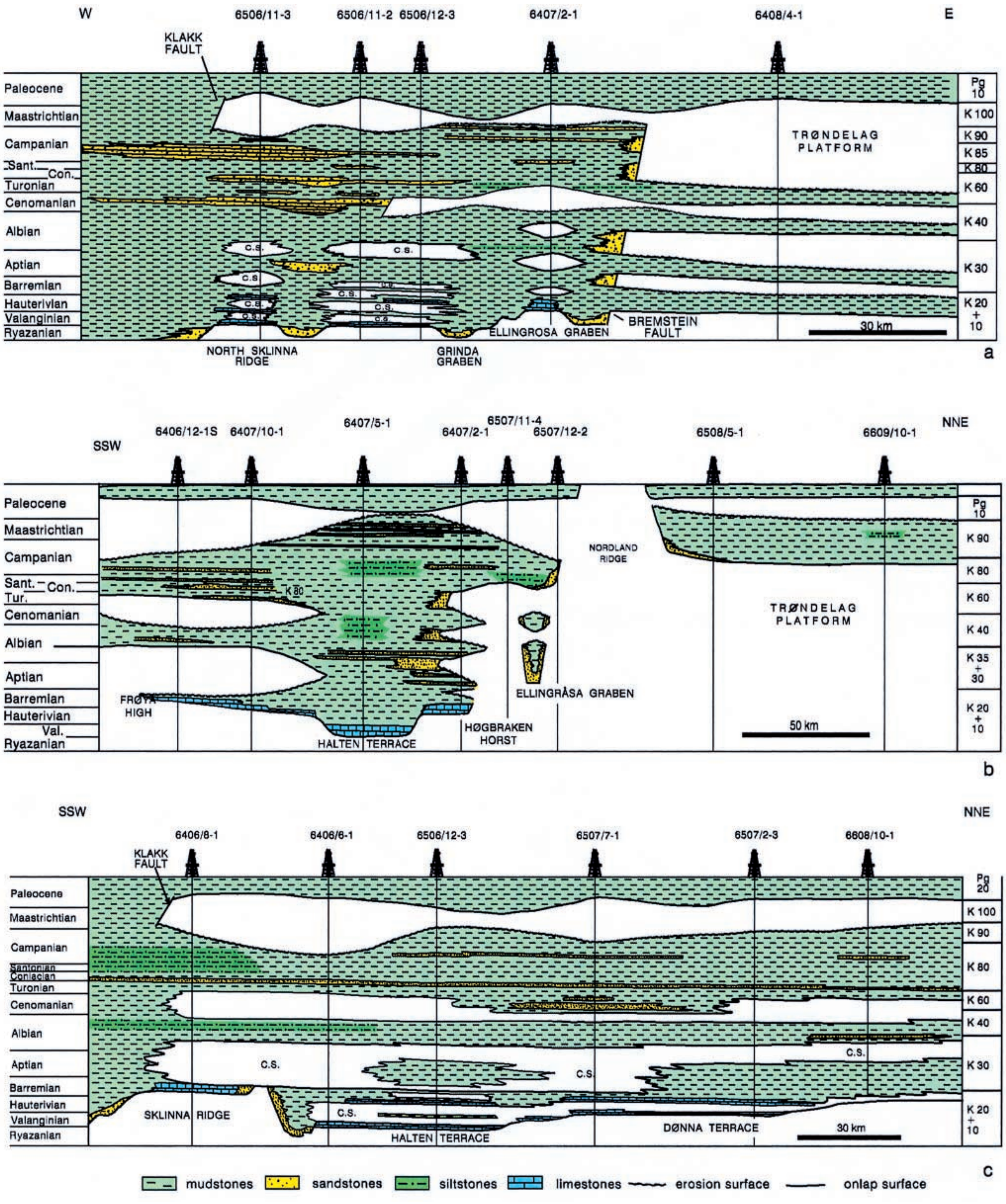

Fig. 5. Chronostratigraphic well correlations: (**a**) across the Halten Terrace; (**b**) along the Halten Terrace and Trøndelag Platform; and (**c**) along the Halten and Dønna terraces. For location of wells see Figure 1. Time-scale in Figure 4.

FACIES MAPS AND BASIN FILL

The sandstone distribution patterns mapped here generally depict the lowstand system tract (LST) in sequences K40–K80. The LST has an enhanced potential for sand accumulation in the deep-water realm because entry points displace basinward to the exposed shelf edge, while during the rest of the cycle (transgressive and highstand system tracts) sands are preferably trapped on the shelf (cf. Richards 1996). As discussed, tectonic events seem to be the main factors governing Mid-Cretaceous deep-water sand sedimentation (cf. Lundin & Doré 1997), and

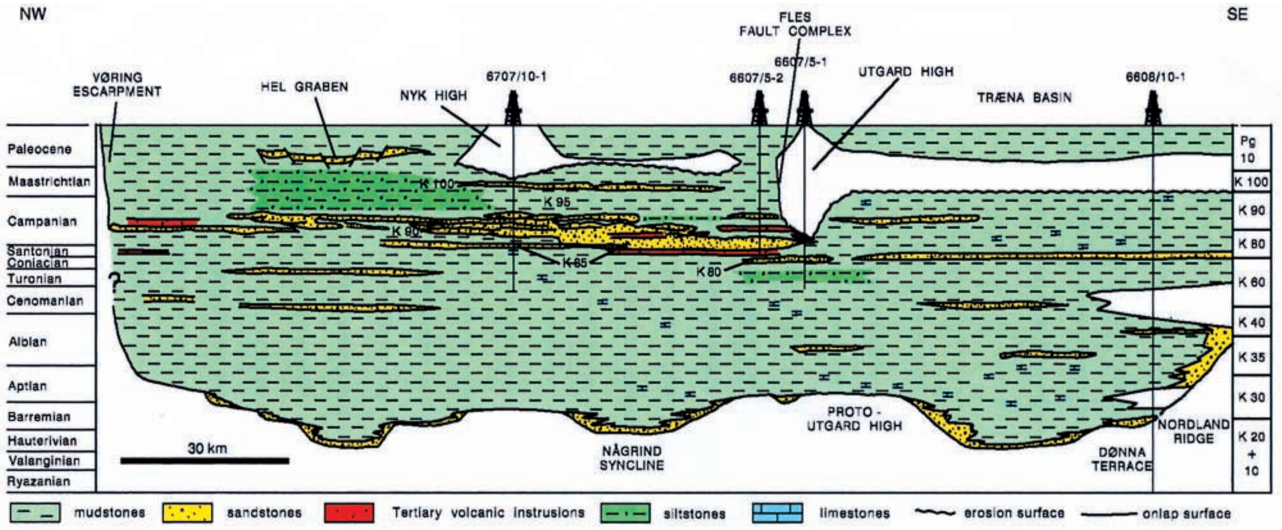

Fig. 6. Chronostratigraphic well correlation, Vøring Basin. For location of wells see Figure 1. Time-scale in Figure 4.

