Reconstructing morphological and depositional characteristics in subsurface sedimentary systems: An example from the Maastrichtian–Danian Ormen Lange system, Møre Basin, Norwegian Sea

Tor O. Sømme, Ole J. Martinsen, and John B. Thurmond

ABSTRACT

Understanding large-scale sediment distribution patterns and morphological characteristics in subsurface sedimentary systems is highly challenging and generally requires regional seismic and well coverage. Here, we test a method that aims to predict first-order morphological characteristics and type of sedimentary transport system in ancient source-to-sink systems based on trends observed in submodern (Pliocene–Holocene) depositional environments. An example from the Paleocene Ormen Lange system (Møre Basin, Norwegian Sea) demonstrates the application of the method, and several descriptive parameters are estimated for this ancient subsurface system. In the Ormen Lange system, basin-floor fan and distal-slope parameters are well constrained from seismic and well control. However, knowledge of the morphology and relationships between upper slope, shelf, and catchment characteristics and their relationships to deep-water systems is poor, and these are the parameters that are discussed in this study.

Estimated parameters of catchment size derived from this technique are in good agreement with preserved remnants of fluvial valleys located onshore. Predicted sediment transport characteristics are also comparable to the depositional

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mechanisms interpreted from cores and well logs, suggesting a small tectonically active system with high fluvial discharge and low sediment storage potential in the catchment and shelf subenvironments.

The discussed method is thus capable of predicting first-order segment characteristics in subsurface sedimentary systems with an uncertainty of one to two orders of magnitude. This information can be used to increase the understanding of unexplored basins or to add data and uncertainty ranges to well-known petroleum systems.

INTRODUCTION

Slope and basin-floor depositional systems constitute important subsurface hydrocarbon reservoirs both offshore Norway as well as globally, and a good understanding of their depositional history, sedimentary characteristics, and lateral extent is therefore crucial for exploration in these areas. In the early stages of margin exploration and in areas with poor seismic data and well control, the area and volume of such deep-marine depositional units are commonly estimated with simplistic methods from two-dimensional (2-D) seismic data. More detailed information on the depositional environments and sediment distribution patterns commonly requires high-resolution, three-dimensional (3-D) seismic data sets and good well control, as well as detailed knowledge of the basin geology (e.g., Martinsen et al., 2005).

The length and width of deep-marine fans are widely recognized to closely reflect the type of margins where they are located (Mutti and Normark, 1987; Shanmugam and Moiola, 1988; Reading and Richards, 1994; Bouma, 2000; Mattern, 2005). Passive margin systems that have long- and low-gradient rivers are also typically associated with fine-grained, elongated, high-efficiency fans, whereas tectonically active margins typically have short and steep rivers that feed more confined, coarser grained fans. Additionally, Wetzel (1993) recognized a relationship between fan area or fan length, and long-term fan deposition rate, reflecting increasing sediment supply in larger and more fine-grained transport systems.

Scaling relationships in river catchments have also been thoroughly studied, and several causal relationships between catchment area and hypsometry, river length and gradient, water discharge and sediment supply, among others, have been established (e.g., Strahler, 1952; Meade et al., 1990; Milliman and Syvitski, 1992; Mulder and Syvitski, 1996; Allen et al., 2000; Castelltort and Simpson, 2006).

A more detailed study on morphological parameters (Figure 1) in submodern (Pliocene–Holocene) source-to-sink systems demonstrates that area, length, and gradient relationships exist within and between all segments in these erosional-depositional systems (Sømme et al., 2009). When systems of various scales are compared, the observations suggest that they develop in a semipredictable way, in which modification and development of one or several segment parameters (e.g., in the catchment) result in a morphological response in the adjacent segment(s) (e.g., in the basin-floor fan). By extending these relationships back in time, predicting several segment characteristics in ancient, subsurface depositional systems is therefore possible.

Whereas forward modeling from catchment to basin floor is of major importance when using source-to-sink methods in exploration, inversion using basin-floor fan parameters to predict size and geological characteristics of the catchment provides important insight into the reliability of the method. In this study, morphological parameters are predicted for the shelf, slope, and catchment segments in the Maastrichtian–Danian Ormen Lange system using input values obtained from the basin-floor fan segment. The actual size of the paleocatchment is poorly constrained, and predictive relationships derived from analog systems can be used to estimate the catchment size at the time of fan deposition. By identifying the typical system size, the mode of sediment transport can also be inferred, as systems characterized by small, high-gradient rivers are expected to be associated with different depositional features than larger and lower gradient systems.

Thus, the aim of this article is twofold: (1) to apply an inverse test of the global relationships

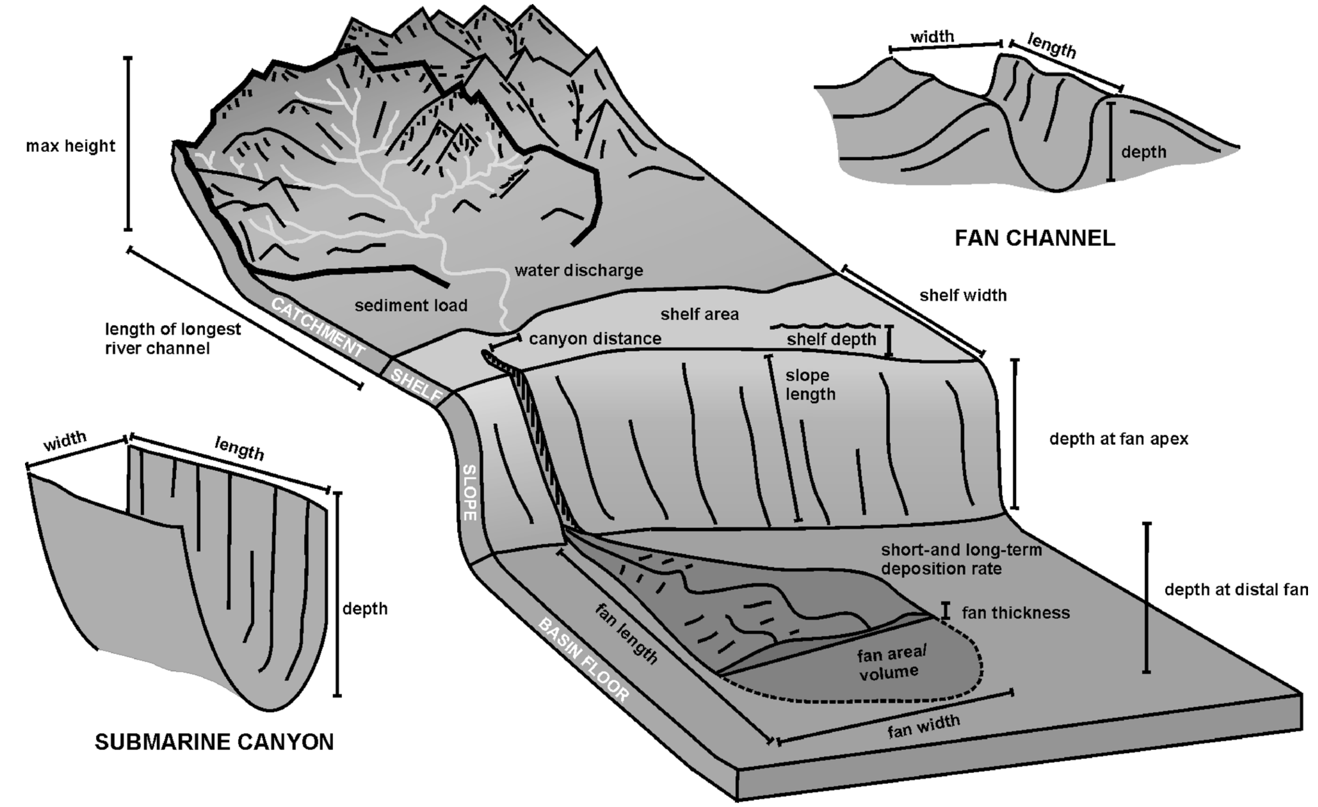


Figure 1. Overview of the four main segments (catchment, shelf, slope, and basin floor), which constitute the building blocks of the genetically related source-to-sink system. The diagram also summarizes the number of sedimentological (e.g., deposition rate) and geomorphic (e.g., slope length) parameters used by Sømme et al. (2009) to develop semiquantitative guidelines capable of predicting similar characteristics in ancient, subsurface systems such as the Ormen Lange.

derived by Sømme et al. (2009) to test whether the method is capable of predicting realistic system characteristics in an ancient source-to-sink setting, and (2) to enhance the understanding of the latest Cretaceous and early Paleogene geological systems onshore central Norway.

OFFSHORE REGIONAL HISTORY AND DEPOSITIONAL SETTING

The Møre Basin is located in the eastern part of the Norwegian Sea (Figure 2) and was formed by marginal downwarping following Late Jurassic–Early Cretaceous rifting and crustal thinning; a process that caused the formation of several horsts and half-graben basins later to be filled by Cretaceous sediments (Brekke, 2000). A new tectonic phase characterized by crustal uplift commenced in the latest Cretaceous–Paleocene, partly coinciding with the timing of deposition of the Ormen Lange Fan (Gjelberg et al., 2001). In the southern part of the Møre Basin, the Paleozoic and Mesozoic movement along the basinal continuation of the Møre-Trøndelag fault complex (MTFC) resulted in the formation of several local highs (e.g., Gossa, Giske, and Ona) (Figure 2). The basins between the highs were filled by Cretaceous sediments, thus defining several shallow, intraslope basins (e.g., Slørebotn Subbasin, Brekke, 2000).

Despite incipient breakup and sea floor spreading, the late Paleocene–Eocene is commonly recognized as a period of tectonic quiescence in the marginal areas of the Norwegian Sea, representing a major shift to a passive margin setting dominated by basin subsidence, overall transgression, and a decreased sediment input to the deep basins (Brekke et al., 2001; Færseth and Lien, 2002; Lien, 2005). However, renewed pulses of regional onshore uplift continued throughout the Paleogene, causing

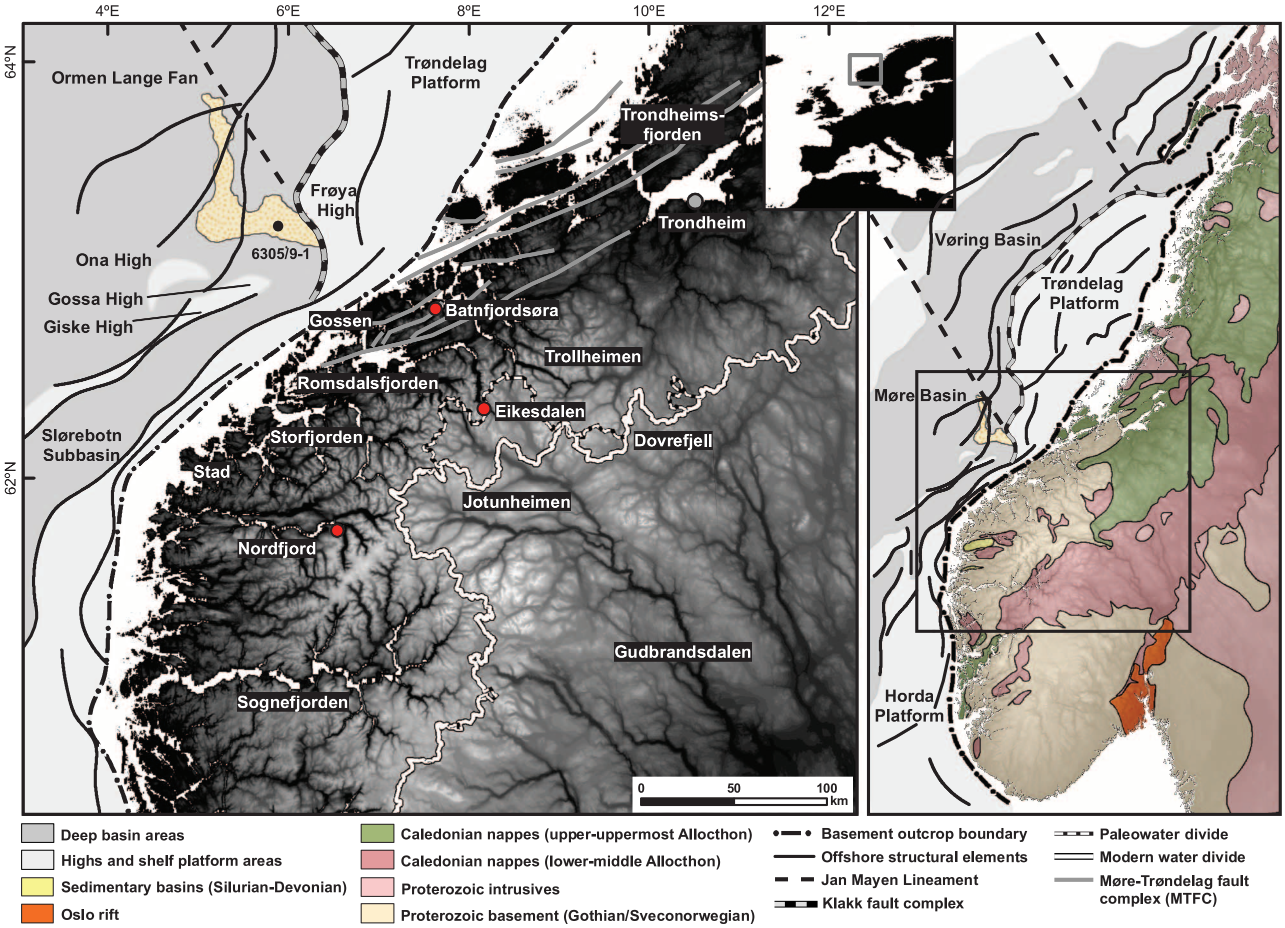


Figure 2. Overview of the location of the Ormen Lange Fan along the Norwegian margin. Structural domains have been simplified from Brekke (2000). The geological map is from Solli and Nordgulen (2006). Red circles refer to the picture locations in Figure 5.

localized deposition of numerous shallow- and deep-marine wedges in the Paleocene–earliest Eocene (Martinsen et al., 1999; Brekke et al., 2001; Faleide et al., 2002; Martinsen, 2005).

