Paper IV

Cretaceous and Palaeogene turbidite systems in the North Sea and Norwegian Sea Basins: source, staging area and basin physiography controls on reservoir development

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Abstract: The Cretaceous and Palaeogene succession in the North Sea and Norwegian Sea basins show widely variable deep-water sedimentary systems in terms of processes, facies, geometries, scale and distribution. The primary controls on the large-scale variability are considered to be source area size, basin and basin margin physiography and bathymetry, tectonic history and resulting morphology of drainage and delivery systems of sediments to deep-water areas, and the rate of sediment delivery. The North Sea and Norwegian Sea basins were comparable during the earliest Cretaceous, but thereafter developed in widely different ways as a response to proximity to oncoming North Atlantic seafloor spreading.

In the North Sea Basin, the Cretaceous and Palaeogene turbidite systems were controlled by an inherited structural template from Late Jurassic rifting, and by source area size. Poorly developed or small drainage systems on the Norwegian margin and the broad Horda Platform gave little sand supply from the east to the Viking Graben area. Sand-rich systems were sourced from a relatively large hinterland and shallow marine staging area on the East Shetland Platform. North of the Horda Platform, sand supply was abundant in very discrete periods, particularly in the Early Eocene.

In the Norwegian Sea basins, the Late Jurassic structural template controlled Early Cretaceous deep-water sedimentary systems in a manner similar to the North Sea Basin. Generally small and poorly developed drainage systems caused development of mud-rich systems. In contrast, in the Late Cretaceous, onset of precursor tectonic activity to sea-floor spreading led to increased sand supply from the west into the Vøring Basin. A relatively narrow palaeoshelf and a large source area contributed to forming sand-rich systems. Smaller turbidite systems developed along the Norwegian margin, which were sourced from the east from smaller drainage areas, and partially across broad shelves, such as the Trøndelag Platform. Both in the Cretaceous and Palaeogene, the sandiest systems are found only to the south and the north of the inherited structural features.

Keywords: turbidite systems, Cretaceous, Palaeogene, North Sea, Norwegian Sea

Offshore Norway, Cretaceous and Palaeogene oil and gas prospectivity is almost exclusively within rocks deposited in deep-water sedimentary systems (Figs 1 and 2), apart from the huge chalk discoveries in the southernmost Norwegian North Sea. To date, only the Paleocene Ormen Lange Field in the Møre Basin (Fig. 1), and a few upper Cretaceous discoveries on the eastern margin of Vøring Basin are commercial discoveries in reservoir rocks derived from the Norwegian mainland. Understanding the temporal and spatial distribution of Cretaceous and Palaeogene reservoir rocks is a major challenge. Large sand accumulations are only found in the northwestern part of the Vøring Basin and were fed from the western basin margin in Greenland. Elsewhere, including the Paleocene Ormen Lange system, sand accumulations are generally sparse and occur within otherwise mud-rich deep-water sedimentary systems.

The aim of this paper is to illustrate eight different turbidite bearing depositional systems of Cretaceous and Palaeogene age. The controls on their development varied in time and space as a response to basin evolution controlled by inherited bathymetry and shelf physiography from latest Jurassic rifting, and initial, Late Cretaceous pre-drift rifting in the Norwegian Sea. In addition, although more difficult to specify, hinterland source area size appears to have exerted a major control on sand and overall sediment supply. The eight systems are discussed in a sediment source-to-sink perspective to illustrate the spatial and temporal changes of dominant control factors. Because of data availability, only deep-water depositional systems occurring on the Norwegian continental shelf are included.

Controls on turbidite system development

A number of processes or critical factors can influence the development of deep-water sedimentary systems (Table 1). These controls vary from hinterland onshore source area through the nearshore linking/staging zone where sediments are temporarily stored, to the deep-water area itself where sediments finally are deposited. In any basin, only a few of the factors will dominate, dependent on basin type and other extrinsic factors (Martinsen *et al.* 2003). In Atlantic margin basins, Cretaceous and Cenozoic deep-water sedimentary system development has varied significantly because: (i) the timing of rifting followed by seafloor spreading and subsequent sediment fill draping topography has varied significantly; (ii) hinterland source area, drainage basin size, and consequent sediment delivery are quite different in areas where major rivers such as the Congo and Amazon meet the sea, compared to areas such as the Norwegian margin where no major rivers occur; (iii) sea-level cyclicity has been much more pronounced in glacial periods such as the Neogene; (iv) shelf width, as an outcome of previous tectonics, varied considerably, particularly in the Norwegian Sea basins.

Therefore, specific models for deep-water deposition are apparently more appealing than globally applicable models. Facies models, such as those of Mutti & Ricci Lucchi (1972), Normark (1978), and Walker (1978) only apply as models for very specific systems and have limited general value. Nevertheless, they should not be discarded, since they describe specific types of turbidite systems in detail. More recent models are

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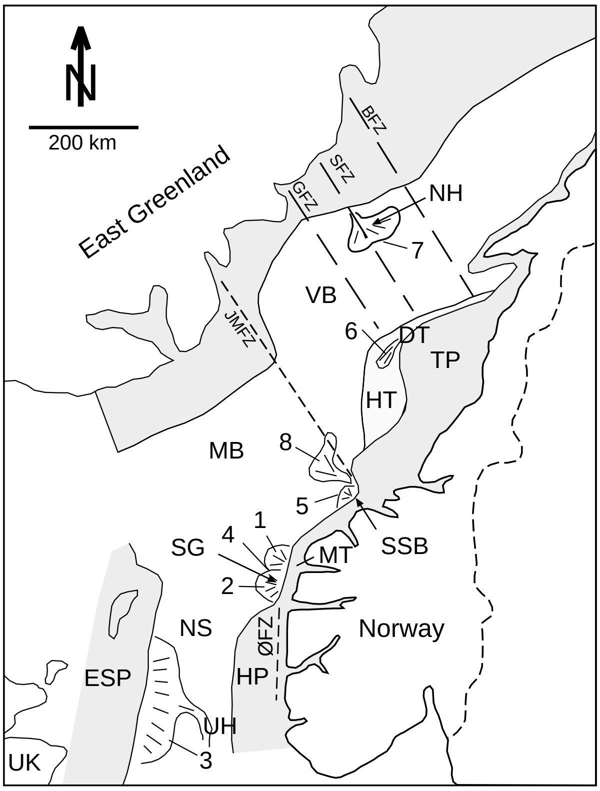


Fig. 1. Location map of the eight turbidite depositional systems described in this paper. Major structural features are shown, and the shaded areas indicate palaeoshelf areas. BFZ, Bivrost fracture zone; DT, Dønna Terrace; ESP, East Shetland Platform; GFZ, Gleipne fracture zone; HP, Horda Platform; HT, Halten Terrace; JMFZ, Jan Mayen fracture zone; MT, Måløy Terrace; MB, Møre Basin; NH, Nyk High; NS, North Sea; SG, Sogn Graben; SFZ, Surt fracture zone; SSB, Sløreboth Subbasin; TP: Trøndelag Platform; UH: Utsira High; VB: Vøring Basin; ØFZ, Øygarden fault zone.

more generally applicable, but still only use a few critical factors (cf. Table 1). Wetzel (1993) for instance, used sediment delivery rate as proxy for source area size and compared it with the sizes of actual submarine fans. In addition, Wetzel (1993) showed how estuaries were more efficient in delivering sediments to deep-water systems than were deltas, thus focusing on the type of shallow-marine system. Reading & Richards (1994) used the type of delivery system (point-, ramp- and line-sourced) vs. dominant grain size as discriminating factors for classifying turbidite systems but did not discuss the role of basin bathymetry. Prather *et al.* (1998) showed how slope sedimentation and deformation controlled slope accommodation and this approach is of general importance for prediction of reservoir sand distribution. Castellort & Driessche (2003) discussed how climate influenced river length and consequently sediment delivery to deep-water basins. Prather (2003), and Steffens *et al.* (2003) have recently discussed, respectively, controls on sedimentation in deep-water slope settings and the influence of receiving basin configuration. The publications referred to above show how a few (of many potentially available) processes in each case dominate to create highly variable depositional systems.

The following eight examples of deep-water sedimentary systems from the North Sea and Norwegian Sea Basins (Table 2) illustrate the importance of taking a process-based approach to understanding deep-water sedimentary system development. The list of critical factors (Table 1) is a useful guide for comparison and prediction. A universal model is impossible to apply, simply because controlling processes varied in time and space.

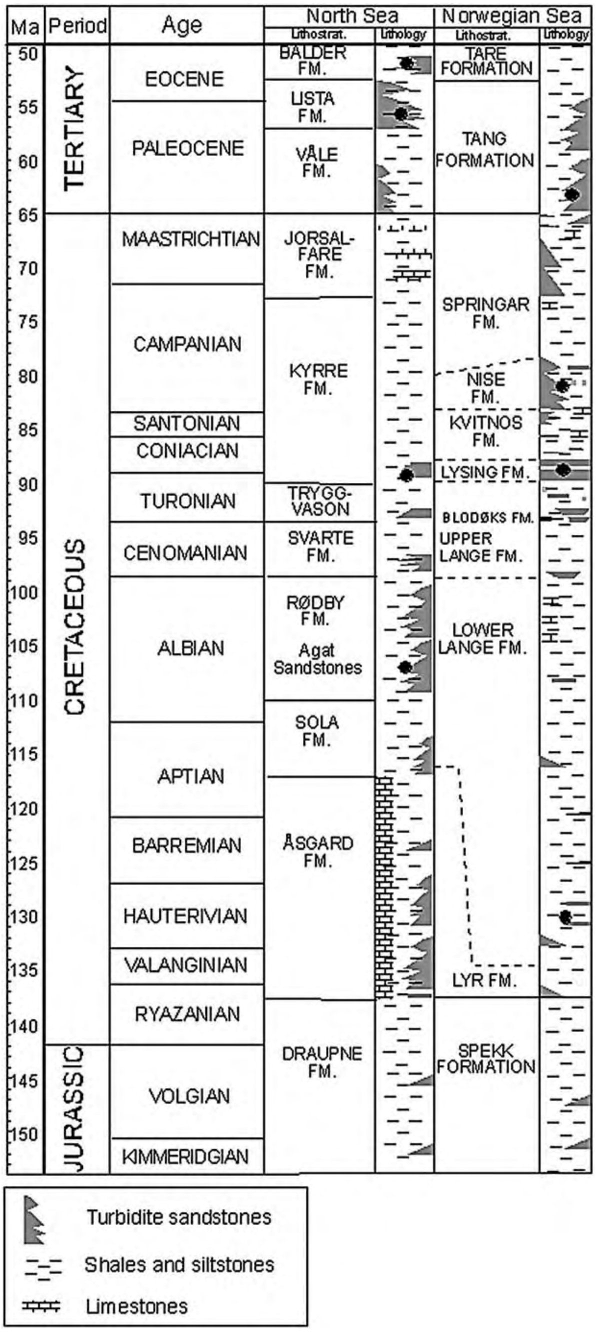


Fig. 2. North Sea and Norwegian Sea uppermost Jurassic, Cretaceous and Palaeogene stratigraphy and ages (black circles) of investigated deep-water depositional systems. The North Sea and Norwegian Sea columns show sediment supply directions from western (left side of columns) and eastern (right side of columns).