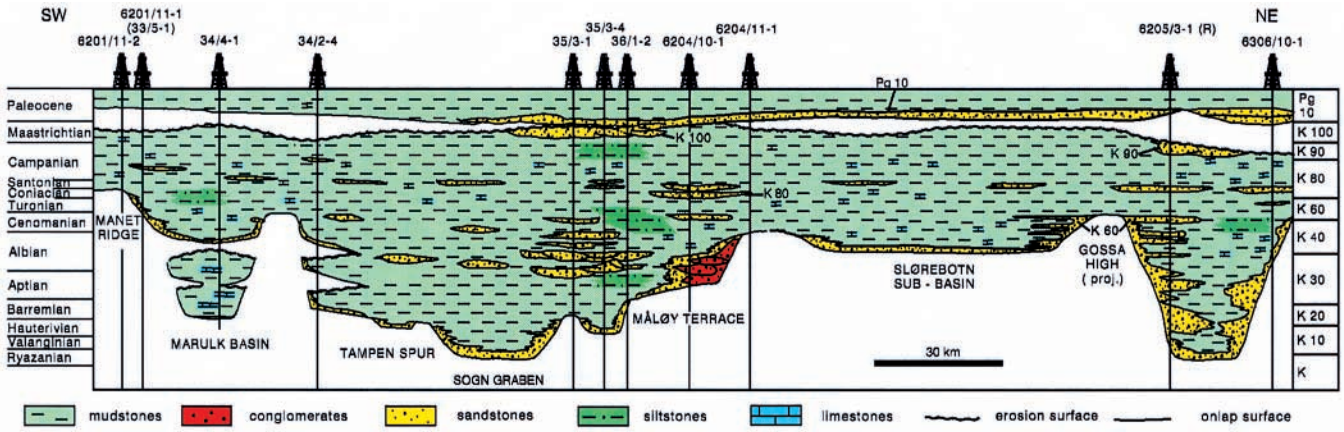

Fig. 7. Chronostratigraphic well correlation, Møre Basin. For location of wells see Figure 1. Time-scale in Figure 4.

also Cenozoic deposition in the Møre Basin (Martinsen *et al.* 1999). The main mechanisms of accommodation were extensional downwarp, post-rift thermal and compactional subsidence.

Short lived, large, emergent areas developed during sea level lowstands (incised shelfs) and dominated the palaeogeographies of sequences K40–80 in the marginal areas, but represent only the early part of the cycle involved, commonly of third order. Other sequences or sequence sets (K85+K90; Pg10) could not be mapped separately on seismic data and represent an amalgamation of sandy turbidites or debris flows of several system tracts.

Basin floor fans are often associated with turbidite-derived sands, but Armentrout *et al.* (1993) coined the term **basin floor thick** to avoid such an implication. There is a better chance to encounter sandstones in such basin floor thicks because of the compactional effect of sand in contrast to mudstones. In sequence stratigraphic models slope fans commonly imply development of channel-levee complexes, yet these are hardly identifiable in the regional seismic lines of the study area. Therefore, in this work we refer to slope fans as those shingled turbiditic deposits developed on the slopes of palaeohighs (lowstand prograding complex). The lack of unequivocal evidence for channels (e.g. incision surfaces, sinuous fills in time slices) in the 2D/3D seismic surveys available makes it difficult to separate slope fans from the lowstand prograding complex and leads us to suspect that many of the turbidite systems mapped here correspond to widespread non-channelized or unconfined deposits.

In addition, plastic flows, such as slumps or debris flows, have been mapped at the basin margins prone to these processes. The rheology of deep-water sandstone sedimentation is important to constrain depositional models, and currently a matter of considerable debate (Shanmugan *et al.* 1994; Hiscott *et al.* 1997; Shanmugan 2000), but our models are based on regional seismic mapping with well control rather than on sedimentologically driven approaches.

K40 facies map (Fig. 8)

The sandstones occur mainly around remanent palaeohighs formed during the Late Jurassic, such as the Vigra, Grip, Ona, Gnaussen, Selje, Gossa and Manet Ridge, which acted as emerged areas (Figs. 7, 8). The sandstones were sourced from the Norwegian mainland (hinterland) to the east of the basin and occur close to the eastern slope of the Slørebotn Sub-Basin and the Selje High, which were local provenance areas. Conglomeratic deposits on top of this slope in well 6204/10-1 are possibly coeval to K40 and may respond to proximal hyperconcentrated debris flows. A bathyal environment with

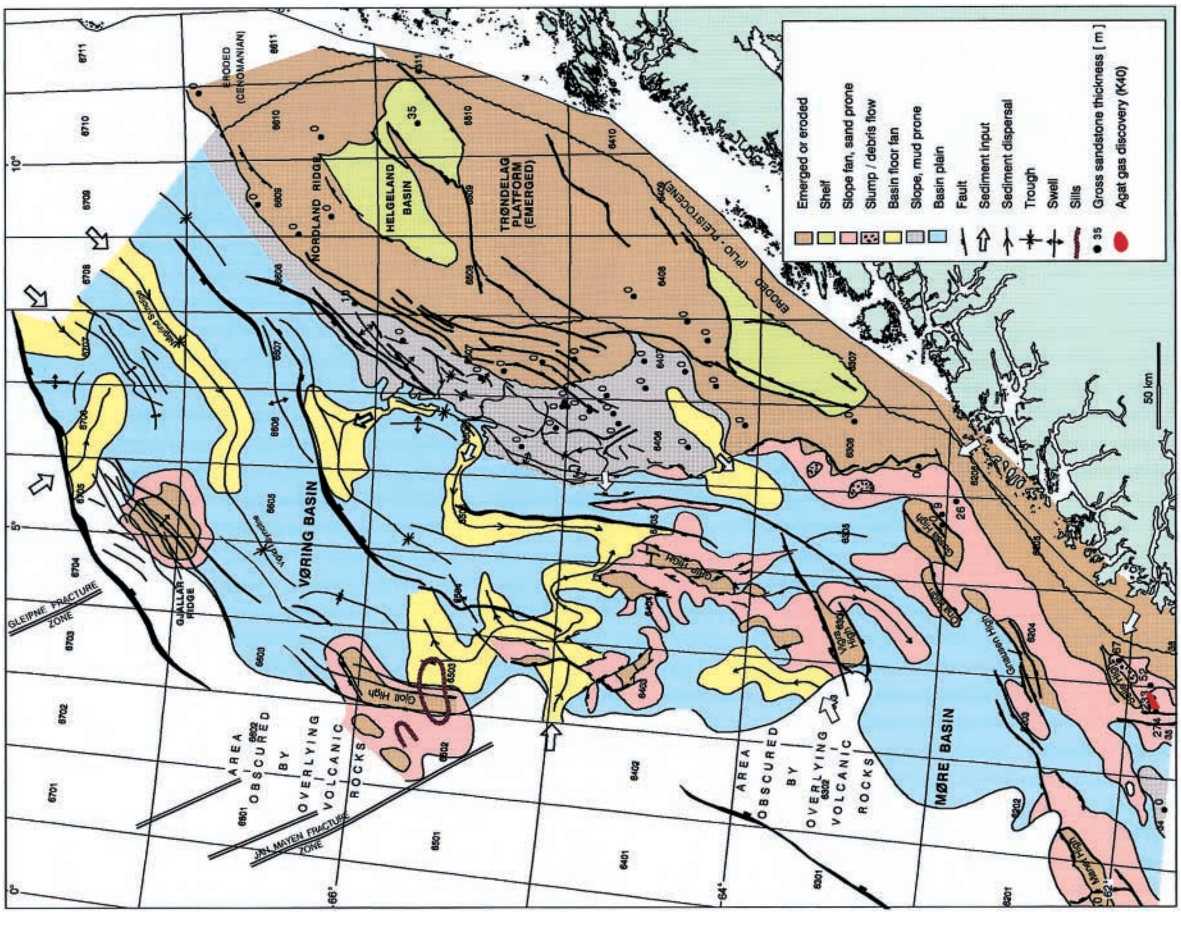

Fig. 8. Facies map for the lowstand system tract of sequence K40 (Agat Formation).