During the Late Cretaceous–Paleogene, two main depocenters existed along the Møre margin: the Slørebotn Subbasin and the central part of the main Møre Basin where the Ormen Lange Fan was deposited (Gjelberg et al., 2001) (Figure 2).

The Ormen Lange depocenter is divided into two parts constrained by two normal faults (Figure 2) parallel to the structural grain of the MTFC. In the southeastern subbasin, well 6305/9-1 proved 85 m (279 ft) of coarse-grained, upper Maastrichtian and lower Danian sandstones (Figure 3). Deposition of sands in this part of the depocenter was controlled by subtle subsidence between the two major faults, whereas the southeastern part of the Ormen Lange depocenter was probably subjected to a fill-and-spill situation over a relatively short period concurrent with deposition in the main northwestern depocenter. In contrast, deposition in the Slørebotn

Figure 3. Simplified stratigraphic column of the Norwegian Sea (modified from Møller et al., 2004; Martinsen et al., 2005) together with (A) gamma-ray log, (B) core log, and (C) core photos from well 6305/9-1. Note the upward increase in sand content from the heterolithic Maastrichtian Springar Formation through the Paleocene Tang Formation and Egga Member in panel A. Note the position of Våle tight. The main reservoir unit in the sandy Egga Member consists of stacked sandstone beds interpreted as alternating high- and low-density turbidites (B, C). Pictures in panel C show sandy, deep-marine deposits from the Egga Member covering the uppermost 10 m (33 ft) in panel B (red line). Scales in panels A and B are in meters. The scale in panel C is 1 m (3 ft) with 1-cm (0.3-in.) increments. See Figure 2 for the well location.

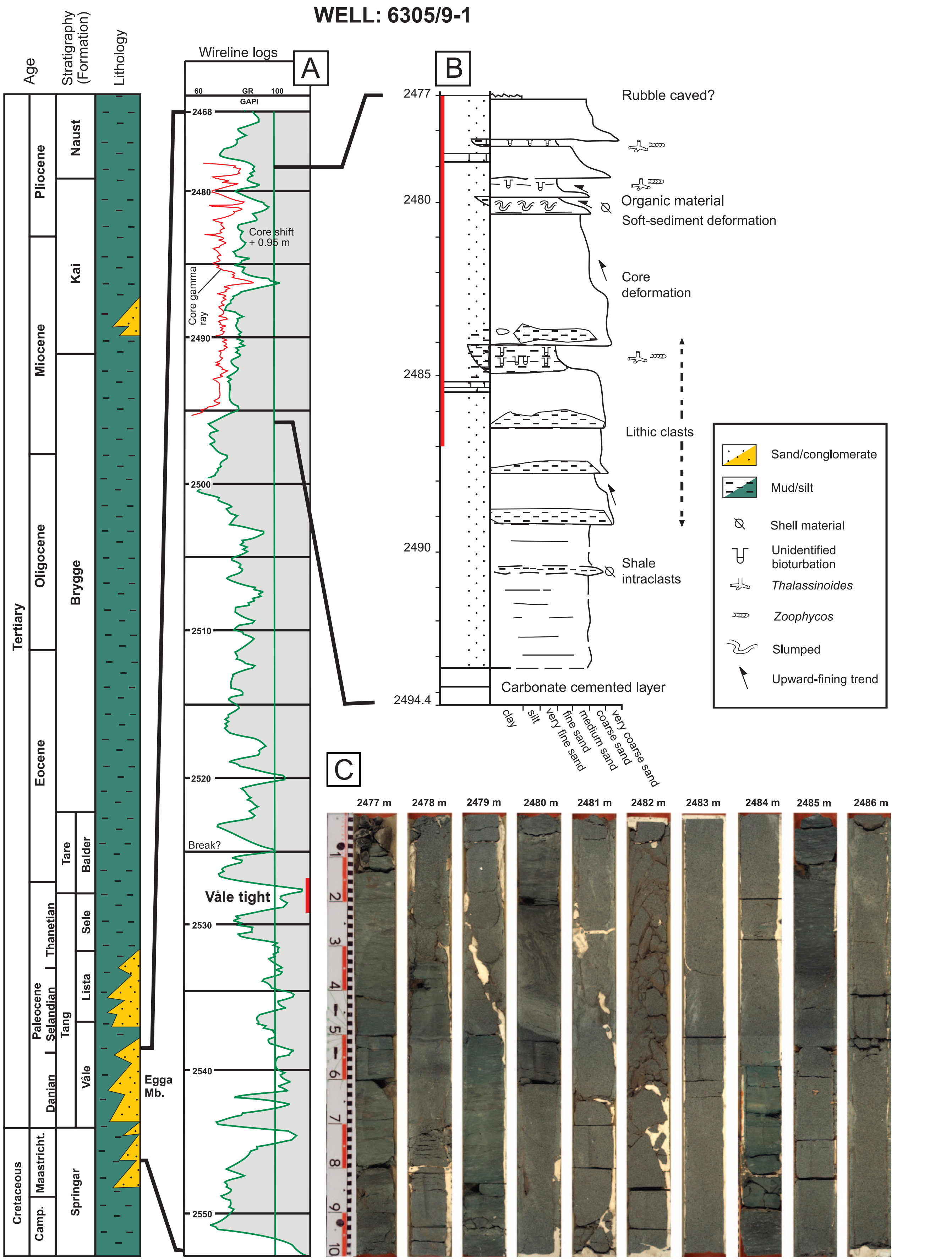
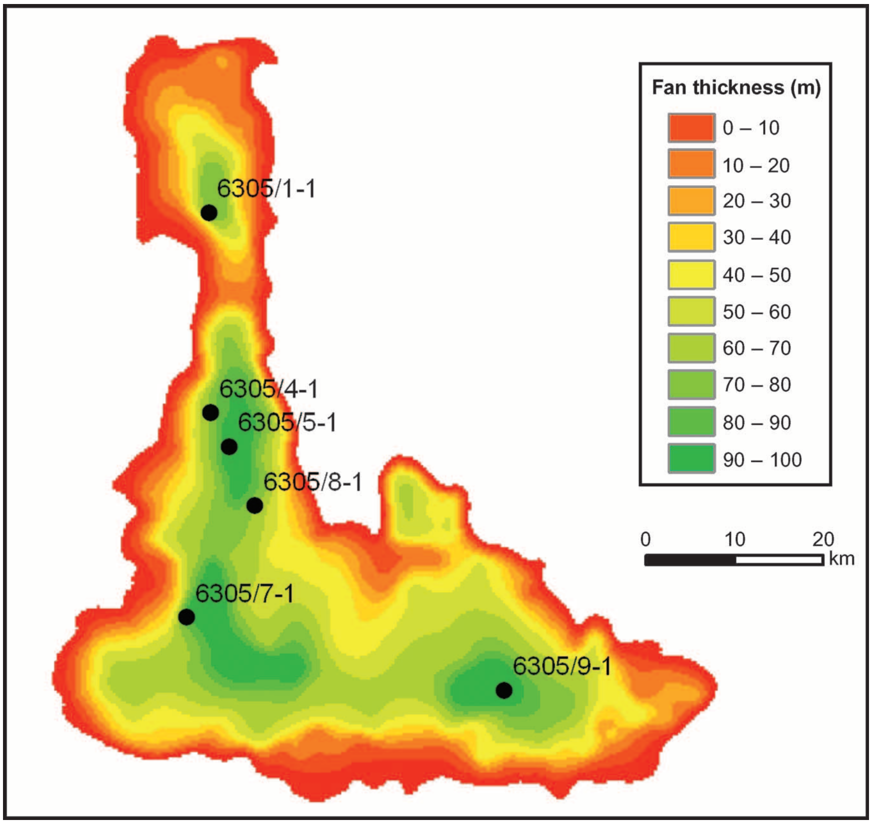

WELL: 6305/9-1
Age
Stratigraphy (Formation)
Lithology
Wireline logs
A
B
C
60
GR
100
GAPI
Tertiary
Cretaceous
Pliocene
Miocene
Oligocene
Eocene
Paleocene
Thanetian
Selandian
Danian
Maastricht.
Camp.
Naust
Kai
Brygge
Tare
Balder
Sele
Lista
Tang
Våle
Springar
Egga Mb.
Core shift + 0.95 m
Core gamma ray
Break?
Våle tight
2468
2480
2490
2500
2510
2520
2530
2540
2550
2477
2485
2494.4
Rubble caved?
Organic material
Soft-sediment deformation
Core deformation
Lithic clasts
Shale intraclasts
Carbonate cemented layer
clay
silt
very fine sand
fine sand
medium sand
coarse sand
very coarse sand
Sand/conglomerate
Mud/silt
Shell material
Unidentified bioturbation
Thalassinoides
Zoophycos
Slumped
Upward-fining trend
2477 m
2478 m
2479 m
2480 m
2481 m
2482 m
2483 m
2484 m
2485 m
2486 m

Figure 4. Calculated thickness map of the Maastrichtian–Paleocene succession in the eastern part of the Møre Basin based on a time isochore map from Gjelberg et al. (2001). Well locations used for lateral thickness calculation are indicated. See Figure 2 for the fan location.



Subbasin occurred after the abandonment of the Ormen Lange system.

The Ormen Lange Fan has a length of about 108 km (67 mi), an area of about 2500 km^2 (965 mi^2), and is located approximately 45 km (28 mi) from the present shoreline (Figure 2). The fan has been interpreted as a sand-rich submarine fan, primarily fed by a point source located at the intersection between the Jan Mayen lineament and the MTFC (Gjelberg et al., 2001; Møller et al., 2004; Gjelberg et al., 2005) (Figure 2). Based on published isochore maps and core data (Gjelberg et al., 2005), the fan reaches a maximum thickness of approximately 110 m (361 ft) in the proximal part, from where it gradually thins laterally into heterolithic lobe fringe deposits at its lateral termination, thus yielding a fan volume of about 104 km^3 (65 mi^3) (Figure 4).

The Ormen Lange Fan succession comprises parts of the Maastrichtian Springar Formation and the Danian Egga Member of the Våle Formation (Gjelberg et al., 2001) (Figure 3), representing 7.8 m.y. of deposition (M. Charnock, 2008, personal communication). The Maastrichtian succession (upper part of the Springar Formation) covers the initial stage of fan deposition, consisting of a sandy, upward-coarsening unit composed of high-density turbidite sandstones accompanied by low-density turbidite sandstone and mudstone interbeds (Gjelberg et al., 2001; Smith and Møller, 2003; Gjelberg et al., 2005) (Figure 3A, C). The amount of time represented by this lower unit ranges between approximately 2.5 and 4.2 m.y., as deposition was initiated later in the more distal parts of the basin, representing fan progradation and a fill-and-spill pattern between the two main subbasins. This lower section is overlain by a heterolithic mudstone interval, termed the Våle tight (Figure 3B), which marks the transition across the Cretaceous-Tertiary boundary, representing approximately 0.7 m.y. of deposition (Gjelberg et al., 2001). This succession is then overlain by the sand-dominated Egga Member, which mainly consists of mature, medium- to coarse-grained sandstones (sometimes amalgamated) with thin sandstone and mudstone interbeds, interpreted as high-density turbidite deposits (Gjelberg et al., 2001; Smith and Møller, 2003; Gjelberg et al., 2005) (Figure 3B, C). This unit thus represents about 2.9 m.y. of active fan growth. Provenance studies based on heavy minerals from these deposits suggest that the Gothian and Sveconorwegian basement (Figure 2) was the main source for the sediment deposited in the fan (Fonneland et al., 2004; Morton et al., 2005). Later in the Danian, a shift of depocenters from the main Møre Basin to the more proximal intraslope Slørebotn Subbasin caused abandonment of the main fan (Gjelberg et al., 2005).

MØRE-TRØNDELAG FAULT COMPLEX

The MTFC is an up to 50-km (31-mi) wide, northeast-southwest–trending fault complex that extends for more than 300 km (186 mi) from central mid-Norway (Figure 2). Along the Møre coast, the MTFC crosses the shelf north of Stad (around 62°N) before it defines several subbasins (e.g., Slørebotn Subbasin) at the southern margin of the Møre Basin. The MTFC is a long-lived feature that originated in the Ordovician–Silurian in relation to the Caledonian orogeny, and apatite fission track analysis indicates that it has experienced vertical offset of up to 4 km (2.5 mi) since its formation (Grønlie et al., 1994; Roberts, 1998; Redfield et al., 2005a). The timing of movement along the fault complex also coincides with periods of major faulting and tectonic activity in the Norwegian Sea, indicating a close relationship between onshore and offshore topographical features in these areas (Grønlie and Roberts, 1989; Gabrielsen et al., 1999; Smethurst, 2000).

The age and regional extension of the MTFC suggests that the fault array and movement of individual fault blocks were major factors in defining paleotopography in central Norway, and its potential for influencing past regional drainage patterns is evident from the preservation of down-faulted Jurassic sediments within the fault complex (Bøe and Bjerkli, 1989; Sommaruga and Bøe, 2002). Even at present, the influence can be observed along the Møre coast, where low areas between fault blocks have captured local drainages. This shows that the relief created along these faults may have acted as a primary control on the position and orientation of rivers draining this area, in addition to having the potential of trapping significant amounts of sediments in local, fault-controlled basins. Because of the close proximity of the Trøndelag Platform, which was a wide and shallow shelf platform throughout most the Cretaceous and Paleogene (Lien, 2005), a redirection of rivers to the north (toward a wide shelf) or to the south (toward a narrow shelf) would have had major implications for the distribution of sediments into shallow- and deep-marine basins in this region (Figure 2).

Of primary importance is the overall oblique orientation of the MTFC to the present-day coastline (Figure 2). If the hypothesis is correct that the low areas controlled the paleodrainage in the latest Cretaceous and early Paleogene, then this means that onshore drainages were focused in a southwesterly orientation toward the mouth of the current Romsdalsfjorden, in the area of the island of Gossa (Martinsen et al., 2002). This idea is explained further below and substantiated by other data.