North Sea and Norwegian Sea basin and basin margin development

Basin formation and bathymetry

Both the North Sea and Norwegian Sea sedimentary basins originated prior to the Mesozoic (Ziegler 1988). Their present shapes were influenced by three main tectonic events: (i) Permo-Triassic rifting; (ii) Late Jurassic–earliest Cretaceous rifting; (iii) Late Cretaceous rifting (from Campanian) and subsequent drift and seafloor spreading (from Eocene). The last tectonic phase primarily had its effect in the Norwegian Sea basins, while the North Sea Basin continued to be an aulacogen, albeit with pronounced uplift of basin margins (Nadin & Kusznir 1995; Martinsen *et al.* 1999). Volcanism and uplift of the Shetland

Table 1. Overview of critical factors for deep-water sedimentation

Onshore	Linking zone	Offshore
Drainage basin size	Type of shallow-marine system and processes	Gravitational processes
Climate		Slope angle
Topographic relief	Shelf width	Slope accommodation and topography
Geomorphology	Sea-level changes	
Tectonic activity and structures		Sediment calibre
Type of river system		Type of feeder system
Hinterland bedrock type		Basin shape
		Basin bathymetry

Platform provoked clastic sediment delivery to the North Sea Basin by changing the basin from a chalk-dominated basin to an area receiving large volumes of clastic material (Parker 1993, and references therein).

Prior to the Late Jurassic, the Mesozoic era in all basins had been dominated by fluvial, nearshore marine and marine shelf deposition. The Late Jurassic–earliest Cretaceous rift episode left a pronounced differential bathymetry into which deep-water sedimentation eventually took place after a significant sea-level rise (Kyrkjebø *et al.* 2001). Both in the North Sea and Norwegian Sea basins, the lowermost Cretaceous sediments filled half-grabens inherited from the previous rift episode. The differential bathymetry was largely filled by Albian–Cenomanian time, from which period sedimentation was more evenly distributed, although a number of sedimentation breaks occurred (Kyrkjebø *et al.* 2001; Færseth & Lien 2003).

Based on information from areas such as the southeastern Møre Basin (see Gjelberg *et al.* 2005), it is obvious that the overall bathymetric configuration was also maintained in the Palaeogene in both the North Sea and in the Norwegian Sea basins. Differential subsidence, controlled by differential compaction of the overall fine-grained Cretaceous sediment succession, but perhaps also by movement on faults created in the Jurassic, formed subtle bathymetry and deep-water accommodation that controlled deep-water sedimentation. Such a situation is also seen in the southern Viking Graben area. The westerly derived turbidite systems, such as those forming the reservoirs in the Grane Field, gradually became perched on the Utsira High as the Viking Graben continued subsiding (Mangerud *et al.* 1999). This situation was advantageous for trap formation and migration of hydrocarbons, but limited Eocene reservoir development west of the Utsira High.

Palaeoshelf areas

Two large structural highs have been identified on the Norwegian basin margin; the Horda Platform in the North Sea and the Trøndelag Platform in the Norwegian Sea (Fig. 1). Since the Jurassic, and probably as far back as the final phase of Caledonian tectonism in the Silurian, these highs formed salient, broad shelf areas (Blystad *et al.* 1995; Færseth 1996; Færseth & Lien 2003). In the Møre and Vøring basins, the palaeoshelf area on the Trøndelag Platform is bounded to the south by the extension of the Jan Mayen Lineament, a major oceanic transform fault (Blystad *et al.* 1995). To the north, a comparable transform fault, the Bivrost Lineament occurs, marking the northern end of the wide palaeoshelf area (Fig. 1).

On the western margin in the Norwegian Sea, the extension of the Jan Mayen lineament appears to create an opposite effect to

Table 2. Characteristic parameters of each turbidite depositional system. The numbers are average estimates based on topographic maps, seismic mapping and well information

#	Basin	Location	Age	Drainage area	Shelf width	Sediment type	Thickness	System Area	Morphology
1	North Sea	Agat	Aptian-Albian	5000–8000 km^2	20–30 km	Sand/mud-rich	200–400 m	200 km^2	Slope apron
2	North Sea	Måløy slope	Turonian	5000–8000 km^2	20–30 km	Sand/mud-rich	50–150 m	500 km^2	Slope apron
3	North Sea	Grane	Paleocene	? 20 000 km^2	200 km	Sand-rich	70 m	40 km^2	Basin floor mound
4	North Sea	Q35, Northern North Sea	Eocene	5000–8000 km^2	20–30 km	Sand-rich	200 m	300 km^2	Basin floor sheet
5	Norwegian Sea	Møre Margin	Hauterivian	250 km^2	25 km	Coarse-grained mixed	50–70 m	100 km^2	Fault apron
6	Norwegian Sea	Dønna Terrace	Turonian	1 000 km^2	200 km	Sand/mud-rich	20–50 m	500 km^2	Local basin floor sheet
7	Norwegian Sea	Vøring Basin	Campanian	25 000 km^2	50 km	Sand-rich	500–1000 m	3000 km^2	Basin floor sheet
8	Norwegian Sea	Møre Basin	Paleocene	10 000 km^2	30 km	Sand-rich	50–100 m	1500 km^2	Slope channels and basin floor sheet

that on the eastern basin margin (Fig. 1). Apparently a large palaeoshelf area occurred to its south, and a narrow shelf area to the north, based on interpretations of magnetic anomalies. Structural reconstructions by Whitham *et al.* (1999) suggest that a narrow palaeoshelf existed offshore on the Greenland coastline at Hold with Hope. In contrast, south of the Jan Mayen lineament, in-house work suggests that continental crust probably extends out onto the shelf, supporting its role as a palaeoshelf area in the Cretaceous and Palaeogene (Fig. 1). This conjugate tectonic situation, which probably originated in Jurassic time, has been documented and discussed by a number of authors such as Brekke (2000) and Mosar (2003), but the direct effect on deep-water sedimentation has not been discussed previously.

Basin margin sediment source areas

Hinterland source area size is the primary control on the volume of long-term sediment delivery to deep-water basins (Wetzel 1993). In the Cretaceous and Palaeogene, sediment delivery is assumed to have varied significantly from one basin margin to another in the Norwegian offshore basins. Deep-water sediments delivered from the western basin margins, both in the North Sea and in the Norwegian Sea, are much more voluminous, but perhaps surprisingly also more sandy than those delivered from the eastern, Norwegian margin (cf. Parker 1993 and references therein; Kittilsen *et al.* 1999; Martinsen *et al.* 1999). The Norwegian margin probably delivered relatively little sediment throughout the Cretaceous and Palaeogene. One reason is that since the Jurassic, the watershed (and subsequently the easternmost limit of drainage basins), lay more or less where it is today, i.e. only some 100–150 km from the present coastline, based on identification of palaeogeomorphic surfaces (Torske 1972; Riis & Fjeldskaar 1992; Martinsen *et al.* 1999; Gjelberg *et al.* 2005).

In contrast, the Greenland and Shetland Platform eastern basin margins provided abundant sediment (e.g. Parker 1993 and references therein; Larsen *et al.* 2001; Surlyk & Noe-Nygaard 2001). The present Greenland fjord systems are considered to have linked up with major sediment delivery routes from a large hinterland, providing abundant sediment volumes to nearshore and shelf areas where temporary sediment storage took place (Whitham *et al.* 1999; Hartz *et al.* 2002). The Shetland Platform was a major sediment storage area both in the Cretaceous and Palaeogene (e.g. Jones & Milton 1994), linking a periodically uplifted hinterland with the deep-water areas in the North Sea.

In the Norwegian Sea, Cretaceous deep-water sediments derived from the western Greenland margin reach at least as far east as the Ormen Lange Dome and Helland-Hansen Arch (Fonneland *et al.* 2003), both considered to lie well within the eastern margin area. In contrast, there are no traces of easterly derived sediments in any of the western wells. These observations support the dominance of sediment supply from the western basin margins in the Norwegian Sea.

North Sea and Norwegian Sea deep-water sedimentary systems

In the following section, the eight selected deep-water depositional systems are described in terms of basin setting and source area, lithology and depositional facies, and system morphology. Obviously, the background data vary in quality and quantity from area to area and there are several assumptions and speculations. Nevertheless, particularly the Norwegian Sea, but also parts of the North Sea, are underexplored and covered by few wells and high-resolution 3D seismic where ground-truthing is possible. The ambition is therefore an attempt to draw together the 'state-of-the-art' knowledge and make some more general interpretations of how deep-water sedimentary systems varied in time and space in these vast basins. Interpretations of source areas are particularly uncertain and prone to circular reasoning, but as Wetzel (1993) has shown, this factor is of critical importance to understanding sediment calibre, quantity and quality. Thus, for completeness, a discussion of this factor is needed in this paper.

Depositional system 1: Early Cretaceous (Agat)

Basin setting and source area. Early Cretaceous deposition in the North Sea was strongly influenced by the basin topography created by Late Jurassic rifting (Fig. 3). Grabens in the west and terraces/structural highs and slopes in the east controlled accommodation, transport directions and available source areas (Fig. 1). During the late Early Cretaceous the Måløy Terrace (Fig. 1) had a low-gradient slope towards the deeper Sogn Graben in the west (Shanmugham, 1995; Bugge *et al.* 2001). Accommodation on the terrace was controlled by differential subsidence of underlying mud-rich sediments along a N–S trend controlled by the Jurassic faults, and/or by slope accommodation created by large-scale slides or slumps (Bugge *et al.* 2001).

Sandstones of the Agat Formation (Isaksen & Tonstad 1989) were deposited on the Måløy Terrace during late Early Cretaceous (Fig. 3). These sandstones were probably deposited during regressive stages within an overall transgressive period and sourced from the Norwegian margin through one or multiple E–W-striking palaeovalleys observed on seismic (Bugge *et al.* 2001). The Agat Formation has a relatively coarse grain size, and high sand and glauconite content (i.e. well 35/3-5). This suggests a sand-rich, possibly shallow-marine source area, and according to Brekke *et al.* (2001), a rejuvenation of older landmasses causing progradational pulses of shelfal sands around the fringe of the North Sea Basin during Aptian and Albian times. The size of the source area is speculative, but observations of the palaeovalleys that align with the present-day fjords, and indications of a shallow marine sandy source relatively close to depositional sites, imply a narrow shelf and a small to moderate source area.

Lithology and depositional facies. The hemipelagic deposition of the Early Cretaceous was interrupted by sandy mass-flow events (Bugge *et al.* 2001). Sandstones of the Agat Formation occur in several wells in Block 35/3. These sandstone beds are typically 10–30 cm thick and are interbedded with thin mudstone beds, but can be amalgamated to thicknesseses of many tens of metres (Bugge *et al.* 2001). The sandstone beds have a fine- to medium and occasional coarse grain-size, are in general massive to normally graded with water escape structures and are interpreted as turbidites. Nystuen (1999) presented a similar interpretation to Bugge *et al.* (2001). However, Shanmugam *et al.* (1995) presented an alternative interpretation of the Agat sandstone intervals as sandy debris flows.