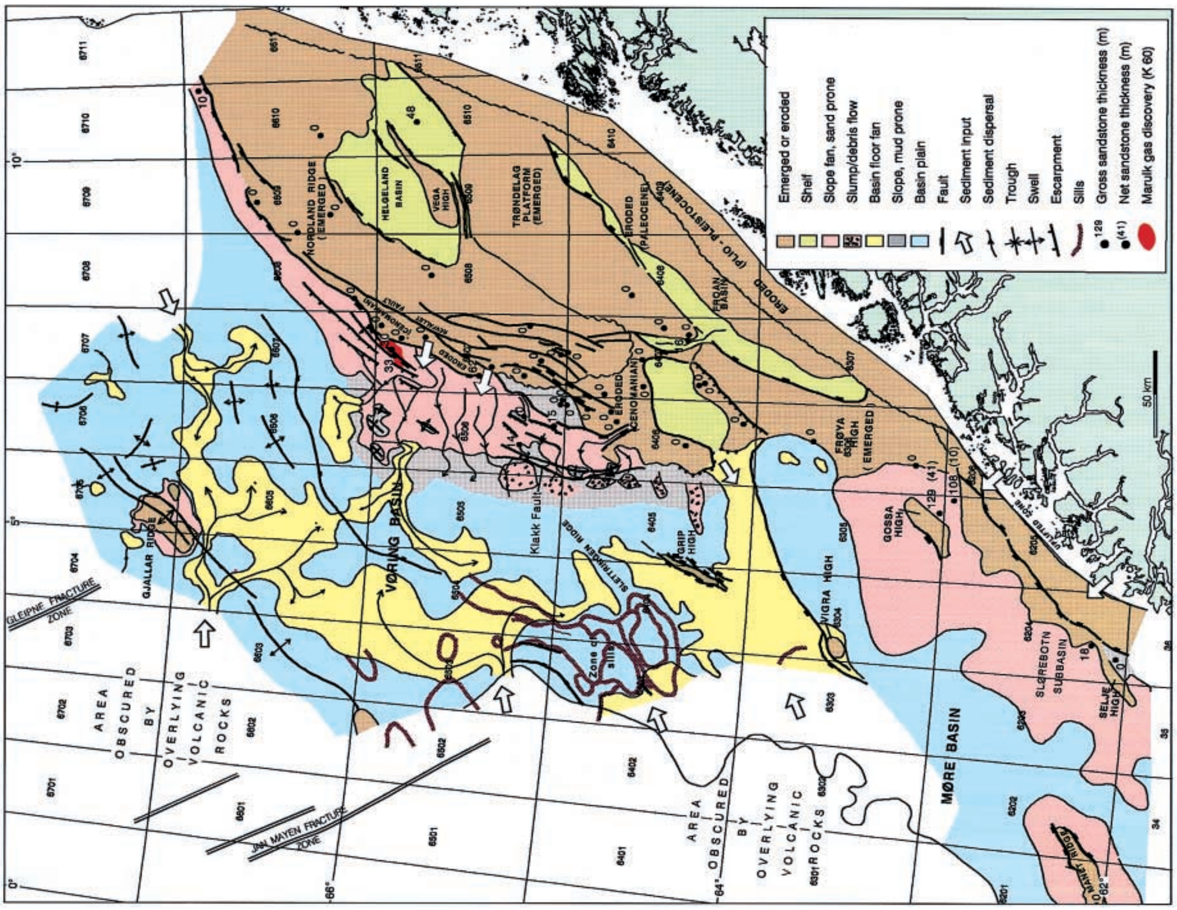

Fig. 9. Facies map for the lowstand system tract of sequence K60 (Upper Lange Formation).

dysaerobic conditions is favoured by Gradstein *et al.* (1999) based on the agglutinated foraminiferal assemblages.

Shanmugan *et al.* (1994) and Skibeli *et al.* (1995) described cores from the Agat Formation as rippled or contorted sandstones with mudstone clasts, interpreted as upper slope mass transport deposits, particularly as slumps having different provenances, while Nystuen (1999) favoured a submarine fan system with a major feeding channel. The lack of gas communication between the sandstone bodies of different wells in this field is attributed to different sand lobes, probably with different distributary systems (Gulbrandsen 1987; Nystuen 1999), in a complex scenario. The sand-prone areas mapped regionally adjoin emerged areas, forming a continuous slope apron, prone to contain debris flow type deposits, as around the Selje High (Fig. 8).

South of the Slettringen Ridge and in the Helland Hansen area slope fans of local provenance coalesce with more widespread prograding depositional lobes with a western provenance. Understanding of the K40 sandstone distribution in this area is important because they are potential 'holding tanks' for early generated hydrocarbons that could have remigrated later into younger reservoirs (Doré & Lundin 1996). In the Rås Basin, basin floor fans may have been deposited by gravity flows emerging from the northern Sklinna Ridge area from two entry points. The Halten Terrace was a muddy slope sourced from the long-lived Cretaceous highs of the Nordland Ridge and parts of the Trøndelag Platform.

The only K40 sandstones predicted in the eastern study area may occur on the Helgeland Basin and perhaps in the Froan Basin. The former is considered to be a persistent Cretaceous depocentre on the Trøndelag Platform (cf. Blystad *et al.* 1995). In the Vøring Basin the isochore maps show thickening of the K40 sequence attributable to the presence of sandstones along the Vigrid and Någrind synclines and in the Naglfar Dome area. These sandstones would have had a north to northeast provenance, as did others from younger sequences (see below). The 'Gjoll' High was onlapped, and slope fans are expected around local areas that remained emerged (Fig. 8). The Gjallar Ridge was an emerged swell that divided the drainage of the Fenris Graben from the Vøring Basin. As for the 'Gjoll' High, restricted slope fans are predicted around this feature (Fig. 8).

K60 facies map (Fig. 9)

During the middle Cenomanian, as discussed in the previous section, a possible tectonic event caused a significant sea-level drop. Wide areas away from the already emerged Nordland Ridge (Halten Terrace, Trøndelag Platform, Frøya High, east of the Slørebotn Sub-Basin) became exposed to erosion. In the basinal areas, the Manet Ridge and the Gossa, Vigra and Grip highs still remained as zones of erosion, at least above the storm base level. K60 sediments drape the Ona, Gnaussen, and Giske highs of the Møre Basin (Fig. 9), while other highs were flooded during K65/70 times.

A broad area of coalescing slope fans sourced from the east developed along the Slørebotn Sub-Basin. In deeper parts of the Møre Basin, basin floor fans developed around the Grip High and the Slettringen Ridge, apparently with different provenances as their fairways suggest north, west and east sources (Fig. 9). Over the Halten Terrace a small shallow basin remained below sea-level and received sediments from the Frøya High and Nordland Ridge. This intrashelf mini-basin could have been wider than it appears in Figure 9 (Quadrants 6406-7), but its primary extension is uncertain because all the K60 sequence was subsequently eroded, as discussed above.

The K60 sequence is represented by open marine shales of the transgressive to highstand system tracts in areas of the Halten Terrace (e.g. wells 6407/4-1 and 5-1) that were emerged and bypassed during the lowstand of this cycle (Fig. 9). The thinning of the K60–70 interval occurred on drape anticlines where there is pronounced topography on the BCU, such as those of the Sklinna Ridge and the Dønna Terrace. Sediments sourced from the Nordland Ridge were transported westward into the basin around highs expected to be mud-prone areas (Fig. 9).