ONSHORE REGIONAL HISTORY AND GEOMORPHOLOGY

At the beginning of the Mesozoic, the Caledonides, which were mainly formed during the Late Ordovician–Early Silurian, had been eroded down to a peneplain in response to long periods of tectonic quiescence and deep weathering in a warm and humid climate (Riis, 1996; Lidmar-Bergström, 1999). In the Late Jurassic and the Cretaceous, both offshore highs and parts of the peneplain were transgressed, placing marine sediments on top of a weathered crustal basement (Doré, 1992; Brekke, 2000). The thickness and landward extent of these deposits are unknown because they were later removed during Cenozoic uplift and erosion (Martinsen et al., 1999), but a thickness of 1–2 km (0.6–1.2 mi) has been suggested based on the vitrinite reflectance in coals (Fossen et al., 1997).

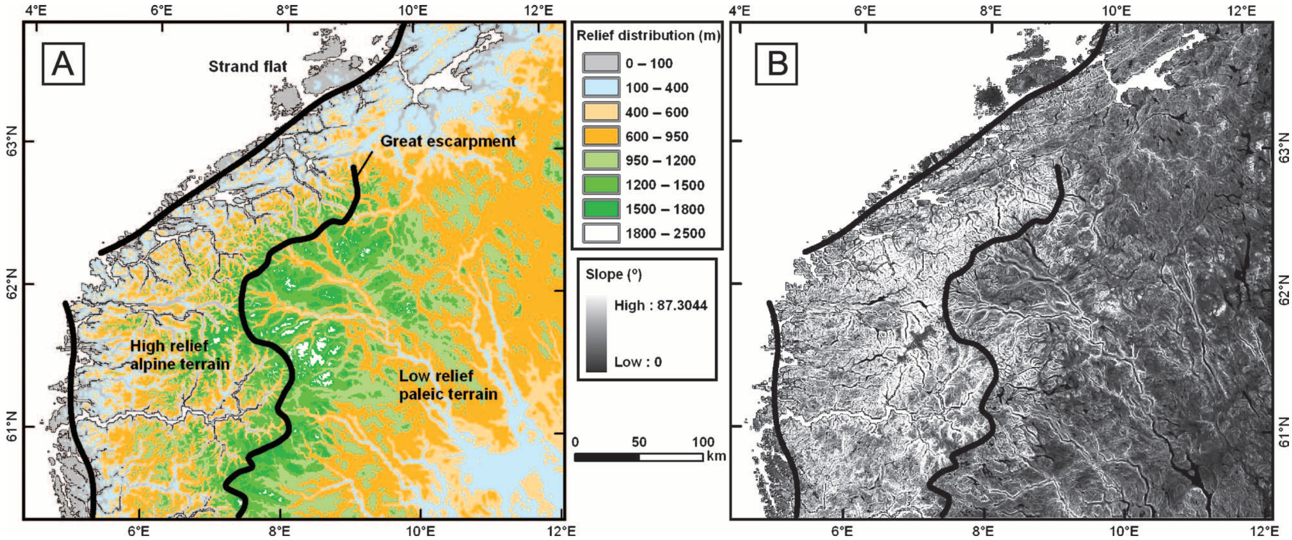


Figure 5. (A) Relief distribution and (B) slope map of central Norway illustrating the morphological characteristics of the three main types of terrain encountered in the area. The left (western) black line represents the transition from the alpine fjord terrain to the strandflat; the right (eastern) black line represents the transition from the paleic to alpine terrain.

Although periods of tectonic activity caused the local uplift of fault blocks during the Cretaceous, the timing of large-scale regional uplift in southern and central Norway is still debated (see Stuevold and Eldholm, 1996), and a Late Cretaceous, early and late Paleogene and Neogene timing has been suggested based primarily on fission track and gravity data as well as offshore depositional patterns and onshore geomorphology (Gjessing, 1967; Torske, 1972; Doré, 1992; Stuevold et al., 1992; Nesje and Whillans, 1994; Rohrman et al., 1995; Riis, 1996; Stuevold and Eldholm, 1996; Lidmar-Bergström, 1999; Martinsen et al., 1999; Jordt et al., 2000; Lidmar-Bergström et al., 2000; Gjelberg et al., 2001; Huuse, 2002; Nielsen et al., 2002; Rohrman et al., 2002; Gabrielsen et al., 2005; Martinsen et al., 2005; Praeg et al., 2005). Later Neogene uplift is also widely evident from erosional surfaces and wedges of marine sediments offshore (Riis and Fjeldskaar, 1992; Stuevold and Eldholm, 1996; Huuse, 2002). Whether this uplift occurred as two main events or as several smaller, high-frequency pulses during the latest Cretaceous–Quaternary, as suggested by several subtle steps in the landscape (Lidmar-Bergström et al., 2000), is also debated. In addition, recent fission track data from the MTFC and central Norway indicate that significant parts of the regional uplift occurred as a crustal warping where displacement primarily occurred along the main MTFC (Redfield et al., 2005a), instead of a regional, asymmetrical dome structure (Lidmar-Bergström et al., 2000). The difference between these two modes of regional uplift could have had major implications for the intrabasinal structural control on the river systems as well as the generation of relief along the Møre margin.

Landscape morphology in central Norway can be divided into three main regions (Figure 5) demonstrating the relationship between Mesozoic peneplanation and Cenozoic uplift and glacial erosion (Gjessing, 1967; Sulebak, 2007). The gently undulating, low-relief landscape characterized by wide valleys and rounded hills, known as the paleic terrain, dominates inland at high altitudes above approximately 900 m (~2952 ft) (Figure 5); however, this type of terrain is also locally preserved at lower altitudes on fjord and valley interfluves along the coast (Anda, 1995; Etzelmüller et al., 2007) (Figure 6). High mountainous areas within the paleic terrain (e.g., Dovrefjell and Jotunheimen) (Figure 2) represent remnants of the ancient high-relief areas that existed at the time of formation of this landscape. In these high-altitude areas as well as in the eastern part of central Norway, these paleic landforms are characterized by wide and low-gradient valleys, basins, and hills, commonly without

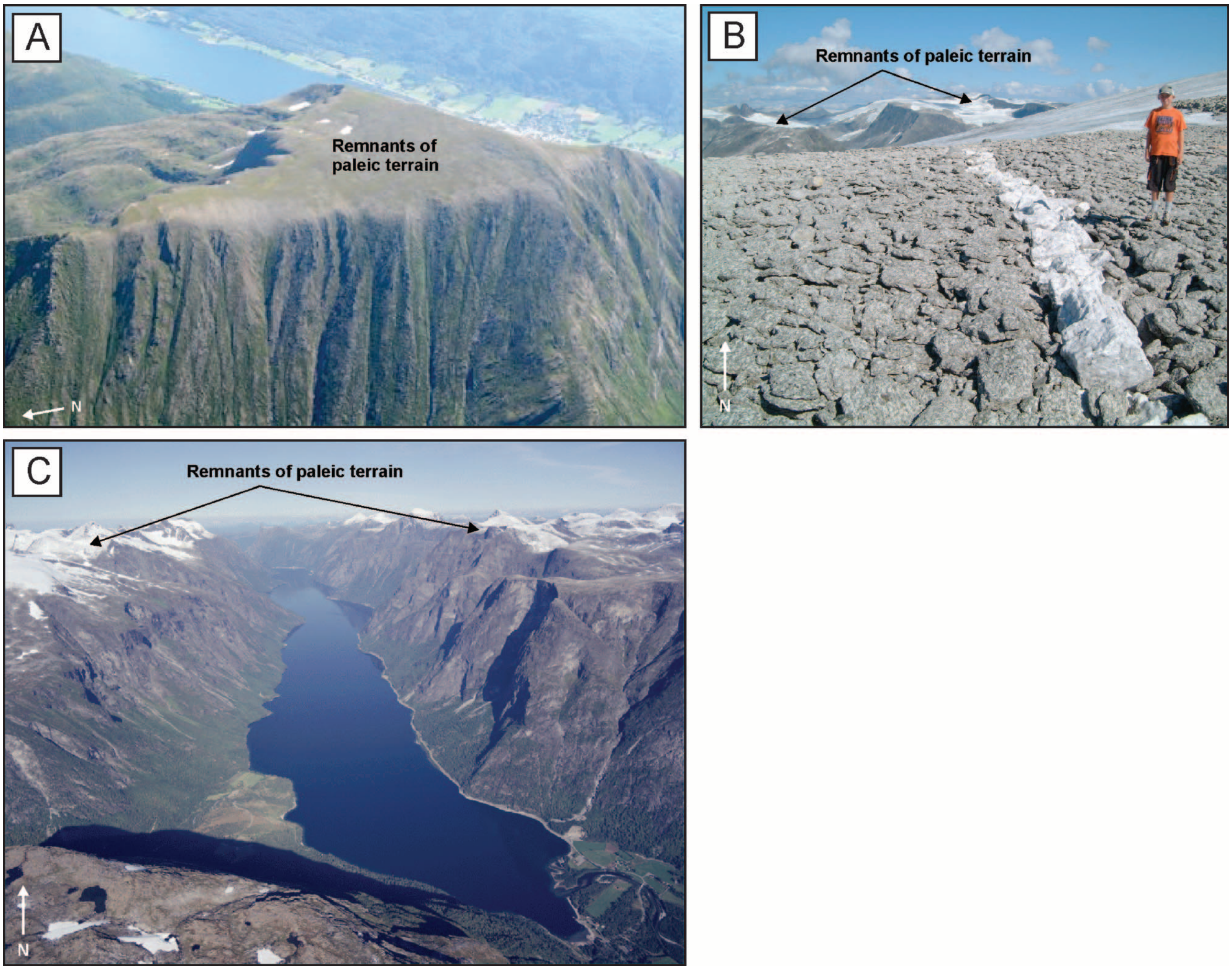


Figure 6. Expression of the paleic terrain in central Norway at (A) Batnfjordsøra (plateau is ~1 km [0.6 mi] long), (B) in the innermost part of Nordfjorden, and (C) in Eikesdalen (the fjord is ~1 km [0.6 mi] wide). Note the difference between the planar, low-gradient paleic terrain and the highly erosional glacial fjord landscape. In the foreground, panel B shows in-situ block fields, which represent preglacial weathering of bed rock; note the weathered quartz vein in the central part of the picture. The tangential surface through the highest peaks in panel C represents the summit surface. See Figure 2 for the locations. The pictures are courtesy of (B) Atle Nesje and (C) Fjellanger-Widerøe.

a distinct drainage network indicating direction of flow (Gjessing, 1967; Anda, 1995).

The varying geographical distribution and weathering characteristics of the paleic terrain suggest that it was formed during periods of tectonic quiescence within a warmer climate than that during the late Miocene and Pliocene–Pleistocene, possibly commencing as early as the middle Mesozoic (Gjessing, 1967; Lidmar-Bergström, 1995). However, the morphological differences between the various parts of the terrain indicate that it has formed over considerable time and is thus highly diachronous.

Within the high-relief alpine terrain, Quaternary glacial erosion has removed up to several thousand of meters of rock, forming steep valleys and deep fjords (Figure 5); the transition between preserved paleic terrain and extensive glacial incision is termed the great escarpment (Lidmar-Bergström et al., 2000). Here, the glaciers have followed weak zones in the bedrock similar to the ancestral river systems, and it is therefore inferred that major glacial drainage systems (individual fjords) reflect the approximate extent of the older fluvial drainage systems (e.g., Nesje and Whillans, 1994).

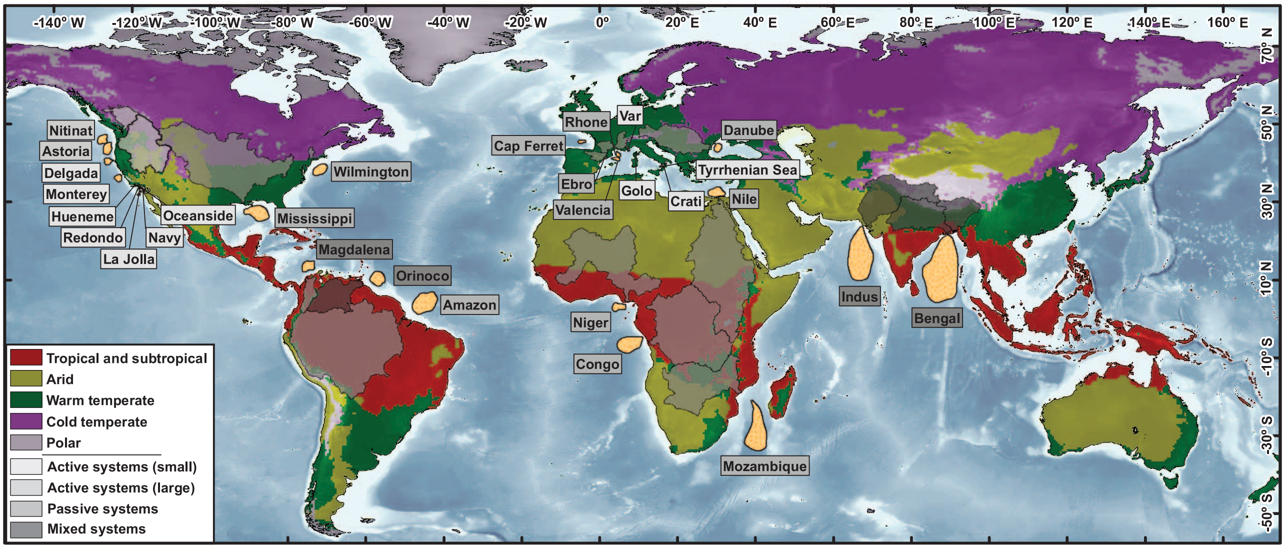


Figure 7. Location of the 29 submodern source-to-sink systems used to obtain relationships between various morphological segment parameters. Climate zones are modified from Kottek et al. (2006).

West of the great escarpment, a low-gradient area termed the strandflat typically extends seaward from the fjord outlets, having a relief of less than 100 m (328 ft).