System morphology. The overall geometry of the Agat sandstone system deposited in Block 35/3 is elongate, trending E–W from the shelf to the basin (Fig. 3). However, the morphology of the system was influenced by the geometry of the slope and local accommodation. Underlying structures controlled local accommodation, where sands accumulated within sites of differential subsidence and onlapped the subtle margins of the local depressions (Fig. 3). Both channel, sheet body and slump elements are observed, indicating a change in slope gradient and slope accommodation. Pressure measurements indicate no communication between the main sandstones, suggesting they occur as isolated bodies within depocentres on the slope (Fig. 3).

Depositional system 2: Late Cretaceous, Måløy slope

Basin setting and source area. The Upper Cretaceous succession of the Norwegian northern North Sea is dominated by mud-rich sediments, which tend to onlap onto the eastern basin margin (Fig. 4). One exception is the Turonian Kyrre sands that occur in

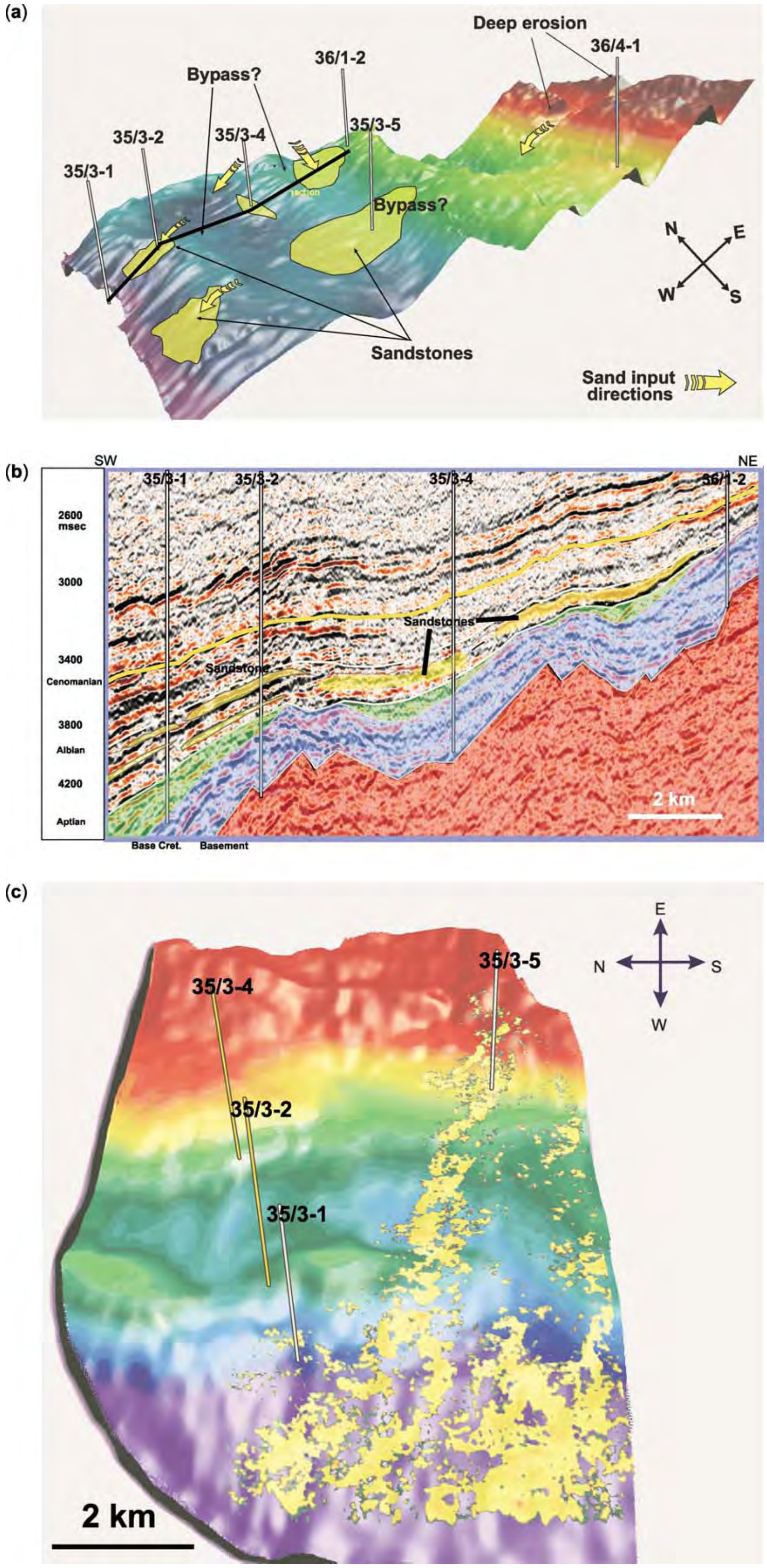


Fig. 3. (**a**) Lower Cretaceous sandstone bodies draped on a top basement map on the Måløy Terrace. Note the correlation between position of the sandstones and the basement lows. The position of the seismic line in (**b**) is shown as a thin black line. (**b**) Seismic line across the Måløy Terrace to the Sogn Graben, showing the Agat Formation sandstones and their primary location in structural lows. (**c**) Base Cretaceous time map overlain by amplitude map of the Agat sandstones penetrated by well 35/3-5 (courtesy of Kristina Heieren). Note the updip (to the east) elongate bodies which fan out towards the west.

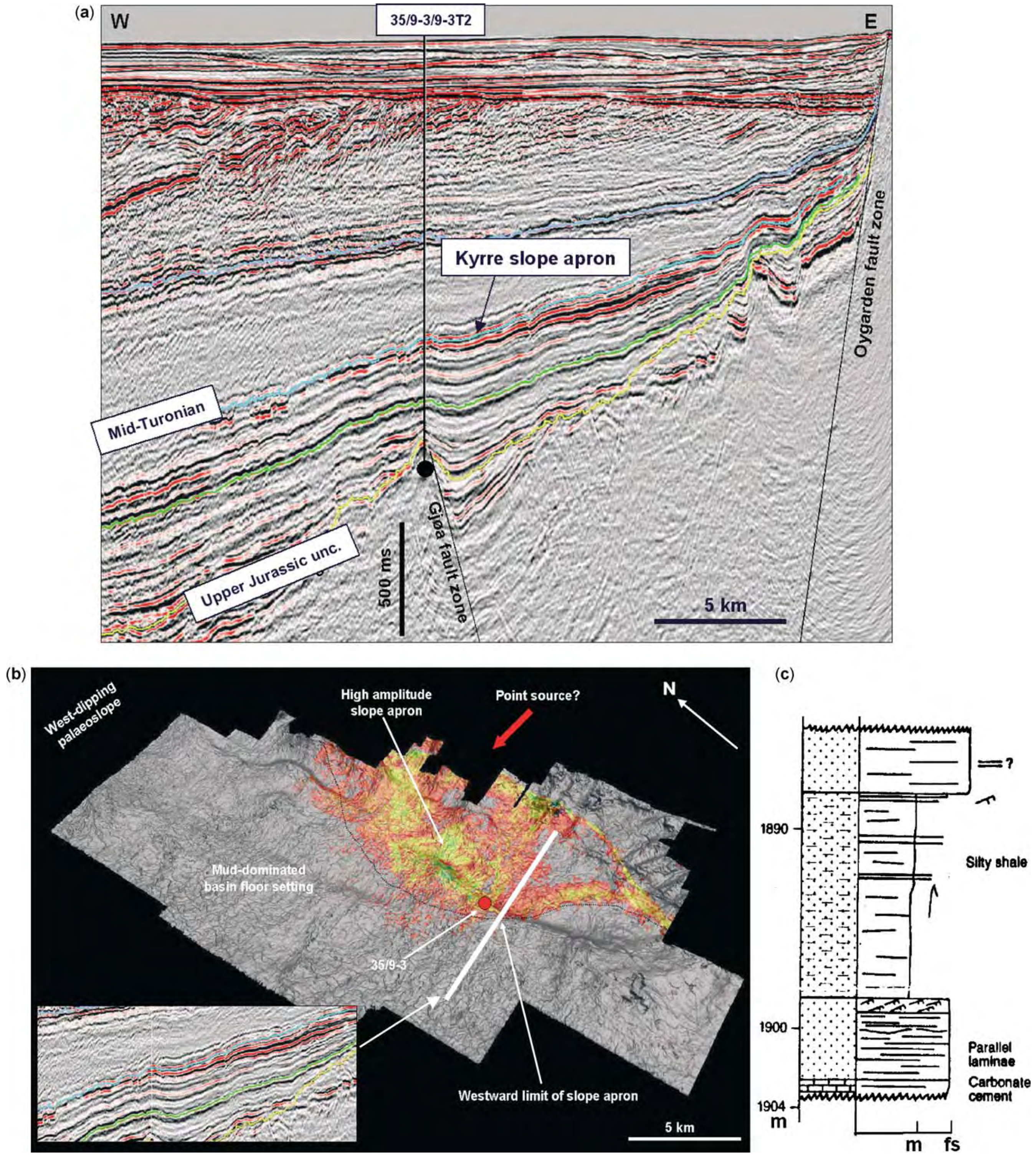


Fig. 4. (**a**) East–west seismic cross section across Block 35/9 in the southern part of the Måløy Terrace (see Fig. 1 for location). The green reflector is the base Turonian reflector also depicted in (b), while the blue reflector is the mid-Turonian reflector which represents the reservoir interval top. (**b**) Seismic attribute map draped onto a time-dip map of the mid-Turonian reflector. Note the lobate nature of interpreted slope apron deposional system. The thick white line is the seismic line shown in (a). Note also the strongly progradational nature of the Paleocene deep-water slope succession on the top. (**c**) Core log of the Turonian Kyrre Formation sands from well 35/9-3.

Blocks 35/9 and 36/7 on the Måløy Terrace. There, a wedge of sediments was deposited and filled the slope accommodation between the Øygarden fault complex in the east, and a subtle structural high off to the west, on the margin of the Sogn Graben (Figs 1 and 4). Thus, the wedge is perched above deeper basin areas to the west.

Slope accommodation probably formed by subtle differential subsidence on major basin bounding faults, and differential subsidence of underlying mainly fine-grained rocks may also have contributed. The sediments were sourced from the Norwegian margin (Fig. 4), perhaps through drainage systems located along today's fjords. This is speculative, but it is unlikely that the drainage basin extended farther east than the present drainage divide (see above). Thus, the Kyrre deep-water system was most likely fed from a relatively small source area.