On the slope of the Klakk Fault Complex gravity flow deposits and slumps are predicted and mapped (Fig. 9). On the Trøndelag Platform minor amounts of sandstones sourced from nearby positive areas appear to have been deposited locally in small grabens, but this platform is viewed as an incised zone with sediment bypass from the Scandinavian landmass to the east, as indicated by hiatuses (Fig. 5a,b). Slope fans on the Dønna Terrace prograded over basinal fans whose extension was hindered by the escarpment of the Fles Fault Complex. In the Vøring Basin, K60 basin floor fans appear to be sourced from two entry points to the west and east. Subsidence along the proto Gjallar Ridge reduced the exposed area which was acting as a sediment source (Fig. 9).

K80 facies map (Fig. 10)

In the Møre Basin an apron similar to that of K60 developed along the eastern margin slope, with possible slumps derived from further up-dip. Wells penetrating this slope apron system have encountered sandstones east of the Selje High (6204/10-1) and east of the Gossa High (6205/3-1R; 6305/12-1 and 6306/10-1). A basal reflector of sequence K80 onlaps the Frøya High along its western edge, but only the succeeding low amplitude reflectors cover this palaeohigh completely. This suggests that the Frøya High was emergent during the K80 lowstand and was subsequently overstepped by the mud-prone transgressive and highstand system tracts. Between the Frøya High and the Nordland Ridge the sea retreated westward beyond the Bremstein Fault Complex during the lowstand period.

Slumps with rotational glide planes seem to occur on the eastern basin slope, based on seismic data. The Lysing reflector, however, rapidly looses amplitude westward into the basin. East of the Vigra High, seismic reflection patterns become chaotic, hummocky and discontinuous, probably representing units due to long range mass movements. On the southern Halten Terrace, south of Quadrant 6406, a possible mass transport complex developed into a major fairway whose entry point occurs in Block 6406/11. Sediments prograding westward along this fairway reached the Slettringen Ridge area and are characterized on seismic data by high amplitudes at K80 level. The area of the Helland Hansen Arch is sand-prone, sourced from the east (compare with Sánchez-Ferrer *et al.* 1999, fig. 20), possibly with multiple fairways that originated on the Halten Terrace. A different, western provenance is also suggested by the seismic amplitude and isochore maps west of this area (Fig. 10).

A cored interval from the Lysing Formation in well 6506/12-5 (Smørbukk South) was interpreted by Shanmugan *et al.* (1994) as a slumped block of tidal sediments. On seismic data one can, indeed, observe evidence for slumping of blocks derived from structural highs (e.g. the Høgbraken Horst, Midgard area: Fig. 5b) that may have reached the Smørbukk South area (Fig. 10). Seismic facies across the Smørbukk area and on the slopes of the Sklinna Ridge can be described as chaotic, these areas being prone to generate plastic flows.

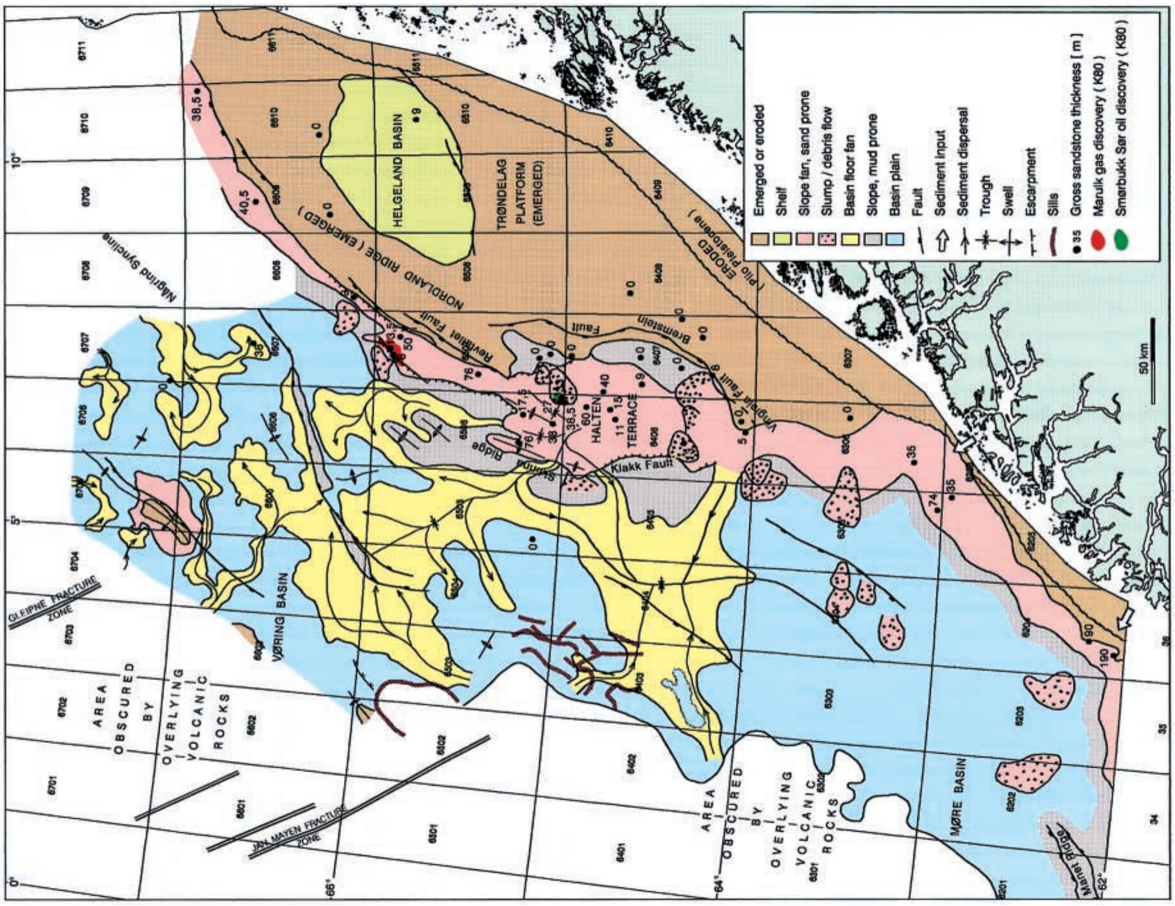

Fig. 10. Facies map for the lowstand system tract of sequence K80 (Lysing Formation).