DATA SET AND METHODOLOGY

The study of submodern source-to-sink systems shows that several predictive relationships exist between parameters describing morphological characteristics within and between basin floor, slope, shelf, and catchment segments (Sømme et al., 2009). To be able to compare these observations and predict equivalent, first-order parameters in ancient systems deposited under poorly or unknown tectonic and geomorphic settings and climate conditions, such as for the latest Cretaceous–early Paleocene Ormen Lange system, the data set used for comparison must cover the main types of margin configurations (i.e., various scale ranges of passive and active settings). The systems used by Sømme et al. (2009), which are also used for comparison in this study, were picked to include a variety of margins ranging from tectonically active to old, passive settings (Figure 7); however, they have been limited to underfilled siliciclastic systems that have a distinct shelf-slope-basin floor configuration only (cf. Hadler-Jacobsen et al., 2005). Thus, the term active margin is used here to describe tectonically active margins, and it does not necessarily imply that the systems are presently active in terms of sediment delivery to the basin floor. Because glacial erosion has the potential to significantly alter the morphological and depositional characteristics of a system more extensively than fluvial erosion (Weaver et al., 2000), pure glacial margins are also excluded from the data set. Furthermore, the submodern systems discussed by Sømme et al. (2009) are characterized by climates ranging from subtropical to dry, wet, and cold temperate conditions (Figure 7), all of which are expected to represent a potential climatic setting within a given source-to-sink system back in time, even during periods when the global climate was warmer or colder than the present. On a smaller, basinal, and intrabasinal scale, however, local climate variations are recognized as a major factor controlling denudation and sediment transportation as well as deposition in source-to-sink systems (e.g., Inman and Jenkins, 1999; Goodbred, 2003). In addition, each system will display an array of local or regional basinal characteristics, such as direction and magnitude of faulting, lithology, and salt or mud tectonics, all of which will be unique to the individual basin.

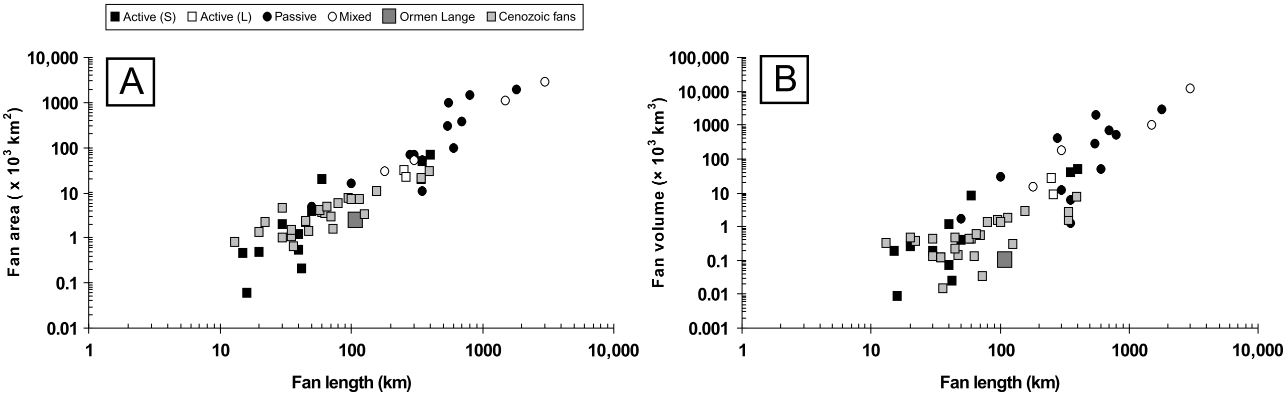


Figure 8. Diagrams comparing fan length with (A) fan area and (B) fan volume for both submodern and Cenozoic fans, and the Ormen Lange Fan. The Ormen Lange Fan fits well within the distribution of both submodern and ancient small active systems demonstrating the time independence of these morphological relationships. Data from the Cenozoic fans are taken from Reynolds (1994). Symbols reflect the type of margins where the systems are located; Active (S) = small tectonically active systems; Active (L) = large tectonically active systems.

Basin-floor fan morphology and sediment characteristics in Sømme et al.'s (2009) data set were primarily gathered from published literature. The size of the submodern fans ranges from 10^3 to 10^6 km^2 (10^3 to 10^6 mi^2) (Figure 7), and the smallest systems are therefore directly comparable to the relatively small, deep-marine reservoir units that are located in the North Sea (e.g., Reynolds, 1994; Martinsen et al., 2005). Catchment characteristics such as relief, area, hypsometry, river length, etc. (Figure 1), was measured from a global digital terrain model (DEM) data set, and the detail level is therefore consistent for all systems (see Sømme et al., 2009, for references and further discussion).

In addition to the regression analysis that was performed by Sømme et al. (2009) to investigate the relationships between several individual parameters, additional step-wise regression of the same data set was used in this study to identify the parameter(s) that could best explain the observed variance in a given parameter.

The lower slope and fan parameters for the Ormen Lange Fan that were used as input for predicting the remaining morphological characteristics of the system were derived from in-house seismic data and published literature (Gjelberg et al., 2001; Gjelberg et al., 2005). Because of the good seismic data and well coverage in the Ormen Lange area, and the amount of work that has been done in the region in relation to exploration and field development, the parameters for the basin-floor fan are well constrained (Gjelberg et al., 2001; Smith and Møller, 2003; Møller et al., 2004; Gjelberg et al., 2005). The accuracy of these input values is important for further estimation of the onshore parameters because some of these are directly based on the offshore values, thus significantly increasing the overall accuracy of the predictions for the entire system.

Onshore, high-resolution satellite images and DEM data from the Møre coast and central Norway were used to identify preserved areas of paleic terrain and to map the distribution and flow direction of paleoriver valleys. The DEM was also used to identify the location of agnor valleys (fluvial valleys captured by eastward migration of the water divide), thus putting constrains on the eastward limit of preglacial catchments in the region (see also Anda, 1995).

Long-term geomorphic development of source-to-sink systems is expected to be time independent in that tectonic processes governing crustal extension, uplift, and subsidence have remained the same throughout the Phanerozoic. In contrast, climate and vegetation varied significantly during this period, and one must assume that these factors may have caused patterns in sediment production, transport, and deposition that are different from what is recognized in the last period of geological time. However, these would probably be subordinate

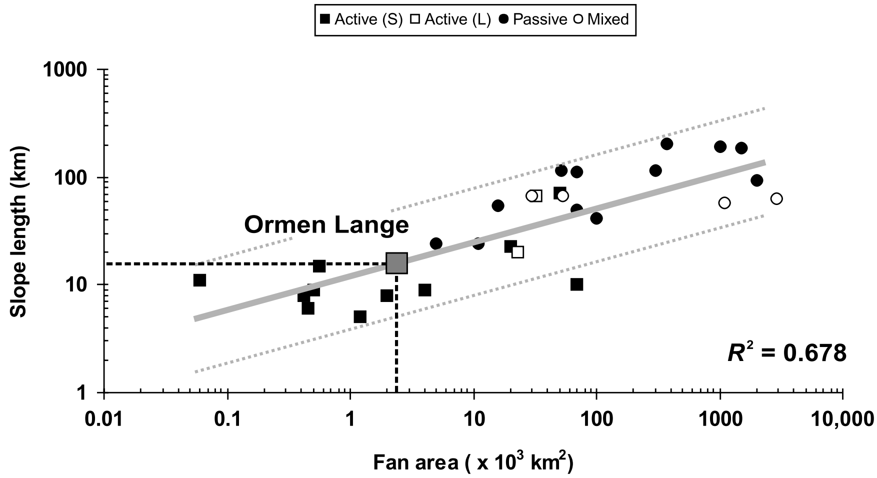


Figure 9. Diagram showing the relationship between the fan area and the slope length for submodern systems, and the location of the Ormen Lange Fan along the main trend line. The gray (broken) lines define the 90% confidence interval, indicating that slope length can be constrained to fan area within one order of magnitude. Symbols reflect the type of margins where the systems are located; Active (S) = small tectonically active systems; Active (L) = large tectonically active systems.

to the overall tectonic signature of the individual system and would likely cause variations comparable to the ranges observed between modern climatic zones. Although these subordinate variations cannot be resolved in the data set, the comparison between submodern fans, early Cenozoic fans, and the Ormen Lange Fan in Figure 8 suggests that the relationships between basin-floor fan length, area, and volume are comparable, and that these relationships are time independent.

Perhaps the most significant difference between submodern and ancient systems is the importance of eustasy in controlling shelf characteristics and timing of sediment delivery to the deep ocean basins. Pliocene–Pleistocene eustatic amplitudes have been shown to have been very different from other periods throughout the Phanerozoic (Miller et al., 2005); this is discussed in more detail in the section entitled Shelf.

PREDICTING MORPHOLOGICAL CHARACTERISTICS FOR THE ORMEN LANGE SOURCE-TO-SINK SYSTEM

The Ormen Lange Fan shows both length-area as well as length-volume relationships in agreement with observed values for submodern basin-floor fans, placing the Ormen Lange among the small tectonically active systems (Figure 8). The proximal segments within the system are therefore expected to show characteristics that are similar to the ones observed along submodern active margins. Plotting of several Cenozoic (primarily late Paleocene) fans from the North Sea within the Maureen, Andrew, Forties, Sele, Balder, and Frigg sequences (Reynolds, 1994) shows that these trends also are valid for ancient fans deposited along tectonically active continental margins.

Slope

Figure 9 shows the relationship between fan area and slope length for submodern systems (Sømme et al., 2009), as well as the location of the Ormen Lange Fan along the trend line. The intersection indicates a paleoslope length of about 15–20 km (9–12 mi), bounded by minimum and maximum values of 50 and 5 km (31 and 3.1 mi), respectively, defined by the 90% confidence band. In general, Figure 9 suggests that the slope length can be predicted to one order of magnitude from a given fan area. At present, only the middle and lower slope is preserved (Figure 10), and can be identified on seismic data. Although the shelf and upper part of the slope has been removed by Neogene uplift and glacial erosion (e.g., Blystad et al., 1995; Gjelberg et al., 2005), the inferred paleoslope length can be compared to modern slope profiles (Figure 11), suggesting a similarity between the Ormen Lange system and the submodern systems described by Sømme et al. (2009). The inferred slope length also fits well with onshore-offshore paleogeographical reconstructions, which suggest that a hinge

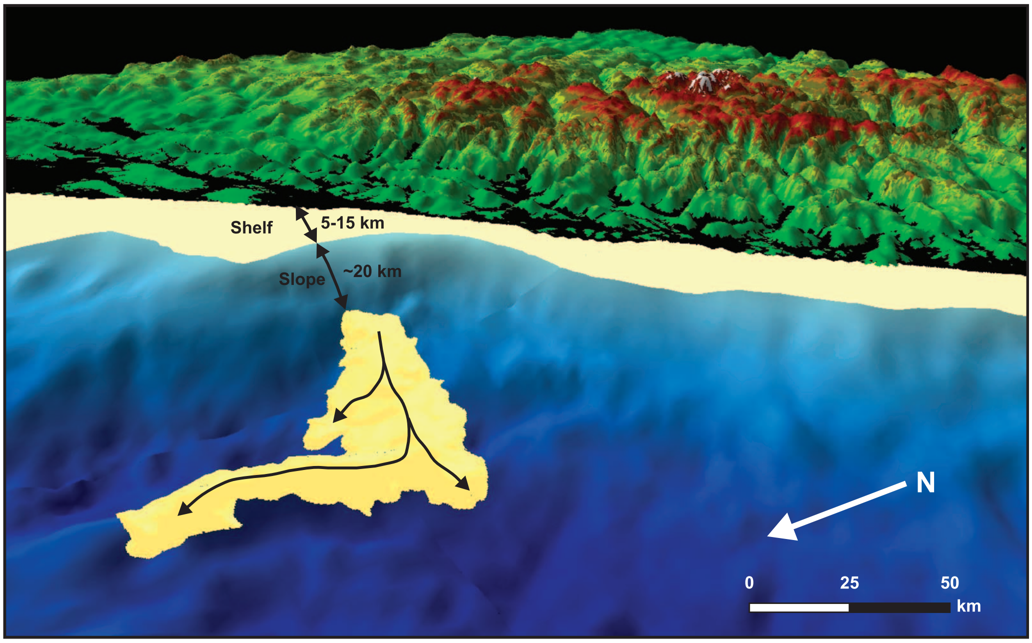


Figure 10. Location of the Ormen Lange Fan and the lower and middle part of the slope (base Tertiary surface), looking toward the southeast. Arrows illustrate the inferred sediment fairway across the slope and distances from the fan apex to the approximate location of the Paleocene shoreline. Note, however, that the location of the shoreline is dependent on the eustatic sea level stand at the time of investigation. The present topography is seen in the background.

area separating onshore uplift from basin subsidence was located 20–30 km (12–19 mi) west of the present shoreline (Stuevold and Eldholm, 1996). This, together with the preservation of paleic terrain close to the coast, indicates a distance of about 45 km (28 mi) between the present shoreline and the fan apex, which is in good agreement with the predicted values for the shelf (see below) and slope segments.

Shelf

In contrast to slope length and gradient, which are mainly controlled by sediment supply and fault patterns at the time of incipient margin rifting, short-term variations in shelf morphology (width, gradient, and depth at shelf edge) are predominantly determined by eustasy on a fourth- to fifth-order scale, the relative timing within the eustatic cycle when measured, the rate of shelf subsidence or uplift, and sediment availability for shoreline progradation. Modern shelf widths are therefore only diagnostic for the present highstand and for past highstands characterized by similar eustatic amplitudes. The use of modern shelf widths will therefore always predict maximum shelf width values for ancient systems. When comparing between various types of systems on longer time scales, the size of the catchment and thereby the length and gradient of the river systems is a direct control on shelf morphology because the shelf merely represents the marine extension of the continent (e.g., Hedberg, 1970). Changes in eustatic sea level will thus shift the coastline in favor of the shelf or of the coastal plain, whereas the coastal plain-shelf profile will remain relatively unchanged. This implies that modern shelf morphologies cannot be used directly for predicting shelf widths and gradients in ancient systems such as the Ormen Lange when eustatic amplitudes are known to have been very different from the Pliocene–Pleistocene icehouse conditions (Miller et al., 2005). Nevertheless, the significance of steep active margins versus low-gradient passive margins, and thus the relationship between the shelf and the coastal plain gradient, would still be the dominating control.