Lithology and depositional facies. Well 35/9-3/3T2 occurs on top of the western structural high and penetrated the toe of the Turonian clastic wedge, finding several 1–7 m thick sandstones (Fig. 4c). The sandstones are fine-grained and vary between structureless and parallel- to cross-laminated, while some beds have dish structures. Several of the sandstone beds appear to have been deposited very rapidly. The well location at the wedge toe occurs immediately downslope from the thickest development (Fig. 4a) and suggests that turbidity currents were halted in this position. The area formed a probable backstop for continued flow towards the Sogn Graben. The structural high on which the well is positioned seems to have controlled local slope accommodation (Fig. 4).

System morphology. The wedge forms a slope apron in plan view (Fig. 4). The slope apron appears to have been fed from a number of small sources, based on its up-dip morphology (Fig. 4b). The feeder systems appear to have linked the onshore drainage system with the deep-water slope across a relatively narrow shelf. The narrow shelf interpretation is based on the fact that there are only a few tens of kilometres distance between the exposed bedrock onshore and the preserved Cretaceous slope setting offshore (Fig. 1). There is no evidence of Cretaceous deposition onshore anywhere in southern Norway and it is therefore speculated that the present-day onshore areas were also land in the Cretaceous.

Depositional system 3: Paleocene, Grane

Basin setting and source area. The Paleocene Grane depositional system is positioned on the flank of the Utsira High, east of the Viking Graben (Fig. 1). At present, the Grane Field is perched above the structural low to the west, but during deposition the area lay on a relatively flat basin floor east of the slope to the East Shetland Platform from where the sediments were sourced (Mangerud *et al.* 1999; cf. Parker 1993 and references therein). Grane forms the distal and easternmost toe of the large Heimdal/Andrew depositional system, which reaches many hundred metres of thickness to the west (Parker 1993 and references therein; Jones & Milton 1994).

The East Shetland Platform became a significant source of clastic supply to the North Sea Basin in Late Paleocene time, following uplift of the hinterland to the west in the British Volcanic Province. Impact of the Iceland hotspot probably caused the uplift (Nadin & Kusznir 1995), and it has been postulated that the British Volcanic Province is an extension of a failed arm of a triple junction in Iceland, where the two other rift branches eventually developed into the Mid-Atlantic Ridge (Lundin 2003). During the Palaeogene, huge quantities of sediment were transported from the hinterland source area to the central and northern North Sea (Parker 1993 and references therein), forming reservoir and sealing rocks for later hydrocarbon accumulations. One particular character of the Palaeogene depositional systems is the high degree of soft-sediment deformation, notably that of mud- and sand injection (e.g. Lonergan & Cartwright 1999; Bergslien 2002). The high proportion of soft-sediment deformation may be attributable to a high sedimentation rate, but also can be explained by rapid sedimentation of sands onto unstable, highly water-charged, smectite-rich muds. Ash deposition from volcanism in the British Volcanic Province supplied the smectite throughout the Late Paleocene and Early Eocene (Haaland *et al.* 2000).

Lithology and depositional facies. Clean, massive sands dominate the Grane depositional system and are up to 70 m in total thickness (Fig. 5). The main reservoir sandstone in the field has a very sharp base and top (Fig. 5). Dish structures and vertical deformation structures, interpreted to represent evidence of water escape, occur (Fig. 5). Injected sands, less than a metre in width occur up to some tens of metres above the main sandstone body (Fig. 5). The base and top of the sandstone body are undulatory (Fig. 5), particularly in the south and horizontal wells have drilled through shale walls several tens of metres above the base. The basal undulations and shale walls are interpreted to represent syn- to post-sedimentary large-scale loading and mud injections.

System morphology. The main reservoir at Grane is mounded and has a N-S elongate shape, but is markedly asymmetric in cross-section (Fig. 5). The western flank is much steeper than the eastern flank. During deposition, the Utsira High to the east probably formed positive basin topography onto which the depositional system onlapped (Martinsen *et al.*1998). Biostratigraphic evidence suggests that deposition was rapid (Mangerud *et al.* 1999), and it is likely that deposition of thick, clean sands onto soft muds was an ideal condition for causing initial loading, mud-injection/diapirism and later sand injection. It is also likely that differential subsidence and relative uplift of the Utsira High caused sliding of the Paleocene–Lower Eocene package towards the west, in part explaining the asymmetric shape of the Grane sand body.

Depositional system 4: Eocene (Q35)

Basin setting and source area. In the northern part of Quadrant 35 in the North Sea, a thick Eocene sandstone occurs which is situated basinwards and at the foot of underlying Paleocene slope deposits (Fig. 6). A Paleocene wedge prograded from the Norwegian margin, and was succeeded by two minor prograding wedges that occur updip (Fig. 6). Because of later tilting and Pleistocene erosion, only the downdip toes of these wedges can be recognized. Subsequently, deposition shifted abruptly basinwards, and an up to 200 m thick basin floor unit was deposited. The unit is very sandy (Fig. 6), and onlaps underlying sediments.

It seems that following Paleocene progradation of the basin margin, relative sea level rose and sedimentation shifted basinwards, when the two partly preserved wedges were deposited. Then, relative sea level must have fallen at the basin margin, forcing sedimentation to occur on the basin floor. Martinsen *et al.* (1999) interpreted this shift of deposition to record basin margin uplift, at the time of Atlantic break-up in Early Eocene time. Well data suggest a prominent shift of lithology from a primarily mud-dominated setting in the Paleocene to a setting with substantially more sand in the Eocene.

The source area of this sandstone probably lay in the western fjord area of Norway, east of the culmination of the Paleic surface (cf. Riis 1996; see above). Lack of provenance data makes it difficult to constrain the area better (see however below). North of the Horda Platform, the area dividing deep-water areas to the west from the hinterland/mainland in the east was probably narrow and at the most only a few tens of kilometres wide. This interpretation is based on evidence of successive uplifts throughout the Late Cretaceous–Cenozoic period (Martinsen *et al.* 1999), keeping the hinterland/mainland in the east (probably broadly coincidental with the present bedrock-dominated Norwegian landmass) relatively high during this period so that there was only a limited area on which shelf sediments could accumulate.

Lithology and depositional facies. There are no core data from this particular Eocene deep-water sandstone unit but wells in Block 35/3 reveal its sand-rich, sharp-based character. Deposition from sand-rich turbidity currents is suggested, probably in lobes. In seismic sections the unit is more transparent than the surrounding stratigraphy (Fig. 6). In some instances, mud diapirs dissect the sandstone unit (Fig. 6). These features indicate that sand deposition was rapid and loaded onto a muddy, unstable substratum.

System morphology. On seismic maps, the sandstone unit has a lobate, fan form, with its apex in the south and pinch out in the north (Fig. 6). Thus, the unit apparently originated in the south and the turbidity currents flowed northwards along the Paleocene slope rather than down it. Consequently, the sandstone sidelaps

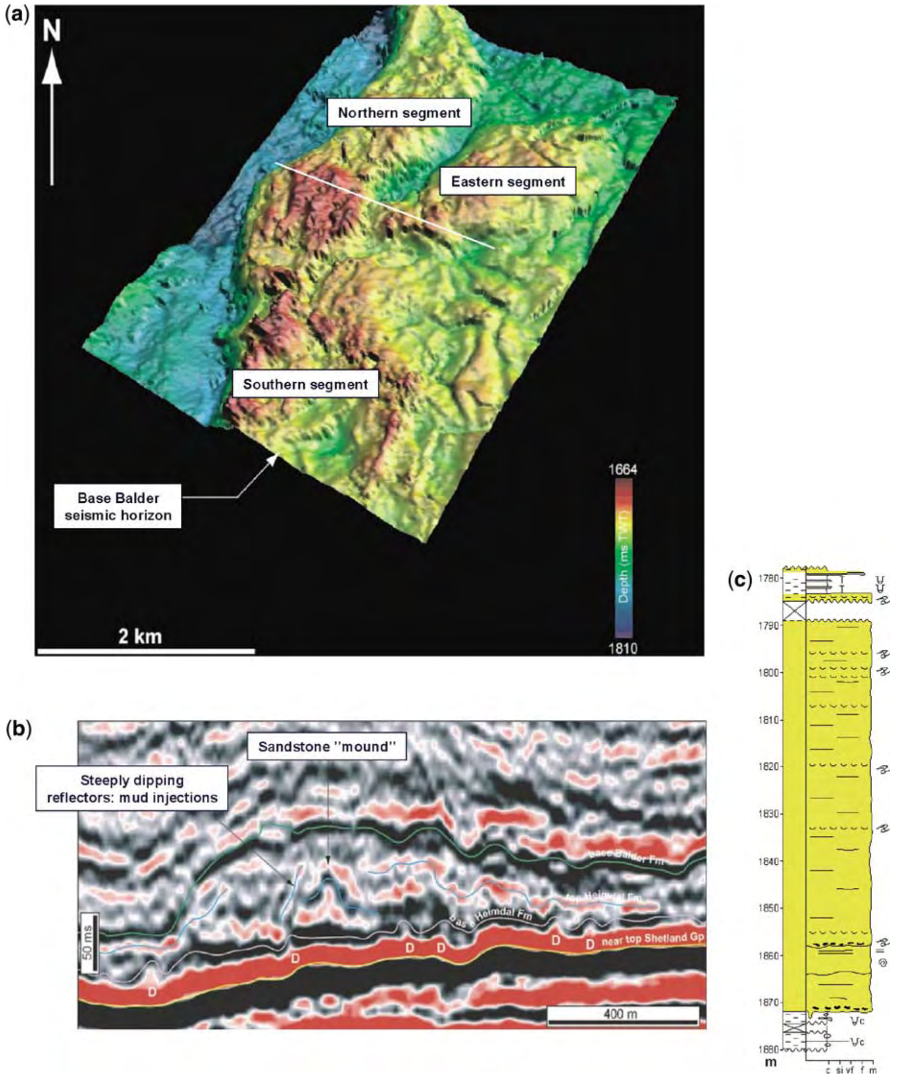


Fig. 5. (**a**) Visualization of base Balder time-depth map showing the mounded nature of the Grane Field (see also (b). The mounds reflect differential compaction as well as accentuation by syn- and post-sedimentary deformation. The location of the seismic line in (b) is shown. (**b**) Seismic cross section of the Grane Field (see (a) for location). Note the disturbed, chaotic nature of internal reflectors in the Paleocene succession. (**c**) Core log of well 25/11-21S showing the massive and homogenous nature of the Grane reservoir sands. The thin sand on the top (1778 m) is an injection sand.

the Paleocene slope deposits in the northernmost area (Fig. 6). Mapping becomes uncertain towards the south, but the fan apex appears to lie more or less directly outside the Sognefjord area. This submarine fan was fed from a feeder system close to the mouth of a palaeovalley that was closely coincidental with the present Sognefjord valley. Martinsen *et al*. (2002) have speculated that most present-day fjords in southern Norway were not of glacial origin but were glacially enhanced former drainage systems active since at least the Late Cretaceous (Gjelberg *et al*. 2005).