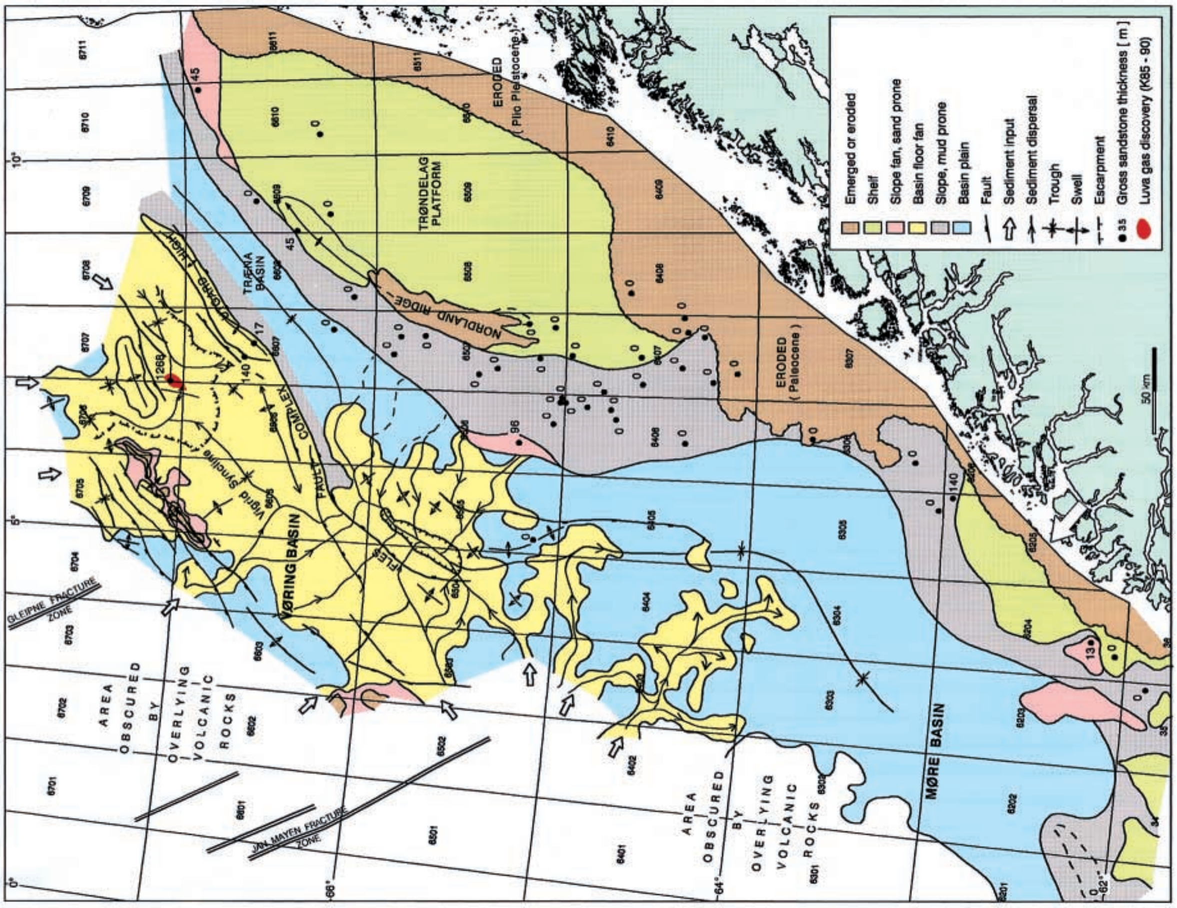

Fig. 11. Facies map for the sequence set K85–K90 (Nise Formation equivalent).

Backstripping of sections across the Halten Terrace indicates palaeo-water depths of several hundred metres during K80 times, which precludes *in-situ* tidal deposits and renders them allochthonous in agreement with Shanmugan *et al.* (1994).

On the Dønna Terrace, strong seismic amplitudes of the Lysing reflector map out as a long zone, broadening northwards, interpreted as a major fairway for basinal fans occurring adjacent to the highs. The Dønna Terrace hosts a sandy fan where the type section of the Lysing Formation (well 6507/7-1) and the Lysing-reservoired Marulk Field occur. The Lysing reflector onlaps the K70 sequence a few kilometres down-dip from the Revfallet Fault escarpment. Slumps occur on this slope; it is suggested that the 'lobe' in Block 6607/12 outlined by Hastings (1986) is one of them.

In the Vøring Basin well 6607/5-1, a 38 m thick sandstone unit was dated Coniacian by RRI; it belongs to the Lysing Formation (Fig. 6; see also Brekke *et al.* 1999), although it appears as Campanian in the operator's report. This is the most basinal known occurrence of the K80 (Lysing) sandstone; it was sourced from the northeast from a lobe of the Någrind Syncline's fan (see Figs. 6, 10). The rocks at TD in the Nyk High (6707/10-1) well were dated as Turonian, with the Coniacian–Turonian boundary placed between 4900 and 4993 m. This is the stratigraphic position of the Lysing Formation, but sandstones are absent there. The entry points of major feeding channels remained unchanged from K60 times in the Vøring Basin. The emergent Gjallar Ridge anticline was becoming narrower and its slope deposits wider. The fans south of the Fles Fault Complex, sourced from the Halten Terrace area became more widespread and accumulated in front of the Fles Fault escarpment, as during K60 times.

K85–K90 facies map (Fig. 11)

Large areas of the Vøring Basin were covered by turbiditic currents sourced from multiple entry points. A depocentre mainly sourced from the north and northeast was penetrated by well 6707/10-1. Sandstones of sequence K85 from the Utgard High are described as 'K2 type sandstones' with a north or northwest provenance by Morton & Grant (1998). A northeast provenance is favoured here for the sandstones encountered in the Nyk well (Fig. 11; see also Brekke *et al.* 1999, fig. 6c). This was also suggested by Høgseth *et al.* (1999), who stated that the Nyk High by this time was in a more proximal position than the Vema Dome just to the west.

Cores from well 6707/10-1 have been interpreted as turbiditic sandstones followed by possible debris flows (Kittilsen *et al.* 1999). The Naglfar area is located along the fairway of this depocentre, which was delimited to the south by a fault escarpment that spilled sediments travelling northwards along the Vigrid Syncline (Fig. 11).

Along the Fles Fault Complex, westward tilting allowed probable sand accumulation in the Någrind and Vigrid synclines. The sands onlapped the still-emergent anticline of the Gjallar Ridge and thinned down-dip from the crest. On its western limb thick amounts of sediment accumulated in the Fenris Graben. Further south, a major basinal depocentre occurs east of the Fles Fault in Quadrants 6504 and 6505. There sediments were mainly sourced from old and new entry points to the west, but also from the Halten Terrace, ponded in a structurally controlled trough. Well 6505/10-1, which encountered little or no sandstones in these sequences, is located on a swell (Fig. 11). A similar complex, also multi-sourced from the west, fed the Slettringen Ridge area resulting in a thick accumulation of deep-water basin floor fans.

On the Halten Terrace, sandstones of K85–K90 are reported in cuttings from well 6506/11-3, belonging to a 96 m thick package interpreted as a toe-of-slope fan. Otherwise, only thick (up to 430 m) bathyal shales with minor sandstone interbeds occur. The Nordland Ridge was draped completely in its northern portion (well 6609/7-1), but the southern part could still have remained emerged (Fig. 11). South of the Møre Basin, shelf sediments from the eastern hinterland prograded across the Tampen Spur and the Måløy Terrace, whose corresponding slope sediments subcrop as mudstones in well 6201/11-1 and in the Agat Field wells in Block 35/3. Further east, the K85–K90 sequences are truncated together with sequence K100 and unconformably overlain by Tertiary deposits.

Pg10 facies map (Fig. 12)

The 'Egga' sandstone reservoir, assigned to sequence Pg10, is described from cores of the Ormen Lange discovery as deep-water turbiditic deposits (Gjelberg *et al.* 1999) and interpreted as bathyal deposits in other wells of the Møre Basin. The facies map (Fig. 12) shows the Møre Basin being prograded by thick sand-prone units coming from both eastern and western source areas. The isochore-time map shows the main Paleocene depocentres (Fig. 2). They were supplied from emergent areas that developed during the Danian as widespread thermal uplift in the North Atlantic (Iceland plume) occurred. In the Møre Basin, deposits around well 6305/5-1 are interpreted as a basin floor fan sourced from the southeast. From base to top the well records increasingly older, reworked (late and early) Maastrichtian palynomorphs in the 'Egga' reservoir (PGS non-exclusive report) which points towards a minimum late Maastrichtian age for the onset of this uplift event.