Despite the fact that modern shelves are not representative for ancient systems, the study of submodern depositional environments shows that systems having fan lengths and slope lengths similar to

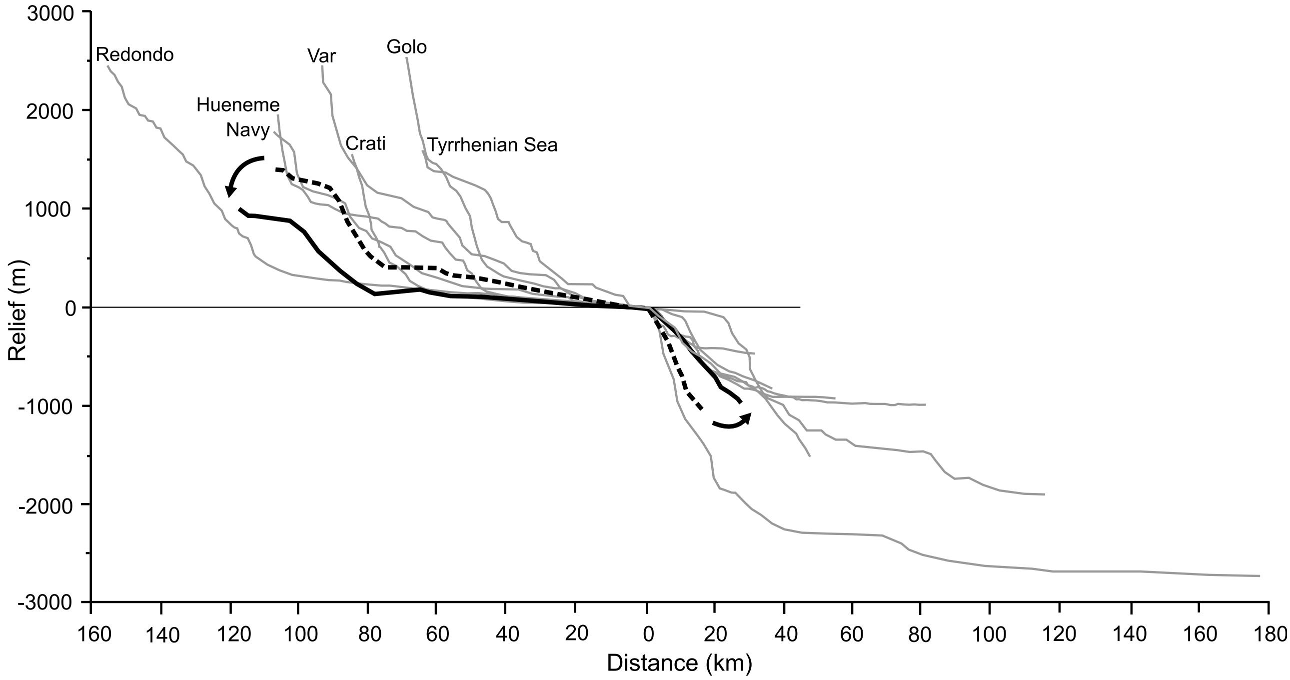


Figure 11. Comparison between catchment-shelf-slope-basin floor profiles (gray lines) from modern, small tectonically active systems from Sømme et al. (2009) (see Figure 7), and the Ormen Lange profile derived from the preserved paleic terrain and the subsurface base Tertiary surface (broken line). The black line shows the profile tilted around the hinge line (arrow), attempting to reconstruct the original profile at the time of deposition prior to regional onshore Cenozoic uplift and basin subsidence. Note the similarity in length between the various segments in paleo–Ormen Lange and modern systems.

the Ormen Lange system (fan length of ~108 km [67 mi] and predicted slope lengths of ~15–20 km [9-12 mi]) typically also have shelves that are 5–15 km (3–9 mi) wide (Sømme et al., 2009). If used as a maximum, first-order approximation, this would position the average Ormen Lange paleoshelf break approximately 25–35 km (16–22 mi) from the present shoreline, which is in accordance with paleogeographic models presented for the area (Vergara et al., 2001; Lien, 2005). Even if these estimates are uncertain, they are bounded by the present shoreline, which approximately represents the maximum possible landward extent of the paleoshelf, and the preserved middle slope, which represents the maximum basinward extent of the paleoshelf (Figure 10).

Most modern source-to-sink systems have well-developed submarine canyon systems that effectively distribute sediments to the slope and basin-floor environments (e.g., Shepard, 1981; Normark and Carlson, 2003). In small, tectonically active systems where the sediment cover is relatively thin, these canyons tend to form in areas of weaker crust, typically in faults or fault zones where they are initiated by gully formation and further widened and deepened because of headward erosion (e.g., Shepard, 1981; Lastras et al., 2009).

In the Ormen Lange system, the fan apex is located in the same area where the Jan Mayen lineament intersects the Klakk fault complex, and at the seaward continuation of the MTFC (Figure 2). The development of a submarine canyon in this area of weakened crust during millions of years of erosion would have had the potential to form a major sediment conduit, which would effectively bypass sediments from the river to the slope and basin floor (Martinsen et al., 2002). Such a canyon point source is inferred from the thickness variations in the isochore map (Figure 4) and is in sharp contrast to the deposits in the Slørebotn Subbasin, which appears to have been fed by a more linear source, thus representing more of a slope apron consisting of several coalescing smaller fans (Martinsen et al., 2002; Gjelberg et al., 2005).

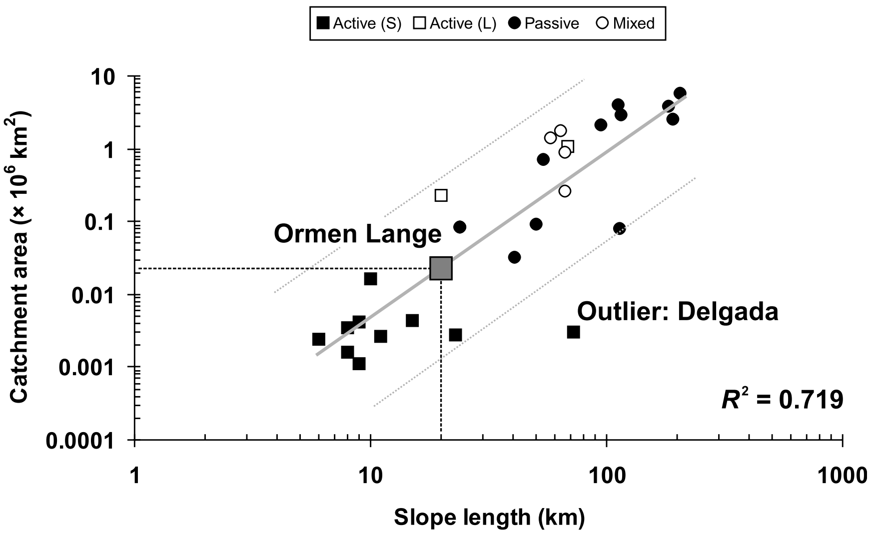


Figure 12. Diagrams showing the general relationships between slope length and catchment area for modern systems, as well as the location of the Ormen Lange system along the trend line (heavy gray lines). The 90% confidence intervals (broken gray lines) suggest prediction within one order of magnitude. Including the Delgada outlier (encircled), the slope length explains 71.9% of the observed variation in the catchment area. If the outlier is excluded, the relationship accounts for 82.1%. See the text for discussion. Symbols reflect the type of margins where the systems are located; Active (S) = small tectonically active systems; Active (L) = large tectonically active systems.

Catchment

Similar to the shelf, slope, and basin-floor segments, morphological characteristics of the catchment area are also related to the overall evolutionary history of the entire source-to-sink system and can therefore be predicted by the use of relationships observed in submodern erosional-depositional environments (cf. Sømme et al., 2009).

As discussed in the section above, a good correlation between shelf width and gradient, and river length and gradient in submodern systems is observed (Sømme et al., 2009). Because large drainages supply more sediment to the coast than small drainages, causing the widening of the shelf and flattening of the slope, a direct relationship between the length and gradient parameters in these segments also exists. Regression analysis with the submodern parameter data set shows that slope length alone will explain 71.9% of the observed variance in catchment area, whereas fan area, fan volume, and fan length only account for 63.5%, 62.6%, and 60.6% of the variance, respectively. Excluding an outlier (the Delgada system) from the regression further increases the predictability to 82% for the slope correlation (Figure 12). This catchment-slope regression has an uncertainty of two orders of magnitude and predicts a catchment area of approximately 22 × 10^3 km^2 (~8.5 × 10^3 mi^2) (Figure 12) for the paleo–Ormen Lange catchment if a slope length of 20 km (12 mi) is assumed (excluding the outlier changes the prediction to ~25 × 10^3 km^2 [~9.7 × 10^3 mi^2]). These estimates are bounded by minimum and maximum values of 1 and 560 × 10^3 km^2 (0.38 and 216 × 10^3 mi^2), respectively, as defined by the 90% confidence band (excluding the outlier changes the range to 2–300 × 10^3 km^2 [0.8–116 × 10^3 mi^2]).

Using step-wise regression, we further found that slope length and fan volume collectively account for 77.9% of the observed variance in catchment area; however, the uncertainty increases. Using the above input data on slope length and fan volume, this model predicts a catchment area of about 55 × 10^3 km^2 (21.2 × 10^3 mi^2). Substituting fan volume with fan area or fan length only lowers the coefficient of determination (R^2) to 0.753 and 0.758, respectively, indicating that these variables are almost just as reliable in predicting catchment area as fan volume. However, including them into the regression does not improve the model.

Small tectonically active systems are commonly more complex in terms of drainage configuration than passive systems, and fans are frequently fed by several catchments along a stretch of coastal mountains (Schwalbach and Gorsline, 1985; Covault et al., 2007). In addition, rivers commonly merge during periods of low eustatic sea level, causing the formation of larger river systems capable of delivering increased amounts of sediment to the slope and basin-floor

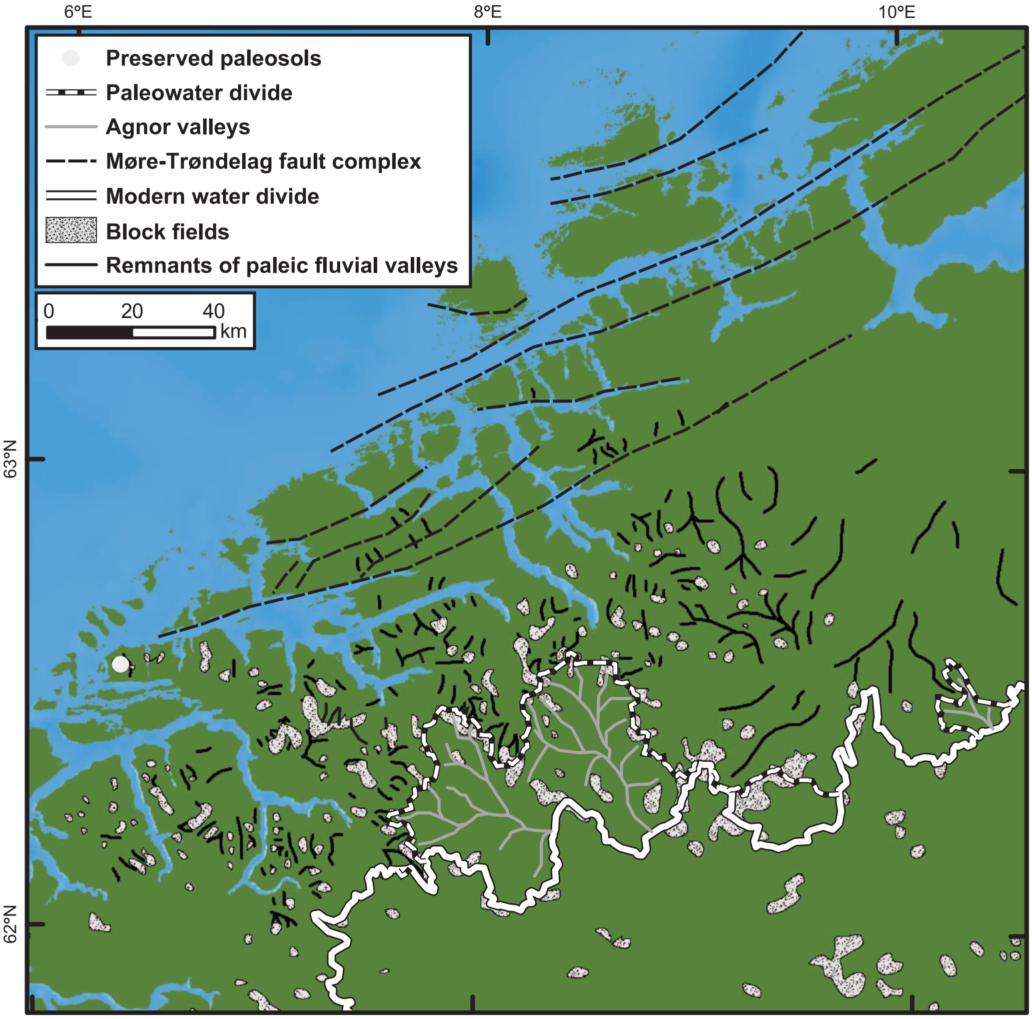


Figure 13. Map showing the distribution of localities with preserved paleosols, block fields, and old fluvial valleys used to reconstruct the Paleogene drainage configuration in central Norway. Agnor valleys southeast of the paleowater divide are also shown. Note the decrease of preserved soils and river valleys within the MTFC. The block field distribution is from Nesje et al. (1988).

segments (Mulder and Syvitski, 1996). Such systems may therefore display an inconsistent relationship between net catchment size, river length, and fan size, and thereby cause an overestimation in the prediction of river channel lengths and an underestimation in the prediction of combined catchment size during lowstands.

To be able to evaluate whether the estimated catchment area fits with the paleo–Ormen Lange system, examining the remnants of the drainages that existed within the paleic terrain in this region is necessary.