Depositional system 5: Early Cretaceous (Slørebotn)

Basin setting and source area. Late Jurassic syn-rift sequences represent only a minor constituent of half-graben successions offshore Norway. The major part of the sediments in the half-graben fill represents the Early Cretaceous post-rift stage of basin evolution (Færseth & Lien 2003). Along the southeastern margin of the Møre Basin, a normal fault with a vertical offset of some 5–6 km at Jurassic levels separates the Slørebotn Subbasin (Fig. 1) from a narrow platform to the east. A rotated Jurassic fault block approximately 40 km wide, capped with Middle Jurassic sediments on the crest, has been mapped below the Slørebotn Subbasin (Færseth & Lien 2003)(Fig. 7). Core and log data from well 6205/3-1R in the Slørebotn Subbasin penetrated a wedge shaped Early Cretaceous succession in the immediate hanging wall of the fault (Fig. 7). The succession onlapped the tilted strata in the hanging wall and represents passive infill of the relief created during Jurassic rifting (Færseth & Lien 2003).

Lithology and depositional facies. The sparse core data from the Early Cretaceous succession in well 6205/3-1R is dominated by coarse-grained, poorly sorted sediments of breccia and conglomerates with angular clasts, interbedded with sandstones and mudstones (Fig. 7d). It is uncertain whether the same facies occur throughout the Lower Cretaceous succession. The cored beds were probably deposited by gravity flows on a submarine slope a short distance from the sediment source area (Fig. 7b).

System morphology. The infilling package of post-rift sediments has a wedge-shaped, apron geometry, and is strongly controlled by the remnant Late Jurassic rift topography. The fault escarpments from the Jurassic rifting had high relief and the subbasins are small and narrow (Fig. 7). This gave small drainage areas, immature sediments and local accommodation. It is believed that such a scenario (Fig. 7c) was typical of Early Cretaceous deep-water sedimentation in the Norwegian Sea.

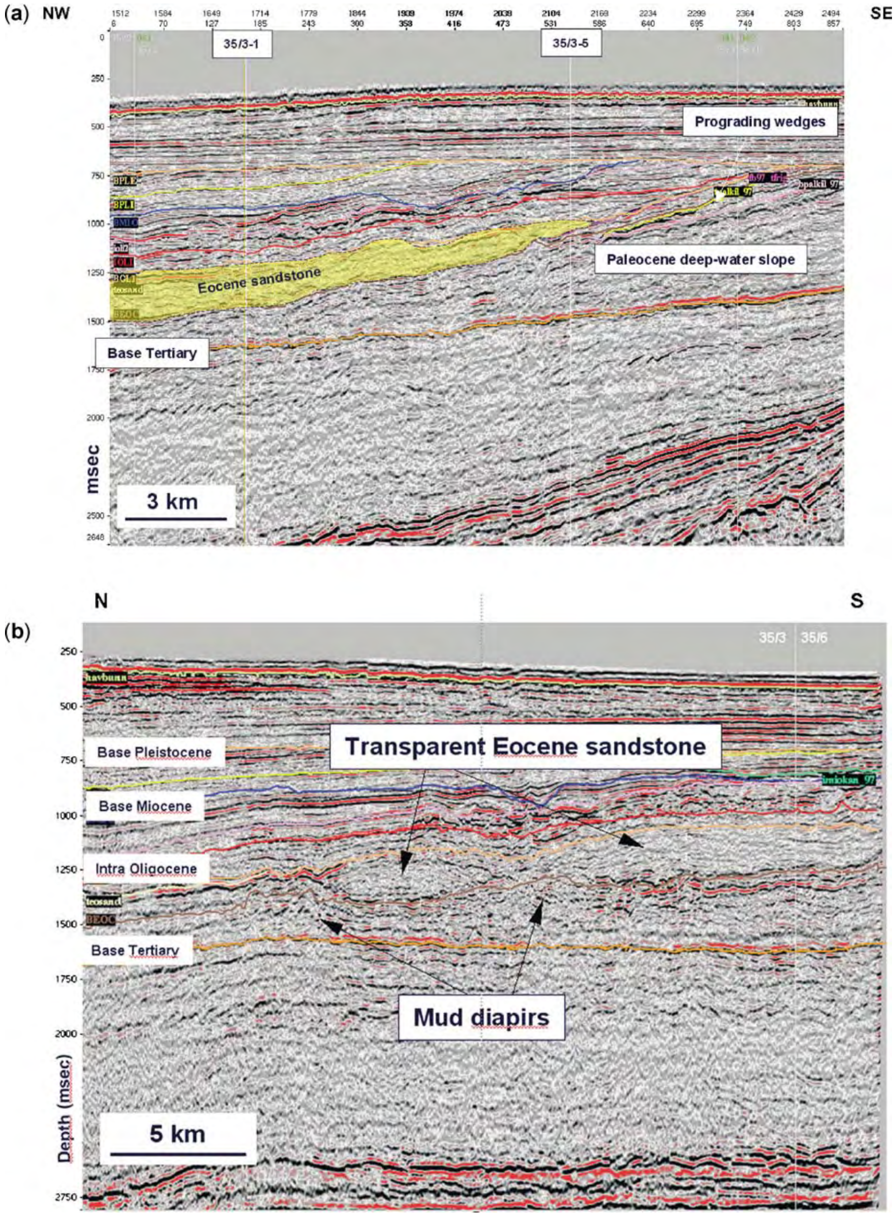


Fig. 6. (**a**) NW–SE random line in Blocks 36/1 and 35/3, Norwegian North Sea, showing sidelapping/onlapping Eocene sandstone unit above Paleocene wedges. See (c) for location of line. (**b**) N–S seismic line in Block 35/3 showing transparent Eocene sandstone unit dissected by diapirs of Paleocene muds. (**c**) Isochore map of parts of the Eocene fan system in Quardrant 35. Note the thinning against the eastern slope suggesting sidelap and the lobate shape affected by diapirism. Locations of seismic lines in (a) and (b) are shown.

Depositional system 6: Early part of Late Cretaceous Lysing Formation, Trøndelag Platform margin

Basin setting and source area. The inherited Late Jurassic basin topography was progressively filled during the Early Cretaceous, and almost eliminated in early Late Cretaceous (Færseth & Lien 2003). Backstepping and onlapping of sediment onto the basin margins occurred, such as along the western Trøndelag Platform (Fig. 8). The combination of decreasing thermal subsidence in the basin and an overall eustatic sea-level rise gave a wide but probably relatively shallow saucer shaped basin. On a regional scale, the Dønna and Halten terraces (Fig. 1) formed a low gradient deep-water slope between the Trøndelag Platform in the east and the Vøring Basin in the west. Differential subsidence of underlying fine-grained rocks controlled by the underlying Jurassic structures, and subtle differential subsidence on major basin bounding faults, formed low relief accommodation on these gentle regional slopes (Færseth & Lien 2003).

The Trøndelag Platform was a relatively wide, low relief, drowned shelf during the Late Cretaceous (Brekke 2000). Regressive periods exposed parts of the platform, and sandstones were deposited in intra-slope accommodation on the Halten and Dønna terraces. The exposed source areas were small, like the Nordland Ridge (Fig. 8), and probably not connected to the main hinterland or to larger drainage systems.

Lithology and depositional facies. The early Late Cretaceous in the Norwegian Sea is dominated by an overall mud- and siltstone lithology interrupted by thin intervals of sandstone (Dalland *et al.* 1988). The Lysing Formation of Late Turonian to Early Coniacian age is the dominant sandstone interval, and was deposited on the Halten and Dønna terraces in intervals up to 80 m thick in well 6507/7-1. The sandstones are in general very fine to medium grained with varying degree of sorting. The facies are interpreted as deep marine deposits, transported by turbidity currents (Fig. 8). Glauconite is common in the Lysing Formation

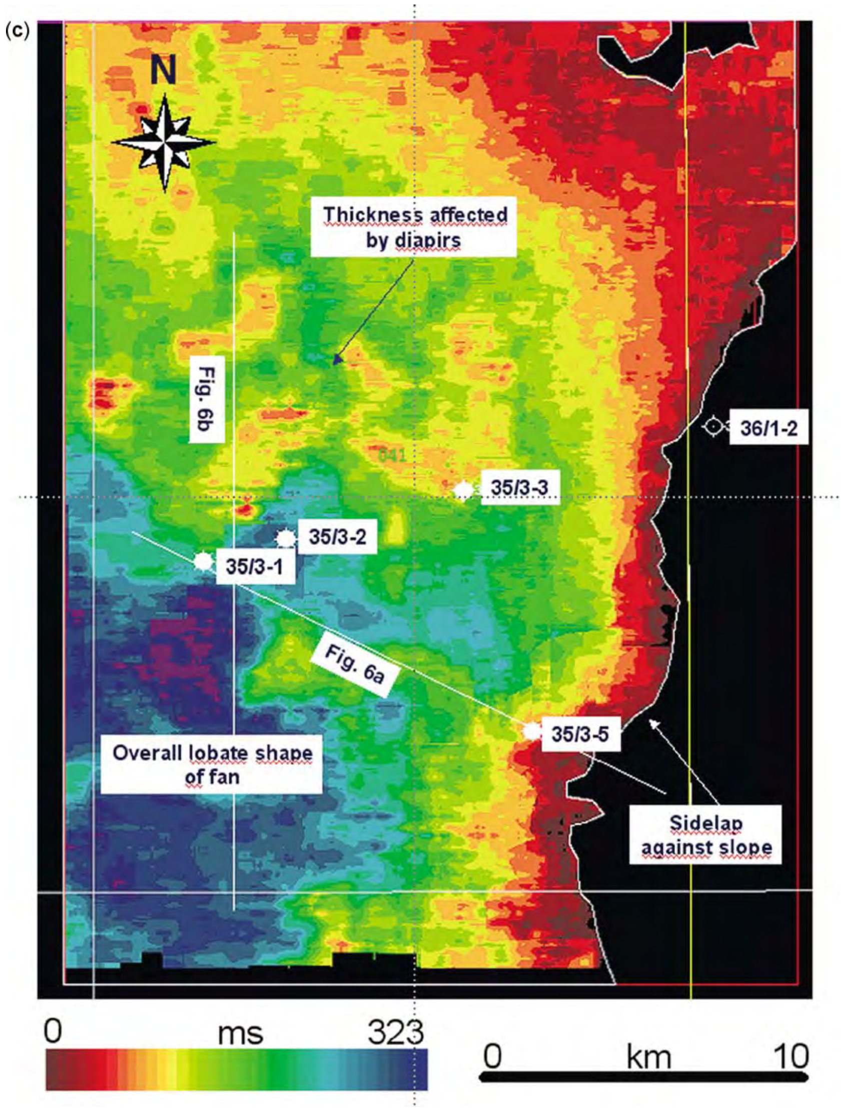


Fig. 6. (*continued*).

along the eastern basin margin (Dalland *et al.* 1988), and possibly reflects re-deposition of shallow marine sand from the palaeoshelf.

System morphology. The Lysing Formation occurs as a thin sheet sand complex, such as the system penetrated by well 6507/2-2 and 6507/2-3 on the Dønna Terrace (Fig. 8). This is a representative system of the Lysing Formation on the terraces along the eastern basin margin. The system morphology can be described as thin sheets or lobes where the geometry was controlled by the subtle topography on the overall gentle slopes. The width of the system is about 10–20 km, and length up to a few tens of kilometres. No major channels, canyons or incisions are associated with the Lysing Formation along the Trøndelag Platform.