Areas that became exposed during this time include the Halten Terrace, Vema Dome, Nyk, Utgard, Møre and Vøring marginal highs. Except for the Halten Terrace and Utgard High, these highs stand out in the Paleocene isochore map (Fig. 2). The uplift in the Halten Terrace and Frøya High accounts for a widespread hiatus observed between the Upper Paleocene and diverse stages of the Upper Cretaceous in numerous wells (Fig. 5a–c). Only Lower Paleocene mudstones of Selandian age in well 6506/12-8 and possibly in well 6507/11-4 are preserved. Deepest erosion of Upper Cretaceous rocks has occurred along the Sklinna Ridge (see Fig. 5a,c), which can be attributed to eastward rotation of the block between the Klakk and Bremstein fault complexes. This is in agreement with the geometry and rotation of the Klakk Fault Complex suggested by Brekke (2000). Martinsen *et al.* (1999) also attributed the base Paleocene unconformity to a minor margin uplift, but incision down to Campanian rocks (Fig. 5a–c) suggests upheaval of a few hundred metres. Note that no slope fan system is mapped along the Halten Terrace because this feature was shedding Cretaceous mudstones, especially towards the Trøndelag Platform, that were efficiently dispersed.

According to the facies map in Figure 12, the fan hosting the Ormen Lange Dome was derived mainly from the Scandinavian mainland, but a small part on the north may have been sourced from the Frøya High. There Upper Cretaceous shales were exposed and shed into the northern part of the fan, possibly affecting the quality of the reservoir (well 6305/1-1), whilst the mainland composed of crystalline rocks delivered cleaner sandstones to the southern part of the structure (well 6305/5-1). The basin floor fan is partly draped by a prograding lowstand wedge, which exhibits a depocentre in the Slørebotn Sub-Basin.

The Paleocene depositional environments in the western Møre and Vøring Basin depicted in Figure 12 are uncertain

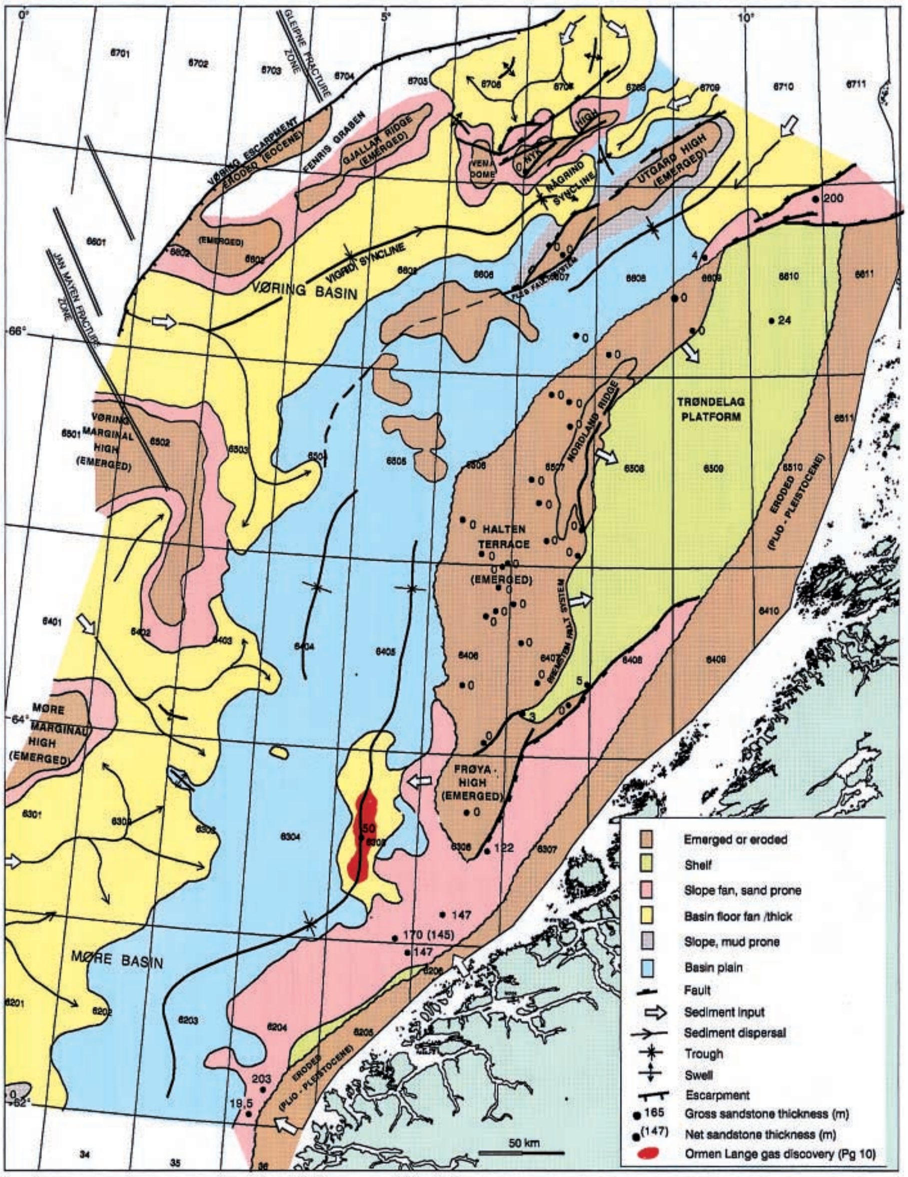

Fig. 12. Facies map for the sequence Pg10 ('Egga' Member).

because of the absence of wells there. The thick eastward prograding systems of these areas are ascribed to basin floor thicks sourced from the Møre and Vøring Marginal highs, and from other western sources in the area of the Gjallar Ridge. Basin floor thicks of considerable proportions occur in the western Møre Basin, apparently multi-sourced from northwest and southwest areas, and in the Vigrid and Någrind synclines. These latter elements formed during the Late Cretaceous and continued growing during the Paleocene (Blystad *et al.* 1995). In the Vøring Basin well 6607/5-2 penetrated a complete Paleocene to Maastrichtian succession of outer shelf and bathyal mudstones (Fig. 6).

On the Nyk High, sequence Pg10 is absent as a result of Late Cretaceous–Early Paleocene uplift. In well 6607/10-1, the sandstone package between 2210 m (base Tertiary) and 2434 m had been placed in the Paleocene, but is now considered of Maastrichtian age (RRI; see Fig. 6). Likewise, the Utgard High was exposed and flooded later during the Late Paleocene. There, well 6607/5-1 encountered Upper Paleocene strata resting unconformably on Campanian rocks.

Around emerged zones (Vøring, Gjallar, Nyk, Utgard, Vema) the isochore map (Fig. 2) indicates steep slopes and deep troughs, particularly around the Vigrid Syncline or the Hel Graben. These slopes, together with the enormous thickness variations, support subsidence in response to horst and graben tectonics instead of the shallow or even lacustrine environments suggested by Brekke *et al.* (1999). The basin axis is traced along zones of very reduced Paleocene section (Figs. 2, 12), except for the Ormen Lange fan. Zones where Pg10 is absent are attributable to: (1) exposure and erosion; (2) shallow-water sediment starvation over a swell that was still submerged, or (3) a deep starved setting beyond sediment progradation and free of axial turbidite avenues. The first option is favoured because these areas follow the Utgard High trend, which was exposed during the Danian, and comply with the regional emergent scenario for this time discussed above.