The difference between the summit surface, which is an assumed, tangential surface through the highest mountains peaks, representing remnants of the Mesozoic peneplain (Gjessing, 1967; Lidmar-Bergström, 1995), and the paleic terrain represents the evolution of the central Norwegian drainage systems from the period of incipient regional uplift and to the initiation of glacial erosion in the late Miocene. Because of poor time constraint on the formation of this terrain, any observed remnants of old fluvial systems may in reality date to any period within this time interval. However, after the early Paleocene and prior to the Pliocene, little coarse-grained clastic sediment reached the central Norwegian basins from Fennoscandia (Martinsen et al., 1999; Martinsen and Dreyer, 2001, and references therein; Færseth and Lien, 2002; Martinsen et al., 2005). Thus, the observed drainage systems developed prior to the Pliocene massive, glacially related clastic sediment flux, and it could well be as early as the Paleocene in age. An interpretation of the paleic catchment configuration based on the

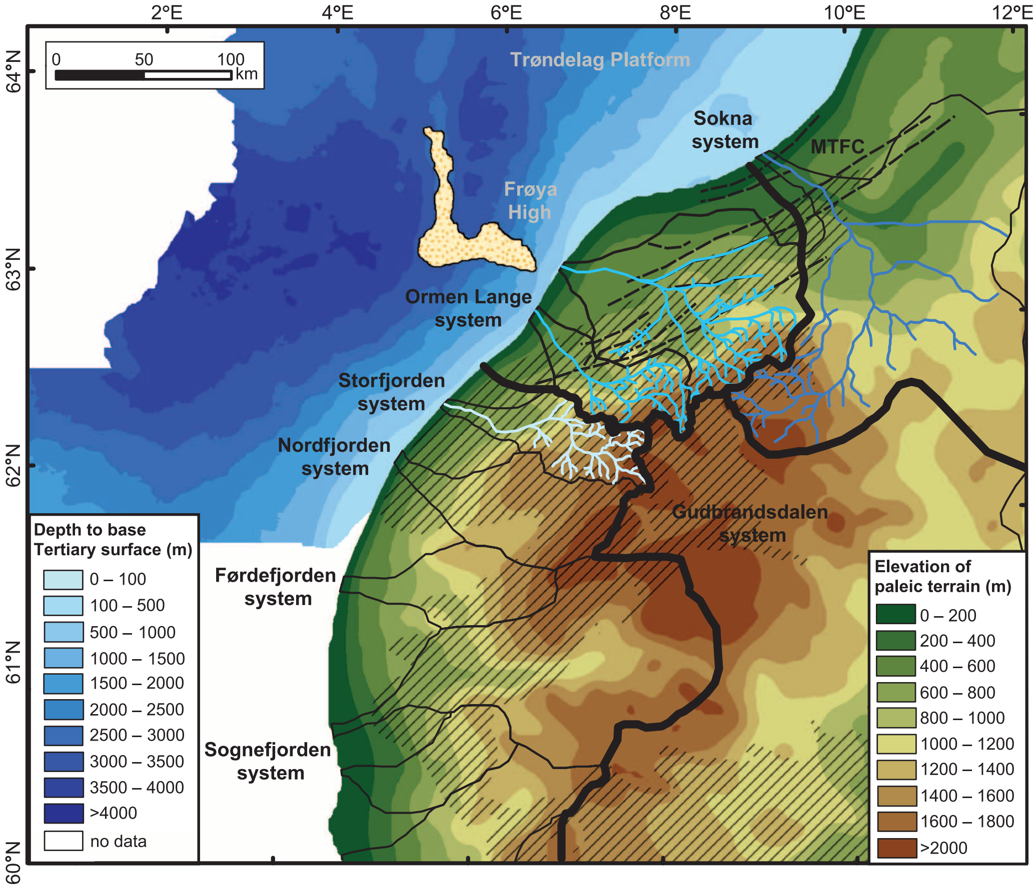


Figure 14. Reconstruction of the paleic terrain (from Nesje, 2007, unpublished data) and the inferred main drainage regions in the central and southern parts of Norway during the Paleogene (heavy black lines). The inferred catchment configuration (thin black lines) is most reliable in the high-altitude areas where the paleic terrain is very well preserved, and less confident in coastal areas where the terrain only is sparsely preserved on fjord interfluves. Locations of river outlets are uncertain because the lower reaches of the fluvial systems were heavily controlled by the Møre-Trøndelag fault complex (MTFC). Note the difference between the small catchments along the western coast, south of the Storfjorden system (light blue), and the larger and better developed catchment in the east, reflecting differential uplift. The presence of the emerged Frøya High may have had great significance for sediment distribution from fault-controlled rivers around and northeast of the Ormen Lange area (blue). In the north, the Sokna system (dark blue) is expected to have represented a prominent sediment source for the southern Trøndelag Platform. The hatched area shows the present extent of the Gothian-Sveconorwegian basement (see also Figure 2).

remnants of exhumed land surfaces, paleosols, and ancient, uplifted river valleys is presented below.

Texture and clay mineral composition of preserved saprolites along the Møre coast (Figure 13) suggests the in-situ weathering of bedrock in a warm and humid climate, probably prior to the Neogene (Roaldset et al., 1982). This indicates that the present land surface has been protected from denudation and glacial erosion since the formation of the soil, and the surface can therefore be considered as a remnant of the preglacial landscape in this area. More regionally, the weathering patterns and mineral composition of soils in preserved block fields located within the paleic terrain (Figures 6B, 13) also suggest formation during periods of warmer and more humid climate conditions (Nesje et al., 1988). Similar to the saprolites, preservation of block fields and their weathering products indicates that the morphological characteristics of that specific area date back to or predate these deposits.

Finally, several old fluvial valleys are located within the same terrain as the preserved paleosols and block fields, suggesting that the morphology of these valleys also predates these deposits (Figure 13). In the high-altitude inland area, the paleic terrain is characterized by low-relief valleys, hills, and

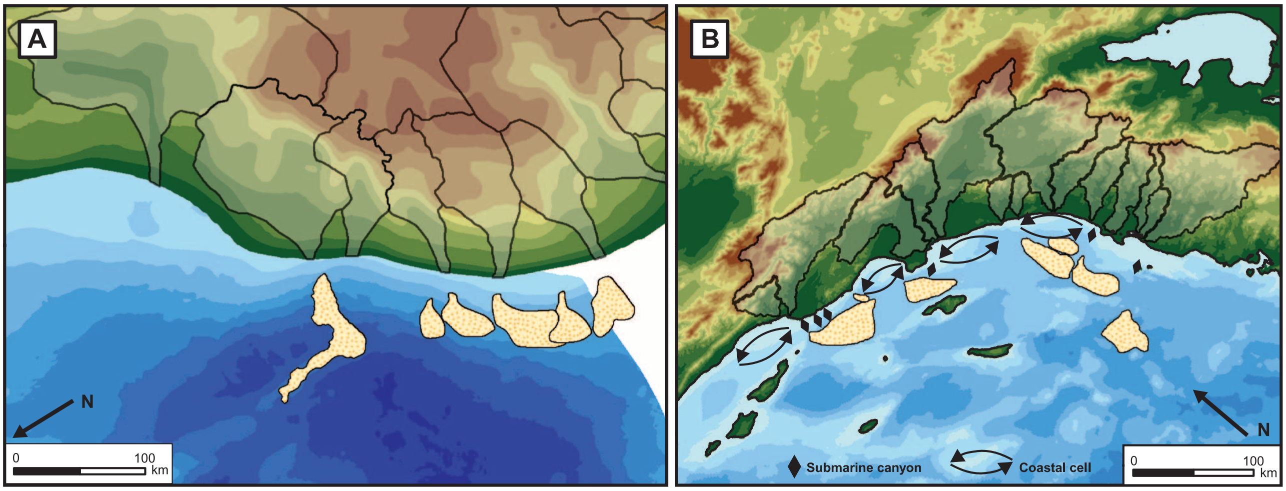


Figure 15. A comparison between (A) the inferred drainage configuration along the Paleogene Møre coast and (B) the present configuration along the active transform margin of the California borderland. Note the similarity between catchment size and fan size in the two areas. In these modern systems, the amount of longshore drift contributing sediment to the various fans is controlled by the spacing of shelf-indented submarine canyons, defining restricted coastal cells, and in many cases, several catchments may deliver significant amounts of sediments to a fan. Similar to what is observed along the Møre margin, these California fans are also deposited in relatively confined, fault-controlled basins. See Figure 14 for the key to the offshore and onshore relief.

depressions, representing deep weathering at times when Fennoscandia was relatively flat and tectonically quiet (Gjessing, 1967; Lidmar-Bergström, 1999). However, as the landmass was uplifted, prominent river systems formed in the highest areas in Trollheimen and Jotunheimen and in smaller uplifted fault blocks within the MTFC. Remnants of some of these valleys can be observed in the outer part of the great escarpment and the southern margin of the MTFC (Anda, 1995) (Figure 13). Here, they show locally complicated drainage patterns, indicating intrabasinal relief created by the different fault segments in the MTFC (Redfield et al., 2005b). The valleys can be recognized by their crosscutting relationship with the younger glacial eroded valleys, and they commonly follow a west-northwest–east-southeast direction of lineaments in this region (Gabrielsen et al., 2002). These old valleys typically form hanging valleys relative to the younger glacial fjords and valleys and are typically oriented approximately perpendicular to the main southwestern direction of ice flow during the Quaternary, indicating a preglacial origin. However, the preserved valleys in the coastal areas have probably experienced varying degrees of glacial erosion and modification, indicating that location and orientation are the best evidence for preglacial river systems. The paleic terrain as a geomorphic feature must therefore be regarded as highly diachronous in origin.

The orientation of these ancient fluvial systems as well as the regional morphology of the paleic terrain allows for a first-order reconstruction of four distinctly different drainage regions in southern and central Norway (Figure 14).

In the southeast, the Gudbrandsdalen catchment along with its tributary valleys represents by far the oldest and best developed drainage systems in the region, covering the highest and most extensive parts of the paleic terrain (Figure 13). In the west, the Sognefjorden Basin, which covered an approximate area of 14×10^3 km^2 (5.4×10^3 mi^2), drained toward a shoreline, which was located only a few kilometers west of the present coastline (Jordt et al., 2000). The catchment had a classic dendritic shape, indicating that it developed over an extended period without significant influence of internal faulting, which would have caused deviations in the fluvial pattern (Summerfield, 1991). The shape of the catchments is still preserved in the glacial drainage (Nesje and Whillans, 1994).

Farther north, three smaller catchments (~3–5 × 10^3 km^2 [1.2–1.9 × 10^3 mi^2]) occupied the steep extensional margin around the present area of Førdefjorden, Nordfjorden, Storfjorden, and their tributaries, and all were characterized by dendritic shapes similar to the larger Sognefjorden catchment (Figure 14). Although small tectonically active systems commonly receive parts of their sediment load from longshore drift, a comparison with submodern systems in the California borderlands shows that the coastal cells distributing sediments along the shoreline commonly operate at scales significantly lower than approximately 80 km (50 mi) (Figure 15), which was the approximate distance from the northernmost basin to the Ormen Lange Fan, indicating that these catchments were located too far south to contribute sediment to the depositional system farther north. However, the size of the coastal cells is primarily defined by the spacing of shelf-indented submarine canyons and the direction and magnitude of longshore currents (Schwalbach and Gorsline, 1985), and may thus be more restricted in heavily fractured areas that are prone to river and canyon incision. These smaller systems are interpreted to have fed sediments to the fans in the Slørebotn Subbasin.

In the north, low relative sea level caused by marginal uplift southeast of the Vøring Basin resulted in the subaerial exposure of the Frøya High in the latest Cretaceous (Brekke, 2000; Vergara et al., 2001; Lien, 2005). This may have caused the northward extension of the catchments in the northeastern part of the Møre coast during the Maastrichtian (Figure 14), where it might have been an important factor in distributing fluvial sediment input to the shoreline in this area. Any rivers entering the ocean southwest of the high would deliver sediments to the narrow, fault-controlled shelf of the Ormen Lange system, whereas rivers entering to the northeast would have delivered sediments to the relative shallow, low-gradient Trøndelag Platform (Figure 14).

At present, the large river systems covering the high areas around Dovrefjell drain toward the west because of Quaternary headward erosion and river capture. Preserved river valleys in the paleic terrain indicate that a large, preglacial river system (termed Sokna; Sulebak, 2007) covered the same high areas around Dovrefjell and drained northward to an area close to Trondheim (Figures 2, 14). Redfield et al. (2005b) interpreted a late Mesozoic–early Cenozoic uplift along the MTFC as a normal faulting with the highest uplift in the west, decreasing to the east along the fault complex. This interpretation would position the Sokna River on the distal flank of the uplifted footwall block, feeding sediments to the low embayment northeast of the Frøya High (Figures 13, 14).

North of Storfjorden, we notice a change in drainage configuration (Figure 14). The MTFC dominates the coastal morphology with two specific characteristics: (1) the major faults that are parallel to longer, northeast-southwest–trending fjord elements are oblique to the present coastline, and (2) together with small cross-faults that can be seen in the shorter northeast-southwest–trending fjord segments, these form a rectangular drainage and fjord pattern in the area (Gabrielsen et al., 2002; Martinsen et al., 2002) (Figure 2). When compared in plan view with the main seismically mapped feeder system to the Ormen Lange system offshore, the confluence of the main northeast-southwest–trending MTFC faults occurs more or less exactly landward of the apex of the feeder system, at the mouth of Romsdalsfjorden, near the island of Gossen (Figure 2). This strongly indicates that the MTFC has a major control on the development of catchments in this region, driving sediment supply to the head or apex of the Ormen Lange system (Figure 14). The inferred catchment for the Ormen Lange Fan was thus located in the areas presently occupied by Romsdalsfjorden and the surrounding tributary fjords to the north, where they occupied the main fault scarp formed by normal displacement along the MTFC (Figures 2, 14). In addition, this catchment would also have drained whatever topography created within the MTFC (Redfield et al., 2005b), thus having an approximate area of 13 × 10^3 km^2 (~5 × 10^3 mi^2). This calculation is comparable to the suggested area of approximately 22 × 10^3 km^2 (~8.5 × 10^3 mi^2) estimated from submodern slope lengths and catchment areas, indicating that this is the best model for predicting the catchment area for the paleo–Ormen Lange system. This river system would have been in close proximity to the Ormen Lange Fan and represents the most likely catchment configuration feeding the fan during the latest Maastrichtian–Paleocene.