Depositional system 7: Late Cretaceous, Nyk High

Basin setting and source area. The Late Cretaceous to Paleocene rift stage in the Vøring Basin was initiated in the Campanian with a progressive change from a low relief, wide basin to a rotated fault-block topography prior to the initiation of the sea-floor spreading (Færseth & Lien 2003). Thick sedimentary successions were deposited in the rift basin in the Någrind and Vigrid synclines. Pre-break-up reconstructions suggest that the East Greenland shelf was located just northwest of the western Vøring Basin (Fig. 1, Skogseid *et al.* 2000; Larsen *et al.* 2001 and references therein), and that it acted as a sediment source to the thick successions in the basin (Morton & Grant 1998; Whitham *et al.* 1999, Fonneland *et al.* 2003). Rift-related uplift of East Greenland resulted in a major unconformity, spanning most of the Campanian and Maastrichtian interval, in the succession along the East Greenland margin (Larsen *et al.* 2001). Structural reconstructions and magnetic anomalies close to the present coastline indicate a narrow palaeoshelf between the uplifted East Greenland margin and the subsiding Vøring Basin in the east (Fig. 1) (Whitham *et al.* 1999). This palaeoshelf is intersected by transform faults, like the Gleipne and Surt lineaments (Fig. 1). These lineaments may have acted as transport pathways from the East Greenland palaeoshelf to the Vøring Basin in the east (Brekke 2000). The Surt Lineament is located close to the Nyk High (Fig. 1) and probably acted as a fairway for sediment transport from the East Greenland palaeoshelf of the thick Upper Cretaceous sandstone successions, such as in the 6707/10-1 well at Nyk (Fig. 9).

Lithology and depositional facies. Well 6707/10-1 drilled on the Nyk High (Figs 1 and 10) penetrated an approximately 1000 m thick Campanian sand-rich succession with a net-to-gross sand ratio of 70% (Kittilsen *et al.* 1999). The sandstones are fine to medium grained with occasional granules and scattered organic debris. Typical facies are amalgamated to interbedded, less than

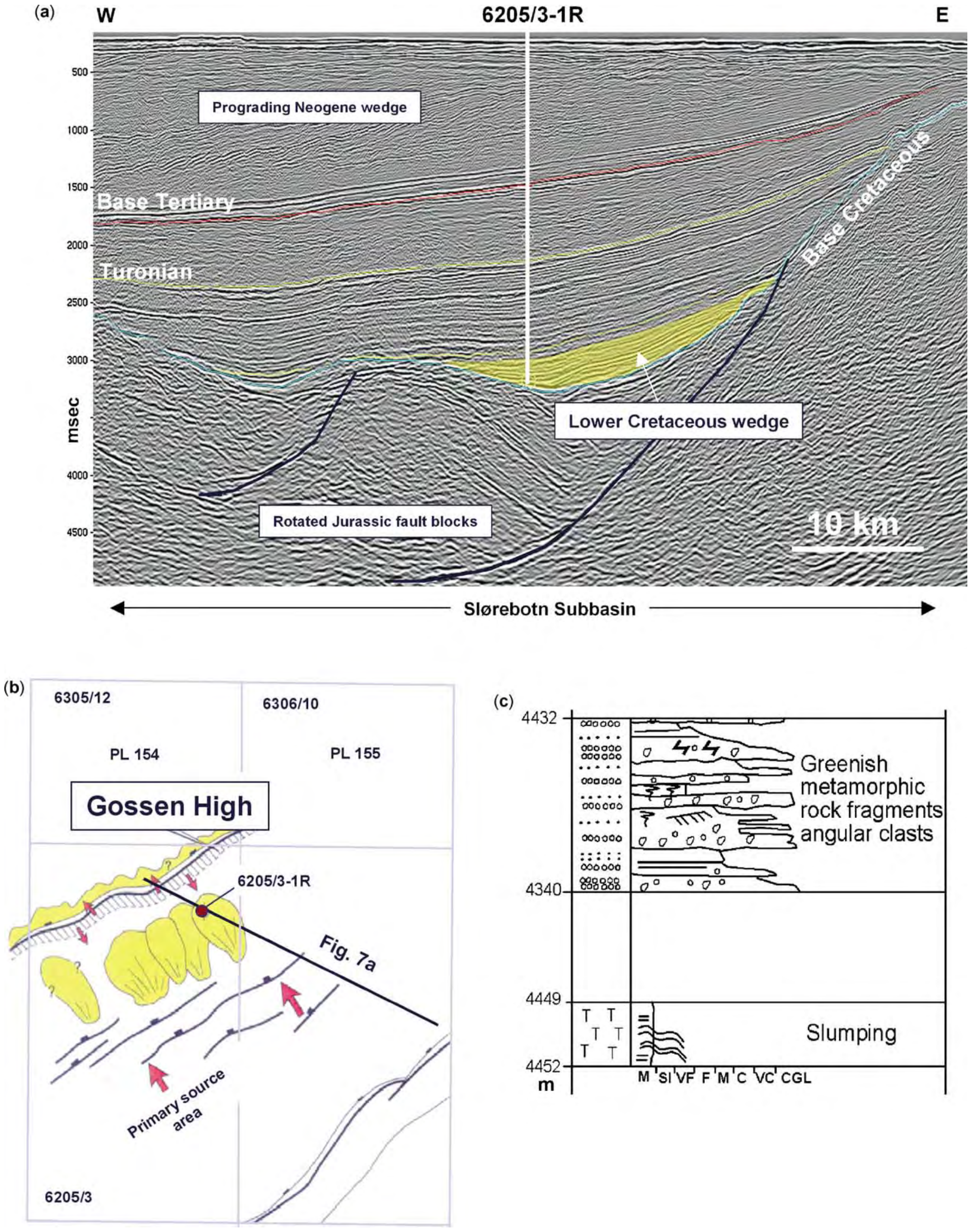


Fig. 7. (**a**) Seismic line across the Sløreboth Subbasin with well 6205/3-1R. Note the Early Cretaceous (Hauterivian) sediments in yellow deposited in the hanging wall-low close to the fault escarpment. (**b**) Areal extent of the Hauterivian sandstones deposited in the Slørebotn Subbasin. Note the strong control by the structural elements on accommodation and proximity to the main faults bounding the depocentres. (**c**) Core description of the Hauterivian sandstones in well 6205/3-1R. Note the immature and poorly sorted coarse sediments associated with slumped material, indicating short transport and deposition in a fault apron.

1 m thick, massive to upward-fining beds with Bouma divisions. Water-escape structures are common, and both thinning and thickening upward trends in bed thickness in the order of few tens of metres are identified (Fig. 9). The sandstones are interpreted as turbidites, and the vertical thickening and thinning trends probably record shifting of depositional lobes within stacked submarine fans.

System morphology. The gently subsiding Någrind and Vigrid synclines east of the Nyk High controlled the geometry of the thick sandy submarine fan successions during the initial stage of the Late Cretaceous rifting (Færseth & Lien 2003). Based on seismic interpretation, the Campanian fan systems penetrated by the Nyk well are more than 50 km wide and possibly more than 80 km long. Parallel reflectors dominate the interval, with an overall thinning

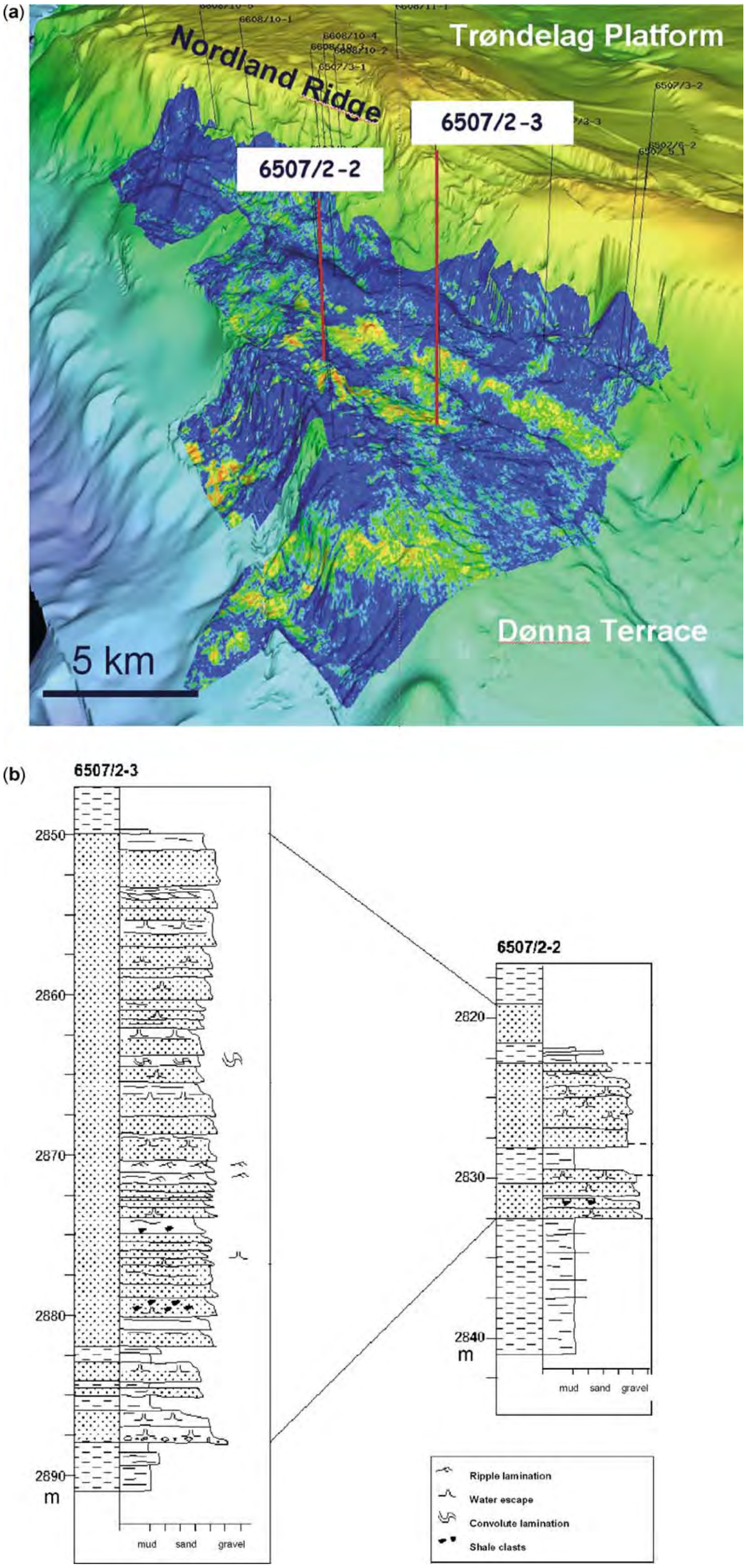


Fig. 8. (**a**) Volume attribute map (40 ms thickness) draped on the Base Cretaceous depth map of the Trøndelag Platform and the Dønna Terrace. Note the early Late Cretaceous Lysing sandstones (in blue) penetrated by the wells 6507/2-2 and 6507/2-3. The geometry and morphology of the fan system are controlled by the underlying structures (interpretation courtesy of Terje Veum). (**b**) Core description of Upper Cretaceous Lysing Formation in the wells 6507/2-3 and 6507/2-2 on the Dønna Terrace. Note interbedding between thin- and thick-bedded turbidte packages.