Southeast of the Halten Terrace, in wells 6407/9-5 (3 m) and 6407/9-8 (5 m), Pg10 sandstones are poorly developed. Isochore maps and the K–K' geoseismic profile of Blystad *et al.* (1995) indicate the continuation of the depocentre from the Sløreboth Sub-Basin towards the northeast into the Froan Basin, which was reactivated as a graben in conjunction with uplift of the adjacent Frøya High. In the Helgeland Basin, well 6610/7-1 contains a 24 m thick sandstone assigned to this interval, probably representing shallow environments that extended widely over parts of the Trøndelag Platform. North of this platform, particularly in front of the Grønøy High, equivalent Pg10 sandstones attain a thickness of 200 m (well 6610/3-1), being their northernmost subcrop in the study area and representing deep marine sandstones possibly sourced from the east via the Vestfjorden Basin (see also Fig. 1).

SUMMARY AND CONCLUSIONS

The Cretaceous and Paleocene stratigraphy of the Norwegian Sea is dominated by deep-water mudstones with subordinate, yet significant sandstone units that are both proven and potential hydrocarbon reservoirs. This paper postulates their distribution in facies maps that constitute screening tools for hydrocarbon exploration. Regional mapping of potential reservoirs was possible because information on known sandstone occurrences in the wells and their seismic expression were integrated and these characteristics were combined with regional isochore maps to infer the occurrence and distribution of sand-prone areas into the undrilled frontier basins. Additional geophysical techniques (e.g. seismic inversion) can help to refine the models, but only future drilling will conclusively test them. Some regional highlights from the facies maps are listed below.

- The mapping of depocentres and sediment dispersal in the Vøring and Møre basins show that the main sediment provenances were from the 'Gjoll' High, the Gjallar and the Nordland Ridge, together with several intrabasinal highs during the early stages of the post-rift Cretaceous Basin.
- Sequence K40 (middle–late Albian) occurred during an immature phase of the basin where most of the palaeohighs strongly controlled distribution of fan systems and slumps. In the eastern basin margin, the Trøndelag Platform became repeatedly exposed or was an area of sediment bypass during the Cretaceous.
- During deposition of sequence K60 (Middle Cenomanian) several highs of the Møre Basin were draped by sediment. The main emerged areas that persisted from this time on were the Gjallar and the Nordland Ridge. In the Halten Terrace the absence of the K60 sequence records a most likely late Cenomanian tectonic event.
- Sequence K80 (Coniacian–Santonian) reveals a period of instability, as it contains slump deposits in parts of the Halten and Dønna terraces (Lysing Formation). The distribution across the Vøring and northern Møre Basin evolved to broadly extended fan-type deposits. The K80 sandstones are absent in well 6707/10-1 on the Nyk High.
- The K85–K90 (late Santonian–late Campanian) sandstone reservoirs of the Nise Formation show the most widespread distribution across the Vøring Basin, with multiple new entry points and very efficient sediment dispersal into huge sand-prone basin floor thicks. A western hinterland for these sandstones became increasingly important as the Nordland Ridge was reduced during Campanian times and what remained exposed apparently started to shed mudstones over the slope of the Halten Terrace. The Vøring Basin received the maximum amount of sand during the Cretaceous, developing remarkable potential reservoirs.
- The Pg10 sequence (Danian–Selandian: 'Egga' Member) is expressed as a basin floor fan in the Ormen Lange area, superseded by a prograding lowstand wedge that is best developed in the Slørebotn Sub-Basin. By Danian times the Halten Terrace rotated eastwards and shed mudstones from the Upper Cretaceous into the basin. In the western Møre and Vøring basins extended basin floor thicks developed around previously and newly exposed areas after uplift of the different blocks occurred during the late Maastrichtian, most probably in conjunction with a known regional thermal doming event.

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REFERENCES

Aram, R. B. 1999. West Greenland versus Vøring Basin: comparison of two deepwater frontier exploration plays. *In:* Fleet, A. J. & Boldy, S. A. R. (eds) *Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference*. Geological Society, London, 315–324.

Armentrout, J. M., Malecek, S. J., Fearn, L. B. *et al.* 1993. Log-motif analysis of Paleogene depositional systems tracts, Central and northern North Sea: defined by sequence stratigraphic analysis. *In:* Parker, J. R. (ed.) *Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference*. Geological Society, London, 45–57.

Bjørnseth, H. M., Grant, S. M., Hansen, E. K., Hossack, J. R., Roberts, D. G. & Thompson, M. 1997. Structural evolution of the Vøring Basin, Norway, during the Late Cretaceous and Paleogene. *Journal of the Geological Society London*, **154**, 559–563.

Blystad, P., Brekke, H., Færseth, R. B., Larsen, B. T., Skogseid, J. & Tørudbakken, B. 1995. Structural elements of the Norwegian continental shelf. Part II: The Norwegian Sea Region. *Norwegian Petroleum Directorate Bulletin*, **8**, 1–45.

Brekke, H. 2000. The tectonic evolution of the Norwegian Sea Continental Margin with emphasis on the Vøring and Møre basins. *In:* Nøttvedt, A. (ed.) *Dynamics of the Norwegian Margin*. Geological Society, London, Special Publications, **167**, 327–378.

Brekke, H., Dahlgren, S., Nyland, B. & Magnus, C. 1999. The prospectivity of the Vøring and Møre Basins on the Norwegian Sea continental margin. *In:* Fleet, A. J. & Boldy, S. A. R. (eds) *Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference*. Geological Society, London, 261–274.

Dalland, A., Worsley, D. & Ofstad, K. 1988. A lithostratigraphic scheme for the Mesozoic and Cenozoic succession offshore mid- and northern Norway. *Norwegian Petroleum Directorate-Bulletin*, **4**, 65.

Doré, A. G. & Lundin, E. R. 1996. Cenozoic compressional structures on the NE Atlantic margin: nature, origin and potential significance for hydrocarbon exploration. *Petroleum Geoscience*, **2**, 299–311.

Doré, A. G., Lundin, E. R., Birkeland, Ø., Elisassen, P. E. & Jensen, L. N. 1997. The NE Atlantic margin: implications of Late Mesozoic and Cenozoic events for hydrocarbon prospectivity. *Petroleum Geoscience*, **3**, 117–131.

Gabrielsen, R. H. & Doré, A. G. 1995. History of tectonic models on the Norwegian continental shelf. *In:* Hanslien, S. (ed.) *Petroleum Exploration and Exploitation in Norway*. NPF Special Publication, **4**, 333–368.

Gabrielsen, R. H., Odinsen, T. & Grunnaleite, I. 1999. Structuring of the Northern Viking Graben and the Møre–Trøndelag Fault Complex. *Marine and Petroleum Geology*, **16**, 443–465.

Gjelberg, J., Enoksen, T., Mangerud, G., Martinsen, O. J. & Roe, E. 1999. Sedimentary environments offshore Norway. *Extended Abstracts Sedimentary Environments Offshore Norway*. Norwegian Petroleum Society, 193–197.

Gradstein, F. M. & Ogg, J. 1996. A Phanerozoic Time Scale. *Episodes*, **19**, 1/2, 3–5.

Gradstein, F. M., Kaminski, M. & Agterberg, F. 1999. Biostratigraphy and paleoceanography of the Cretaceous seaway between Norway and Greenland. *Earth Science Reviews*, **46**, 27–98.

Gulbrandsen, A. 1987. Agat Field. *In:* Spencer, A. M. (ed.) *Geology of the Norwegian oil and gas fields*. Graham and Trotman, London, 363–370.

Hastings, S. 1986. Cretaceous Stratigraphy and reservoir potential, mid Norway Continental Shelf. *In:* Spencer, A. M. (ed.) *Habitat of Hydrocarbons* *on the Norwegian Continental Shelf*. Norwegian Petroleum Society/Graham & Trotman, London, 287–298.