Provenance studies from the Ormen Lange Fan have shown that most of the sand deposited in the basin-floor fan system is derived from the Gothian-Sveconorwegian basement, with little input from the younger Caledonian nappes (Fonneland et al., 2004; Morton et al., 2005) (Figures 2, 14). Following the Caledonian orogeny, the entire southwestern part of Norway was covered by the overthrusted nappes. The presence of sediment derived from the underlying basement in the Ormen Lange Fan suggests that the Caledonian cover had been partly removed, forming a basement window in the latest Cretaceous. The size of the window is unknown; it must have been smaller than its present extent but at the same time large enough to cover a significant part of the paleo–Ormen Lange catchment. The combination of provenance data and the reconstructed paleowater divide thus provides a constraint on the eastern and southernmost extents of the paleo–Ormen Lange catchment.

The drainage configuration outlined above is in good agreement with observations from modern actively growing mountain ranges, which suggest a close relationship between the spacing of rivers (S) and the distance from the water divide to the coast (W) in the form: $S = W/R$, where R is the spacing ratio (Hovius, 1996; Talling et al., 1997; Castelltort and Simpson, 2006). Along the Møre margin, W ranges from approximately 221 km (~137 mi) at the Sognefjorden Basin to 109–130 km (68–81 mi) farther north around the Ormen Lange Basin (mean 144 km [89 mi]). The S ranges between 25 and 130 km (16 and 81 mi) and has a mean of 64 km (40 mi) (Figure 14), thus yielding spacing ratios in the range of 0.9–4.1 (mean 2.5), which is similar to values obtained from modern environments (1.4–4.1, mean of 2.5 for fault blocks and 2.1 for mountain belts; Talling et al., 1997). These relationships are important in estimating the spacing and along-margin location of significant sediment sources and potential reservoir sands in these areas (see below).

CHARACTERISTICS OF THE SEDIMENT TRANSFER SYSTEMS: TYPICAL FOR SMALL TECTONICALLY ACTIVE SYSTEMS

In submodern systems, erosion, transportation, and storage of sediment are primarily dependent on catchment size and relief, and both water discharge and sediment load are directly related to these factors in addition to a regional and local climatic component (e.g., Milliman and Syvitski, 1992; Hovius, 1998; Syvitski et al., 2003). For example, in small systems where channel and floodplain storage of sediment are limited and where peak water discharges are high, the vast majority of sediment delivery occurs during high-magnitude flood events (e.g., Warrick and Milliman, 2003).

In the case of the Ormen Lange system, rough estimates of transport efficiency and sediment load can be achieved by comparison with submodern systems (Sømme et al., 2009). Modern catchments with areas of about 10–20 $\times$ 10^3 km^2 (4–8 $\times$ 10^3 mi^2) all have peak/average water discharge ratios between 100 and 1000, indicating that during periods of maximum flooding, the discharge at the river mouth is between 100 and 1000 times higher than the long-term average. We thus inferred that the rivers feeding the Ormen Lange Fan may have experienced similar discharge ratios. This would have had important implications both for the timing and for the mode of sediment transport in these rivers because high water discharge accompanied by high sediment concentrations tend to trigger turbidity currents (e.g., Milliman and Syvitski, 1992; Mulder et al., 2003). When this is combined with a narrow shelf and the presence of an incised canyon, it provides a highly effective mechanism for transporting both fine and coarse-grained sediment across the shelf (Drake and Gorsline, 1973; Johnson et al., 2001).

The sandy succession in the Ormen Lange Fan and coeval slope deposits consists of alternating amalgamated sandstone beds (up to 2 m [6.6 ft] thick) and sandstone and mudstone interbeds (between a few decimeters and 3 m [9.8 ft] thick) (Figure 3B, C), which have been interpreted as low- and high-density turbidity current deposits (Gjelberg et al., 2001; Martinsen et al., 2002; Smith and Møller, 2003). Many beds are normally graded, and the grain sizes vary from fine to medium to coarse, both within and between beds. Lithified organic material from plants is common in the upper part of the beds.

Grain size and thickness variations indicate that the mechanisms responsible for transporting sediments to the fan varied in magnitude and frequency. These variations are also indicative of a sediment source that was able to deliver a material of different grain sizes instead of a more constant source with well-sorted sediments. In addition, the presence of plant fragments suggests that the sediment was transported quickly from the river to the basin floor, limiting the potential for long-term littoral and shelf storage. These observations and the overall high sand content in the fan suggest sourcing from a steep river with considerable discharge variations and which periodically delivered large amounts of sand close to the shelf edge or to the head of a submarine canyon, where it was funneled downslope.

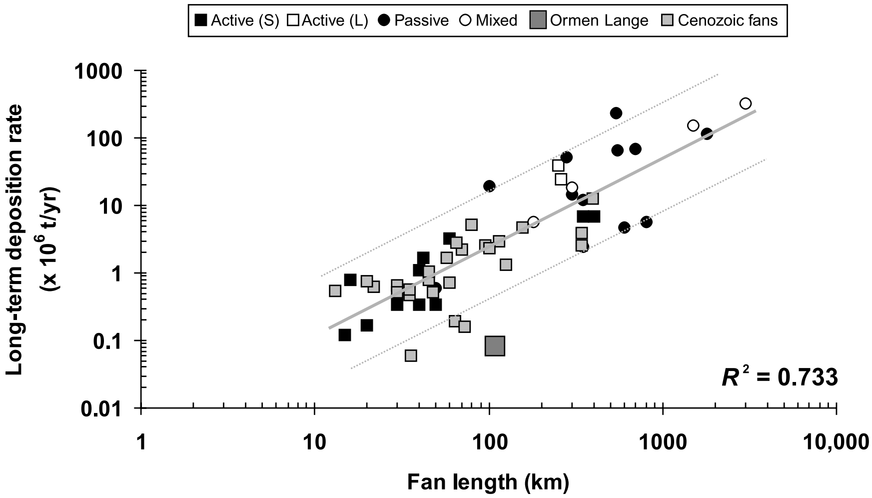
RELATIONSHIPS BETWEEN LONG-TERM DEPOSITION RATE AND DURATION OF FAN DEPOSITION

Studies of submodern deep-sea fans show that, in addition to estimates on geomorphic parameters in ancient systems, the same parameter relationships can also be used to investigate depositional characteristics in the same environments (Wetzel, 1993). Based on core sections, Smith and Møller (2003) calculated long-term deposition rates on the order of 0.023–0.046 $\times$ 10^6 t/yr (metric tons/yr) (using 15% porosity and a density of 2700 kg/m^3) for the entire duration of fan deposition in the Ormen Lange Basin. In this study, a fan volume of 104 km^3 (66 mi^3) and a duration of fan deposition of 2.9 m.y. are used to calculate long-term deposition rates in the fan, suggesting values on the order of 0.082 $\times$ 10^6 t/yr. These rates only cover the Danian Egga part of the fan, which is considered to represent a period of active fan growth within a well-developed source-to-sink system. In contrast, the underlying Maastrichtian interval is interpreted to represent a period of incipient regional uplift onshore, and this is also reflected in an order of magnitude of lower deposition rates (~0.0049 $\times$ 10^6 t/yr). In total, an overall deposition rate of 0.034 $\times$ 10^6 t/yr for the entire fan is in good agreement with the estimates of Smith and Møller (2003).

A comparison between submodern fans and early Cenozoic basin-floor fans from the southern North Sea, however, shows that the total rates obtained from the Ormen Lange are approximately one order of magnitude lower than what would be expected from the correlation, and are outside the 90% confidence interval envelope (Figure 16). Although several uncertainties related to both fan-volume calculation and the time constraints of fan deposition are observed, this cannot fully explain the divergence from the trend line observed in the Ormen Lange system.

Smith and Møller (2003) suggested that the discrepancy can be explained by filtering in the more proximal Slørebotn Subbasin; however, no fill and spill between the Ormen Lange system proper and the Slørebotn Subbasin has been observed. In addition, deposition in the Slørebotn Subbasin postdated the deposition in the more distal Ormen Lange Fan (Gjelberg et al., 2001). Martinsen et al. (2002) interpreted the fill and spill between the subbasin where the 6305/9-1 well is located and the Ormen Lange Subbasin itself (Figure 4), but this cannot account for the entire order-of-magnitude lower deposition rates. Other secondary mechanisms, such as low sediment yield from the catchment, littoral entrapment along the coast, or sediment storage in tectonic basins farther inland, have also been proposed to account for the low deposition rates (Smith and Møller, 2003). Although low sediment yield and littoral storage cannot be excluded, initial deposition of deep-marine fan deposits indicates that the largest inland basins were already filled and that sediment could be bypassed to the marine environment. Large-scale littoral and shelf storage of this magnitude also seems unlikely because one of the main characteristics of small tectonic active systems is limited capacity of shelf storage. Nevertheless, because the Ormen Lange system is characterized by

Figure 16. Comparison between fan length and long-term deposition rate for submodern and Cenozoic basin-floor fans, and the Ormen Lange Fan. The position of the Ormen Lange Fan outside the 90% confidence interval (broken gray line) shows that the fan has abnormally low deposition rates. See the text for further discussion. Cenozoic fan data are taken from Reynolds (1994). Symbols reflect the type of margins where the systems are located; Active (S) = small tectonically active systems; Active (L) = large tectonically active systems.



extensive faulting within the MTFC (which was active at the time of deposition), lateral and/or vertical displacement possibly created fault-controlled basins, similar to the preserved Jurassic basins (Bøe and Bjerkli, 1989; Sommaruga and Bøe, 2002). Such sediment entrapment could in part explain the lower deposition rates that are observed in the fan.

An alternative explanation for the low deposition rates observed in the Ormen Lange Fan may relate to the difference in duration of fan deposition between submodern fans, Cenozoic fans, and the Ormen Lange Fan. Because the stratigraphic record contains only sparse episodic depositional events, long-term deposition rates will decrease with increasing time being investigated, so the longer the time span covered by a sedimentary unit, the larger the interval represented by nondeposition (Sadler and Strauss, 1990; Sommerfield, 2006). Whereas the submodern systems used for comparison are mainly deposited within the Quaternary period (past ~2 m.y.), and the Cenozoic fans in the northern and central North Sea cover time intervals less than 1.6 m.y. (Reynolds, 1994), deposition of the Egga Member sand (Figure 3) in the Ormen Lange persisted for approximately 2.9 m.y. Because of the longer duration of fan deposition in the Ormen Lange Fan, one can therefore expect that this succession will contain more and longer hiatuses than submodern and Cenozoic fans, which could partly explain the lower deposition rates. However, despite the unusual low deposition rate of the Ormen Lange Fan, a strong positive correlation between fan length and long-term deposition rate both for submodern and ancient basin-floor fans is observed (Figure 16).

IMPLICATIONS FOR ONSHORE AND OFFSHORE TOPOGRAPHY DURING THE LATEST CRETACEOUS–PALEOCENE TRANSITION

Uplift in southern and central Norway has been assigned to several periods ranging from the Late Cretaceous to the Neogene (e.g., Stuevold and Eldholm, 1996; Martinsen et al., 1999). However, the timing of the initial regional uplift of the landmass still remains poorly constrained (Japsen and Chalmers, 2000). Here, submodern, small tectonically active source-to-sink systems draining coastal mountains comparable to the ones inferred from the Late Cretaceous–Paleocene Møre coast are used to provide first-order estimations on the onshore and offshore topography during deposition of the Ormen Lange Fan.

Figure 17A shows the relationship between the relief and catchment area for the submodern systems discussed by Sømme et al. (2009). The relatively poor correlation observed in the diagram is related to the fact that several distinctly different types of continental margins are represented in the data set, and that such area-altitude relationships are commonly controlled by a local tectonic component as well the age and type of margin. Despite this scatter, the trend indicates that larger

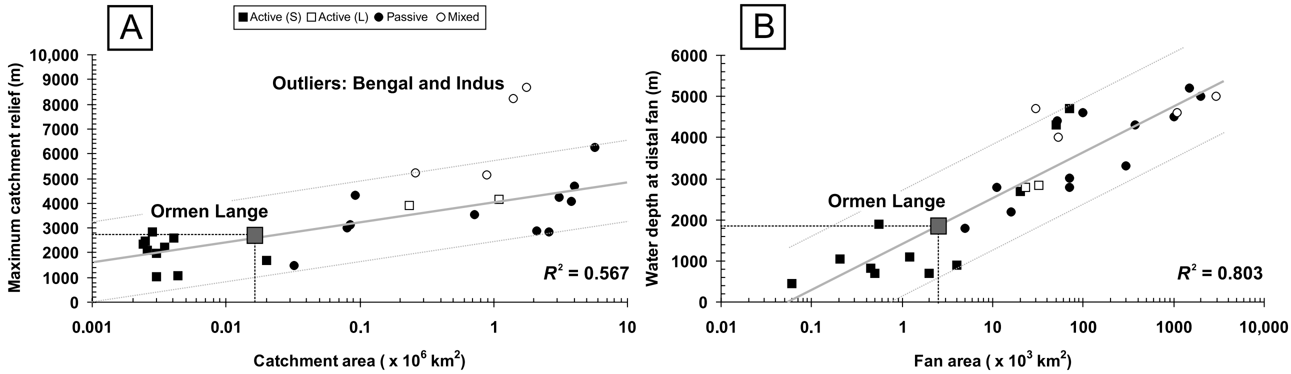


Figure 17. Comparison between (A) maximum catchment height and catchment area, and (B) water depth at the distal part of the fan and fan area for submodern systems, allowing parameter prediction of the Ormen Lange. Symbols reflect the type of margins where the systems are located; Active (S) = small tectonically active systems; Active (L) = large tectonically active systems.

catchments drain higher altitudes than smaller systems. When excluding the Bengal and Indus systems as outliers (as they drain areas >8000 m [26,247 ft]), the correlation in Figure 17A predicts that the paleo–Ormen Lange catchment would drain areas with altitudes of about 2500 m (~8202 ft), with predicted minimum and maximum elevations of 900–4200 m (2952–13,779 ft) defined by the 90% confidence envelope.

The present relief of the paleic terrain is not indicative of the topography that existed at the initiation of regional uplift in south and central Norway because this terrain has been significantly modified throughout the Paleogene and the Neogene (e.g., Lidmar-Bergström, 1999). However, the drainages occupying the terrain have been suggested to have a relief on the order of 200–500 m (656–1640 ft) prior to uplift, and they then were further excavated and modified as the relief increased (Stuevold and Eldholm, 1996; Huuse, 2002). Based on the comparison with submodern catchments of similar size in Figure 17A and the estimated mean paleoelevation of approximately 2500 m (~8202 ft), southern Norway, therefore, possibly experienced uplift on the order of approximately 2000 m (~6562 ft) during the latest Cretaceous, providing the Ormen Lange river systems with sufficient energy to erode and transport the amount of material that is observed in the fan. High relief and steep river channels are required to minimize catchment storage and maintain rapid sediment delivery to the ocean. We therefore inferred that regional doming (e.g., Lidmar-Bergström et al., 2000) or marginal warping (Redfield et al., 2005a) had created significant relief along the Møre coast by the end of the Maastrichtian (Gjelberg et al., 2001; Vergara et al., 2001).