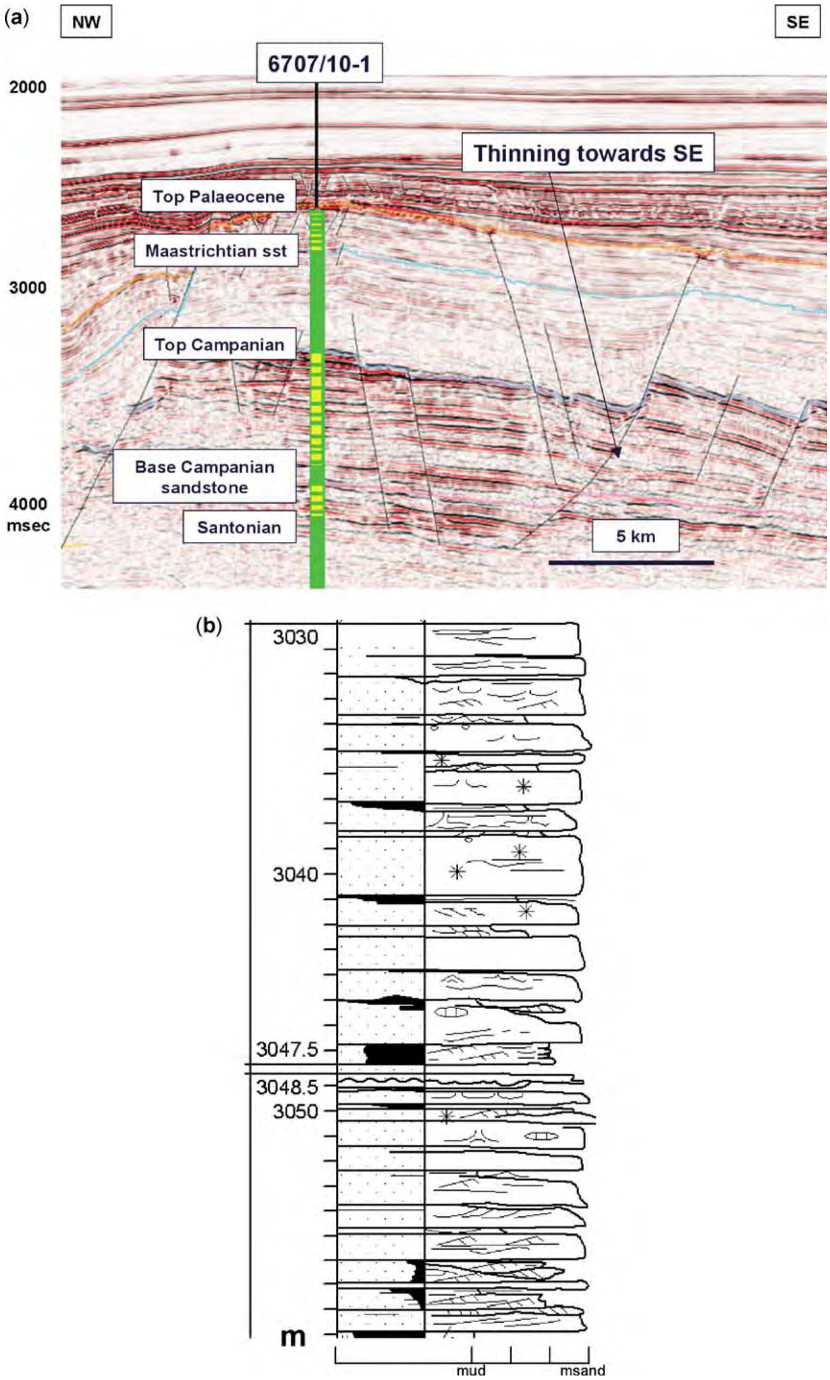


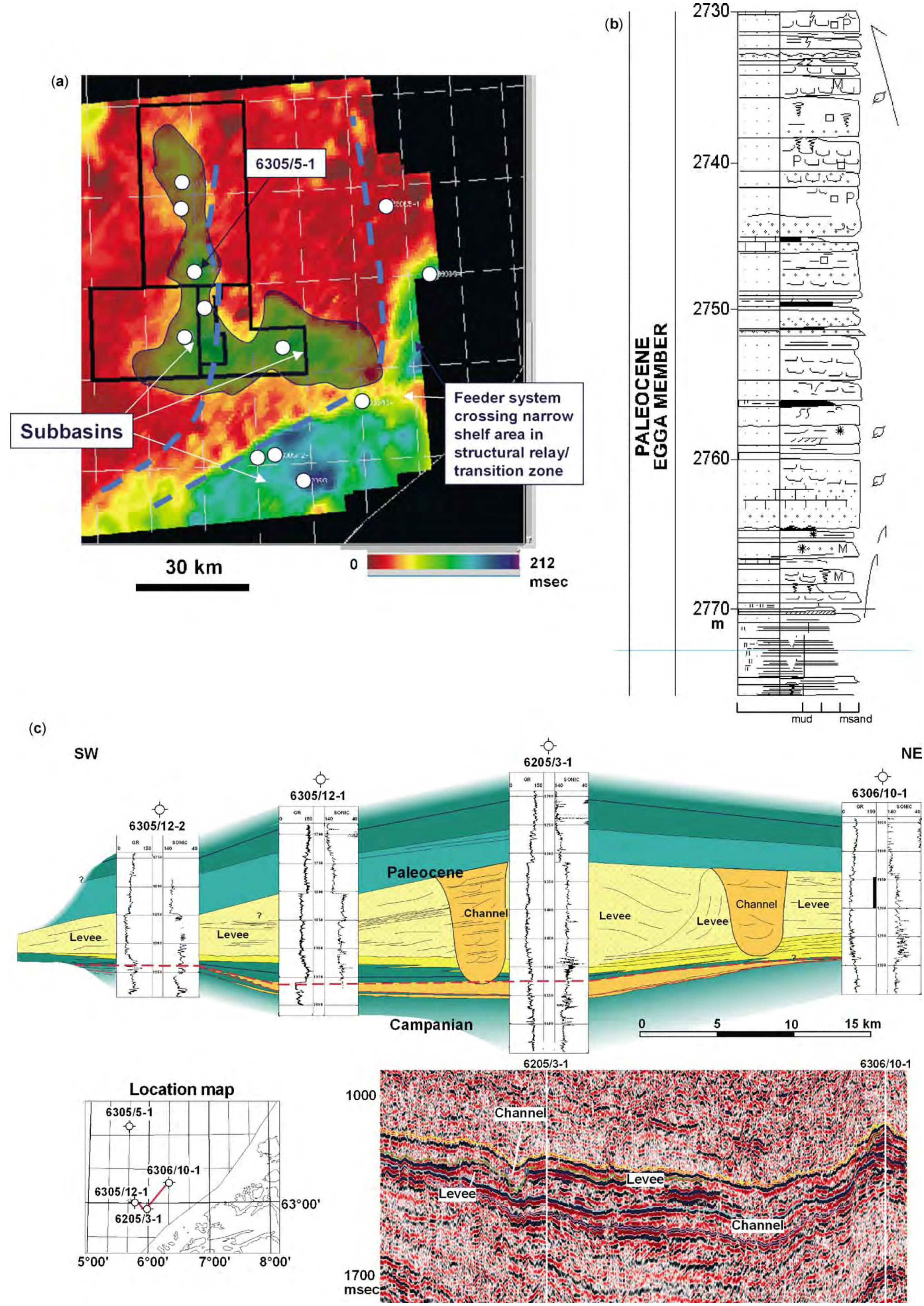
Fig. 9. (**a**) Seismic line through well 6707/10-1 in the Vøring Basin. Note the thick Upper Cretaceous Nise Formation with strong parallel reflectors and overall thinning from northwest to southeast. (**b**) Core log of the 6707/10-1 well classic turbidites deposited in a basin floor setting.

towards the Utgard High in the east (Fjellanger *et al.* 2004). The system can be characterized as a large sand-rich submarine fan, deposited on a relatively flat basin floor bounded by the East Greenland shelf in the west and gentle submarine highs, like the Utgard High, in the east (Færseth & Lien 2003).

Depositional system 8: Paleocene, SE Møre Basin

Basin setting and source area. Lower Paleocene deep-water sedimentary rocks form the reservoir of the Ormen Lange Field in the southeastern Møre Basin (Gjelberg *et al.* 2001; Smith & Möller 2003). The sand-rich submarine fan occurs in a transition zone between the Trøndelag Platform to the north, a wide palaeoshelf area, and the Møre margin to the south, a probable narrow palaeoshelf between onshore bedrock and offshore deep-water areas (Fig. 1). The orientation of the Møre margin is controlled by the long-lived, NE-SW trending Møre-Trøndelag fault zone (Gjelberg *et al.* 2005). Jurassic rifting, which also reactivated older Caledonian structures along the Møre-Trøndelag fault zone, controlled the location of the transition area from narrow to wide shelf areas, across which the turbidites that form the reservoir rocks in Ormen Lange were fed.

Onshore geomorphological evidence suggests that the present-day fjords formed palaeovalleys through which sands were transported to the area just updip of the mapped feeder system (Martinsen *et al.* 2002; Gjelberg *et al.* 2005). The geomorphological evidence is supported by onshore and offshore provenance data (Fonneland *et al.* 2003). These data suggest that the source area was skewed towards the northeast and that the palaeovalleys were structurally controlled and were mainly oriented along the


(a)
6305/5-1
Subbasins
Feeder system crossing narrow shelf area in structural relay/ transition zone
30 km
0
212
msec
(b)
PALEOCENE
EGGA MEMBER
2730
2740
2750
2760
2770
m
mud
msand
(c)
SW
NE
6305/12-2
6305/12-1
6205/3-1
6306/10-1
GR
SONIC
Paleocene
Channel
Levee
Campanian
0
5
10
15 km
Location map
6305/5-1
6306/10-1
6305/12-1
6205/3-1
63°00'
5°00'
6°00'
7°00'
8°00'
1000
1700
msec

palaeo-coast line (Gjelberg *et al.* 2005). The greater Ormen Lange deep-water basin can be divided into three subbasins (Fig. 10), all of which are controlled by deeper Jurassic extensional faults.

Lithology and depositional facies. Deep-water deposits in the greater Ormen Lange subbasin are dominated by classic turbidites, which vary in grain size from very fine-grained to coarse-grained (Fig. 11). The upslope well, 6305/9-1, within the Gossen Subbasin, has more amalgamated and coarse-grained turbidites than in the Ormen Lange Field. These observations suggest some bypass and probably deposition within unconfined channels with high aspect (width/depth) ratios. The sandstones in the Ormen Lange Subbasin were probably deposited in a submarine fan dominated by lobes and some low-relief channels (Gjelberg *et al.* 2005).