Hinz, K., Eldholm, O., Block, M. & Skogseid, J. 1993. Evolution of North Atlantic volcanic continental margins. *In:* Parker, J. R. (ed.) *Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference*. Geological Society, London, 901–913.

Hiscott, R. N., Pickering, K. T., Bouma, A. H., Hand, B. M., Kneller, B. C., Postma, G. & Soh, W. 1997. Basin floor fans in the North Sea: Sequence stratigraphic models vs Sedimentary Facies: Discussion. *American Association of Petroleum Geologists Bulletin*, **81**, 4, 662–665.

Høgseth, K., Vagle, G. B., Bergfjord, E., Granholm, P. G. & Kjervold, R. 1999. The Cretaceous Depositional Systems of the Frontier Vøring Basin – evidence from the Nyk High well (6707/10-1) and the Vema Dome well (6706/11-1). *Extended Abstracts Sedimentary Environments Offshore Norway*. Norwegian Petroleum Society, 199–200.

Isaksen, D. & Tonstad, K. 1989. A revised Cretaceous and Tertiary lithostratigrahic nomenclature for the Norwegian North Sea. *Norwegian Petroleum Directorate Bulletin*, **5**, 1–59.

Kittilsen, J. E., Olsen, R. R., Marten, R. F., Hansen, E. K. & Hollingsworth, R. R. 1999. The first deepwater well in Norway and its implications for the Upper Cretaceous Play, Vøring Basin. *In:* Fleet, A. J. & Boldy, S. A. R. (eds) *Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference*. Geological Society, London, 275–280.

Knott, S. D., Burchell, M. T., Jolley, E. J. & Fraser, A. J. 1993. Mesozoic to Cenozoic plate reconstructions of the North Atlantic and hydrocarbon plays of the Atlantic margins. *In:* Parker, J. R. (ed.) *Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference*. Geological Society, London, 953–974.

Koch, J.-O. & Heum, O. R. 1995. Exploration trends of the Halten Terrace. *In:* Hanshen, S. (ed.) *Petroleum Exploration and Exploitation in Norway*. Norwegian Petroleum Society Special Publication, **4**, 235–251.

Kuvaas, B. & Kodaira, S. 1997. The formation of the Jan Mayen microcontinent: the missing piece in the continental puzzle between the Møre–Vøring Basins and East Greenland. *First Break*, **15**, 239–247.

Larsen, M., Hamberg, L., Olaussen, S., Norgaard-Pedersen, N. & Stemmerik, L. 1999. Basin evolution in southern East Greenland: an outcrop analog for Cretaceous–Paleogene basins on the north Atlantic volcanic margins. *In:* Fleet, A. J. & Boldy, S. A. R. (eds) *Petroleum Geology of NW Europe: Proceedings of the 5th Conference*. Geological Society, London, 41–61.

Lundin, E. R. & Doré, A. G. 1997. A tectonic model for the Norwegian passive margin with implications for the NE Atlantic: Early Cretaceous to breakup. *Journal of the Geological Society, London*, **154**, 545–550.

Martinsen, O. J., Bøen, F., Charnock, M. A., Mangerud, G. & Nøttvedt, A. 1999. Cenozoic development of the Norwegian margin 60–64°N: sequence and sedimentary response to variable basin physiography and tectonic setting. *In:* Fleet, A. J. & Boldy, S. A. R. (eds) *Petroleum Geology of Northwestern Europe, Proceedings of the 5th Conference*. Geological Society, London, 293–304.

Mogensen, T. E., Nyby, R., Karpuz, R. & Haremo, P. 2000. Late Cretaceous and Tertiary structural evolution of the northeastern part of the Vøring Basin, Norwegian Sea. *In:* Nøttvedt, A. (ed.) *Dynamics of the Norwegian Margin*. Geological Society, London, Special Publications, **167**, 379–396.

Morton, A. & Grant, S. 1998. Cretaceous Depositional Systems in the Norwegian Sea: Heavy Mineral Constraints. *American Association of Petroleum Geologists Bulletin*, **82**, 2, 274–290.

Nadin, P. A. & Kusznir, N. J. 1995. Paleocene uplift and Eocene subsidence in the northern North Sea Basin from 2D forward and reverse stratigraphic modelling. *Journal of the Geological Society, London*, **152**, 833–848.

Nystuen, J. P. 1999. Submarine sediment gravity flow deposits and associated facies: core examples from the Agat Formation. *Extended Abstracts Sedimentary Environments Offshore Norway*. Norwegian Petroleum Society, 211–215.

Oakman, C. D. & Partington, M. A. 1998. Cretaceous. *In:* Glennie, K. W. (ed.) *Petroleum Geology of the North Sea: Basic concepts and recent advances* Blackwell, Oxford, 294–349.

Richards, M. T. 1996. Deep-marine Clastic Systems. reprinted 1998 *In:* Emery, D. & Myers, K. J. (eds) *Sequence Stratigraphy*. Blackwell Science, Oxford. 178–210.

Roberts, A. M., Lundin, E. R. & Kusznir, N. J. 1997. Subsidence of the Vøring Basin and the influence of the Atlantic continental margin. *Journal of the Geological Society, London*, **154**, 551–557.

Shanmugan, G. 2000. 50 years of the turbidite paradigm (1950s–1990s) Deep-water processes and facies models – a critical perspective. *Marine and Petroleum Geology*, **17**, 285–342.

Shanmugan, G., Lehtonen, L. R., Straume, T., Syverstsen, S. E., Hodgkinson, R. J. & Skibeli, M. 1994. Slump and Debris-Flow dominated Upper Slope Facies in the Cretaceous of the Norwegian and Northern North Seas (61–67°N): Implications for Sand Distribution. *American Association of Petroleum Geologists Bulletin*, **78**, 6, 910–937.

Skibeli, M., Barnes, K., Straume, T., Syversen, S. E. & Shanmugan, G. 1995. A sequence stratigraphic study of Lower Cretaceous deposits in the northernmost North Sea. *In:* Steel, R. (ed.) *Sequence Stratigraphy on the Northwest European Margin*. Norwegian Petroleum Society Special Publication, **5**, 389–400.

Skogseid, J., Planke, S., Faleide, J. I., Pedersen, T., Eldholm, O. & Neverdal, F. 2000. NE Atlantic continental rifting and volcanic margin formation. *In:* Nøttvedt, A. (ed.) *Dynamics of the Norwegian Margin*. Geological Society, London, Special Publications, **167**, 295–326.

Swiecicki, T., Gibbs, P. B., Farrow, G. E. & Coward, M. P. 1998. A tectonostratigaphic framework for the Mid-Norway region. *Marine and Petroleum Geology*, **15**, 245–276.

Sánchez-Ferrer, F., James, S. D., Lak, B. & Evans, A. M. 1999. Techniques used in the exploration of turbidite reservoirs in a frontier setting – Helland Hansen licence, Vøring Basin, offshore mid Norway. *In:* Fleet, A. J. & Boldy, S. A. R. (eds) *Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference*. Geological Society, London, 281–292.

Van Wagoner, J. C., Mitchum, R. M., Campion, K. M. & Rahmanian, V. D. 1990. *Siliciclastic sequence stratigraphy in well logs, cores and outcrops: concepts for high-resolution correlation of time and facies*. American Association of Petroleum Geologists Methods in Exploration, **7**.

Ziegler, P. A. 1990. *Gelogical Atlas of western and central Europe*. Shell Internationale Petroleum Maatschappij BV., The Hague.

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