Core and well information of the Paleocene succession in the Slørebotn Basin show that medium-grained massive sands were deposited in thick overlapping bodies up to 200 m in thickness. These bodies terminate against the outboard Gossen High, a Jurassic high. In some areas, deep channels, which shallow outboard, incise into the thick sand bodies, and it is tempting to interpret these as large channel-levee systems, but their sandiness is enigmatic (Fig. 10).

System morphology. The plan-view morphology of the greater Ormen Lange turbidite system (Fig. 10) was probably controlled by deposition into differential bathymetry above deep-seated Jurassic structures (Smith & Möller 2003; Gjelberg *et al.* 2005). Differential subsidence of a mainly fine-grained Cretaceous succession above Jurassic faults created slope accommodation into which Paleocene turbidite sedimentation occurred (Martinsen *et al.* 2002). A significant northerly switch occurs between the Gossen Subbasin and the Ormen Lange Subbasin (Fig. 10). Subtle changes in bathymetry probably controlled this switch, making turbidity currents turn to the north.

The updip Slørebotn Subbasin sands post-date deposition in the deeper-water areas to the northwest. This system extends for more than 100 km towards the southwest, towards the Selje High (Gjelberg *et al.* 2005). While the main Ormen Lange turbidite system appears to have been point-sourced from the a hinterland palaeovalley along one of the major Møre-Trøndelag faults updip, the Slørebotn Subbasin system was sourced from a series of smaller palaeovalleys (Gjelberg *et al.* 2005).

Summary discussion

The eight deep-water sedimentary systems described above show highly variable sizes, shapes, basin location (i.e. slope vs. basin floor) and dominant grain sizes dependent on their age, geographic position and tectonic context (Fig. 11; Table 2).

(1) Early Cretaceous systems (Agat, Slørebotn; Table 2) were controlled by an underfilled, basin bathymetry following Jurassic rifting, that gave rise to development of slope and fault aprons (Fig. 11). Small source areas on the western Norwegian margin fed relatively sand-poor systems even though the shelves were narrow. In addition, the Slørebotn fault apron system possibly did not connect to hinterland drainage systems since coarse, locally derived debris flow deposits dominate.

(2) Easterly derived Late Cretaceous systems (Måløy slope, Dønna Terrace)(Table 2) compare in many ways with the Early Cretaceous systems, but are texturally more mature, reflecting better developed, but still small source areas. They were still controlled by inherited bathymetry from the Jurassic rifting (Fig. 11), but to a much lesser extent than those of Early Cretaceous age. The Måløy slope apron occurs outboard of a narrower shelf than the Dønna Terrace system. Whether the wide Trøndelag Platform shelf played a major role in development of the latter system, or whether the deep-water sediments were derived locally from the local Nordland Ridge, is uncertain.

(3) Westerly derived Late Cretaceous systems (such as the Campanian of the Nyk area), are sand-rich, much more voluminous and differ substantially from easterly derived counterpart systems (Table 2, Fig. 11). Although speculative, a larger, much more sand-rich source area must have been the major difference since a narrow shelf area seems to have existed in both cases (Fig. 1). By Late Cretaceous time, the rift-relief in East Greenland had probably been draped and drainage switched from north–south, controlled by half-grabens, to west–east (Surlyk & Noe-Nygaard 2001). Present-day fjords seem to some degree to correspond with major offshore structures, and may have functioned as structurally controlled palaeovalleys that connected a large hinterland with deep-water areas in the Norwegian Sea (Whitham *et al.* 1999; Surlyk & Noe-Nygaard 2001; Larsen *et al.* 2001).

(4) Paleocene systems differ between that of Ormen Lange in the Møre Basin and the Grane system in the North Sea, although both are sand-rich (Table 2, Fig. 11). The Ormen Lange system was controlled by slope and basin bathymetry caused by differential subsidence above older Jurassic structures outboard of a narrow shelf and relatively small source area (Figs 1 and 11). The Grane system formed the distal, basin floor end of a much larger deep-water system and was extensively modified by syn- and post-depositional deformation. A higher depositional rate and a high smectite content in the underlying shale were probably key factors that controlled the different resulting geometry of the Grane system. Initiation of sand deposition in both the Ormen Lange and Grane cases was probably instigated by hinterland uplift.

(5) The sand-rich Eocene system of Quadrant 35 (Fig. 11) in the northern North Sea was probably also controlled by relative sea-level fall on the Norwegian margin, forcing sedimentation out on to the basin floor. A narrow palaeoshelf probably could not trap the sandy sediments although the source area was relatively small.

Major rift phases in the Late Jurassic in the North Sea and Norwegian Sea formed a differential bathymetry into which Early and Late Cretaceous and Palaeogene deep-water sedimentation occurred (Kyrkjebø *et al.* 2001). In addition, the same tectonic phases provided a template for subsequent shelf widths, although in some areas Late Jurassic rift structures closely followed and partly reactivated Palaeozoic structures. The narrow shelf areas were important in ensuring that sandy sediments reached the deep-water areas and were not trapped on shelves. Along the Norwegian eastern basin margin, source areas were smaller and sediment delivery consequently less voluminous than along the western

Fig. 10. (**a**) Paleocene isochore map of the greater Ormen Lange turbidite systems. Note the shaded area which shows the Ormen lange sandy turbidite system, and the division into three subbasins, based on thickness and position of underlying, reactivated Jurassic structures marked with thick, blue stippled lines. The white points denote well locations. (**b**) Core log from the 6305/5-1 well from the Ormen Lange subbasin. Notice the thickening-upward trend of turbidite beds, signifying the outbuilding of the Ormen Lange submarine fan. (**c**) Well correlation along the Slørebotn Subbasin showing more than 200 m thick Paleocene sandstone successions, slightly younger than the sandstones in the Gossen and Ormen Lange subbasins. Note the large channels cutting the sandstone units. Despite their very sandy character, the seismic evidence suggests that these channels are genetically related to the sandy sediments that are interpreted as levees. The red stippled line at the base of the Paleocene succession is a major unconformity separating the Paleocene from underlying lower Campanian rocks.

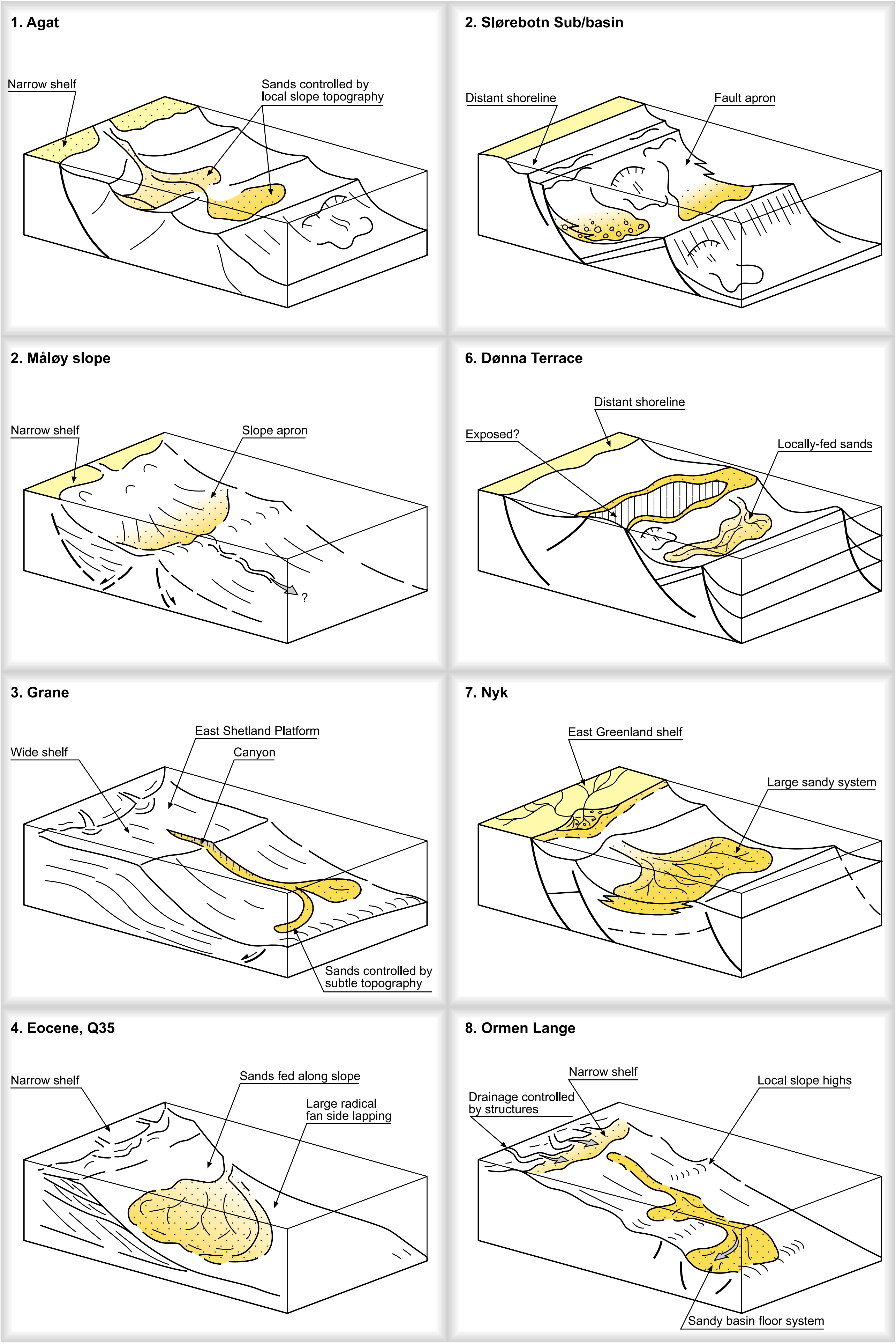


Fig. 11. Cartoons summarizing the eight different deep-water depositional systems illustrated in this article. Outlines of the turbidite systems are shown to illustrate the difference in shape as a result of the controlling processes. Not to scale.

North Sea and Norwegian Sea basin margins (Table 2). In the western Norwegian Sea, Late Cretaceous rifting, prior to Atlantic break-up caused renewed differential bathymetry at a time when the differential bathymetry created by Jurassic rifting had almost been eliminated (Færseth & Lien 2003).

The present study shows the importance of using a process-based approach to analysing deep-water sedimentary systems. By using a list of critical factors by which the individual systems are classified (Table 1), short- and long-term controls on system development are identified. The North Sea and Norwegian Sea deep-water sedimentary systems are classic examples of how local and regional tectonism plays a fundamental role in determining the sizes and shapes of deep-water sedimentary systems. This is probably particularly important in non-glacial settings and times when high-frequency sea level changes are less important (Martinsen *et al*. 2003), such as in the Cretaceous and Palaeogene of the North Sea and Norwegian Sea basins.

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