Similarly, slope and basin-floor bathymetry can also be estimated from trends in submodern systems where the fan area shows a strong positive correlation to water depth at the distal part of the fan (Figure 17B). The correlation indicates that the Ormen Lange Fan was deposited in water depths of about 1800 m (~5905 ft), with predicted minimum and maximum ranges of 600–3200 m (19,68–10,498 ft) defined by the confidence band. These trends are again related to the evolutionary link between the various segments in source-to-sink systems, and because these margins are commonly associated with rifting and fault movement, the slope is commonly defined by several smaller basins, which effectively capture sediment in relatively shallow water (e.g., Prather, 2003). Along the Møre margin, shallow fault-controlled basins acted as the main depocenters from the Middle Jurassic to the establishment of a passive margin configuration in the Eocene (Blystad et al., 1995; Lien, 2005). The Ormen Lange Fan was thus deposited in a transitional stage, postdating major rifting in the basin but predating large-scale cooling and subsidence. The position of the fan within a late rift stage is also in agreement with the position of the segment parameters in the correlation diagrams, where the

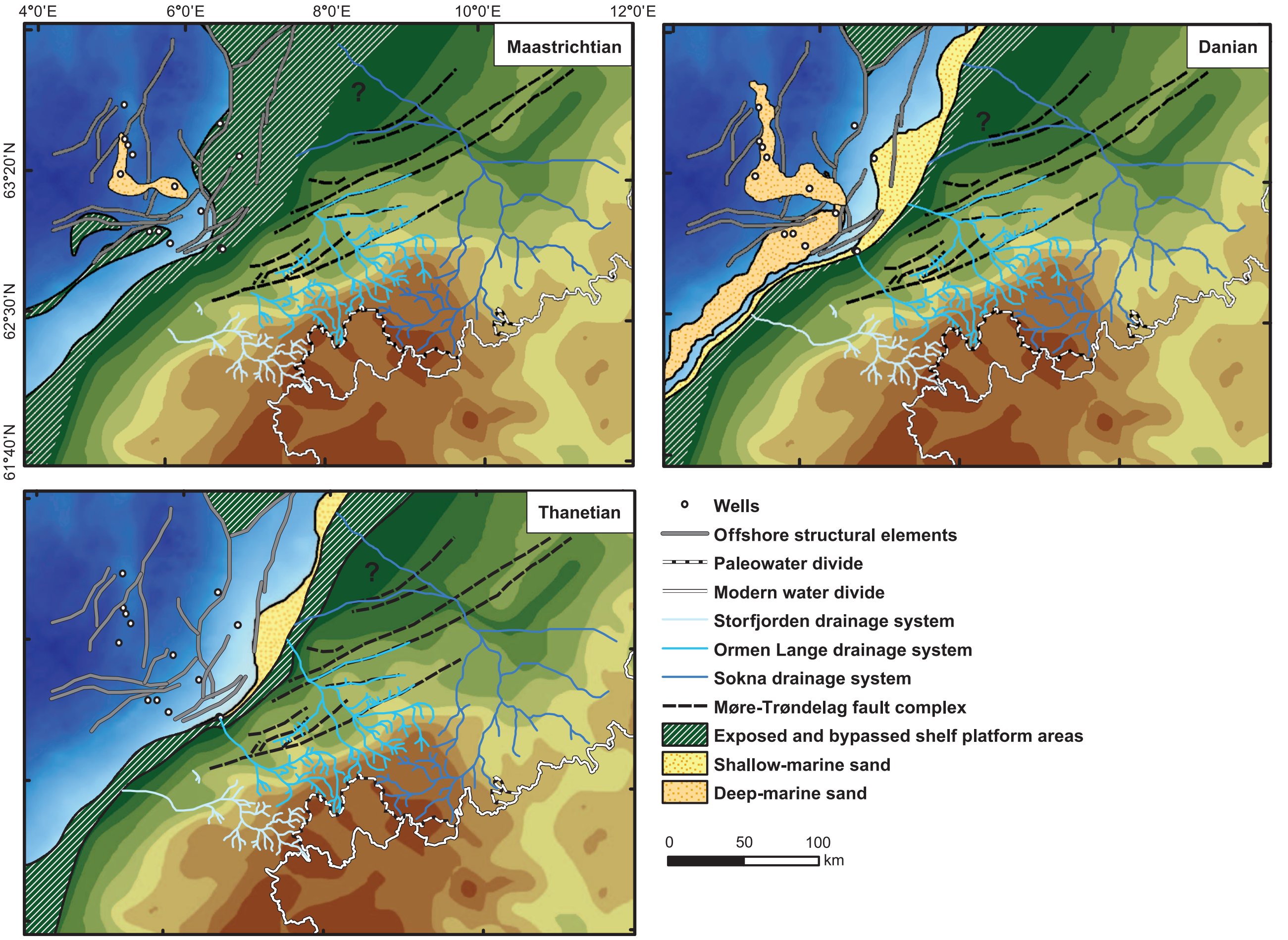


Figure 18. General paleogeographic reconstruction of the central Norwegian margin during the Late Cretaceous–Paleocene. Maastrichtian and Danian deposition represents the upper part of the Springar Formation and the Egga Member sandstones, respectively. Modified from Martinsen et al. (1999), Vergara et al. (2001), Henriksen et al. (2005), and Lien (2005). Offshore structural elements are modified from Gjelberg et al. (2001). See Figure 14 for the key to the offshore and onshore relief.

Ormen Lange segments commonly plot among the largest and most mature small tectonic active systems (e.g., Figure 8).

ADJACENT SOURCE-TO-SINK SYSTEMS ALONG THE MØRE MARGIN

The location and areal extent of the paleo–Ormen Lange catchment indicates that other and larger river systems capable of delivering equal or even higher amounts of sediment existed along the Møre coast during the Maastrichtian–Paleocene (Figures 14, 18). However, except from the thick sandstone succession in the Slørebotn Subbasin, which was most likely supplied from smaller catchments farther south on the Møre coast (e.g., the Storfjorden, Nordfjorden, and Førdefjorden catchments) (Figures 1, 14), no other submarine fan systems have yet been discovered in the area (Vergara et al., 2001; Henriksen et al., 2005). During the Cenomanian–Campanian, prior to deposition of the Ormen Lange, only small, local slope systems, which were sourced from local highs, were deposited, reflecting modest onshore relief and an overall high relative sea level at the time (Swiecicki et al., 1998; Vergara et al., 2001; Martinsen et al., 2005; Smelror et al., 2007). Initiation of uplift in the latest Cretaceous thus had a double effect: (1) expanding and steepening old river systems, which became capable of delivering large amounts of coarse-grained material to the coast, and (2) widening the shelves by exposure of local highs and platform areas (Figure 18).

For the Ormen Lange system, the presence of the MTFC was critical in allowing sediments to be delivered from the rivers to the fan through a point source. Farther south and outside the fault complex, in the Slørebotn Subbasin, the bathymetry was more confined because of the presence of several local highs (Figure 2). In addition, these smaller systems did not have the same well-developed sediment conduit in the form of major faults and may have had to rely on smaller and less developed submarine canyons for delivering sediment to the basin (Figure 18). The result was an elongated, north-south–trending intraslope basin fed by a linear type source (Gjelberg et al., 2005).

To the north, the Sokna paleoriver system delivered sediment to the Trondheimsfjorden area (Sulebak, 2007) (Figures 1, 14, 18). This sediment was probably deposited northeast of the Frøya High, on the southern part of the Trøndelag Platform, where it would have had the potential to form a significant sand-rich depositional unit in this shallow platform area (Figure 18). Both lower (Danian) and upper (Thanetian) Paleocene prograding wedges have been recognized on the southeastern part of the Trøndelag Platform (Henriksen et al., 2005); these may represent shallow-marine and deltaic sediments delivered by the Sokna and smaller surrounding rivers. In other areas, the apparent lack of Paleocene reservoir sandstones probably relates to later Neogene uplift and erosion (e.g., Blystad et al., 1995; Vergara et al., 2001; Henriksen et al., 2005).

The abandonment of fan deposition in the latest Danian and the absence of significant sand-rich units immediately postdating the Ormen Lange Fan in the eastern Møre Basin are also somewhat interesting, as the late Paleocene is recognized as a period of increased clastic input and regional uplift in the North Sea region (Galloway et al., 1993; Liu et al., 1997; Brekke et al., 1999; Henriksen et al., 2005). In contrast to the Late Cretaceous, when the absence of fans can be related to the lack of onshore relief, the stagnation of fan deposition during the latest Danian must have been caused by changes in one or several forcing conditions that were responsible for delivering sediment to the basins. Farther south, deep-water depositional systems developed around the Sognefjorden area and in the Norwegian-Danish Basin during the late Paleocene–earliest Eocene (Martinsen et al., 1999; Martinsen et al., 2005), suggesting that this was also a period when rivers on the Norwegian mainland delivered relatively large amounts of sediment to the coast (Jordt et al., 1995; Swiecicki et al., 1998; Faleide et al., 2002).

This sudden abandonment of deep-marine fan deposition in the Møre area may relate to several regional and/or localized changes in the erosional-depositional system: (1) a relative sea level rise, which drowned the margin and flooded low-lying, coastal areas (Jordt et al., 1995; Faleide et al., 2002); (2) a major shift of depocenters caused by, e.g., tectonic activity along the MTFC and rerouting of the river system; or (3) climate change, which affected sediment productivity and delivery in the fluvial system (Huuse, 2002). The latter, however, is unlikely because the climate in the northern Atlantic was subtropical at the time and was getting continuously warmer and more humid until the Eocene (Jolley and Whitham, 2004). The most plausible explanation is that of regional subsidence associated with the transition from an active to a passive margin, causing a relative sea level rise in the coastal areas (Lien, 2005). Such regional drowning may have triggered sediment entrapment on the widening shelves or in smaller continental basins leading to channel avulsion and rerouting of the sediment fairway away from the Ormen Lange Fan. Because the rivers in the Ormen Lange area intersected and followed the relatively low topography of the MTFC, a regional transgression would have had the highest impact in these areas, explaining why deposition continued around the Sognefjorden area and in the Norwegian-Danish Sea. Subtle movement along the MTFC could have caused localized relative sea level rise and shifting of river courses and depocenters. However, the new source location and depocenter for the Ormen Lange system has not yet been discovered. During the early Eocene, regional transgression across the entire North Sea and Norwegian Sea caused most of the sandy deep-marine systems to be abandoned (Martinsen et al., 1999; Faleide et al., 2002; Henriksen et al., 2005) (Figure 3).

UNCERTAINTIES AND LOCAL BASIN VARIATIONS

The advantage of using submodern systems covering all scales of segment development, ranging from small systems, which can be considered as the embryonic stage of a source-to-sink system, to mature, passive margin systems, is that it permits the investigation of the special characteristics that are associated with each evolutionary step. However, this wide span also represents a disadvantage in terms of accuracy of segment parameter prediction. Because the data set covers several orders in magnitude in terms of catchment area, sediment supply, and slope lengths, for example, in addition to various degrees of local basinal characteristics, it is reasonable that the final predictions extracted from the data set also inherit the same uncertainty ranges. Therefore, the link between submodern and ancient systems primarily allows the extraction of first-order (basinwide) system characteristics (such as catchment area for the Ormen Lange system), whereas second-order characteristics (such as delineating between tectonic and eustatic variations in shelf width, etc.) are below the resolution of the data set.

As an example, slope length and gradient are considered proxies for the maturity of a source-to-sink system because they flatten and widen as the catchment expands and more sediment is being delivered to the marine environment. Small, tectonically active systems with catchments of 2–20 $\times$ 10^3 km^2 (0.8–7.7 $\times$ 10^3 mi^2) typically have slope lengths ranging from 10 to 30 km (6 to 18 mi); however, the modern Delgada system, which is located along the California borderland coast, has a slope width of about 65 km (~40 mi). Thus, the Delgada plots among the small active systems in terms of catchment area but has a slope length that is more similar to passive systems. This atypical slope width is related to the evolution of the Mendocino triple junction (Drake et al., 1989) and illustrates how relatively localized tectonics can influence segment parameters in a source-to-sink system.

However, the relatively wide parameter distribution observed in submodern systems is also expected in ancient systems, irrespective of type and age. The degree of uncertainty in submodern systems will therefore be included in the prediction of ancient system parameters. This provides a strong advantage when dealing with subsurface systems where many or most uncertainties related to local basin variations are below common data set resolution, and which would not be detected with conventional risk-evaluation techniques. When uncertainty ranges are estimated for a specific subsurface system as part of a risk analysis, these can partly be based on and correlated with empirical data from well-studied submodern systems.

Parameters from submodern source-to-sink systems can also be used to identify prospective areas and to increase the understanding of already well-established plays. At either of these stages in margin exploration, the information used to predict subsurface segment parameters will typically be derived from regional seismic surveys, which aim to capture the general architecture of the entire basin. During this process, systems having segments that are strongly controlled by local tectonics should therefore treated with special care because they have the potential to deviate from the main trend and may yield anomalous values.

SUMMARY AND CONCLUSIONS

Investigation of submodern source-to-sink systems shows that several morphological and sedimentological relationships exist within and between basin floor, slope, shelf, and catchment segments (Sømme et al., 2009). Because most of these relationships are considered to be time independent, they can therefore be used to predict first-order values on segment parameters in ancient, subsurface systems where data are missing and/or where more detailed insight into the morphology and the sediment transportation systems is desired. The example from the Paleocene Ormen Lange Fan, where known parameters for a basin-floor fan were used as input for the prediction of the remaining segment parameters, has shown the following.

- A catchment of approximately 22 $\times$ 10^3 km^2 (~8 $\times$ 10^3 mi^2), with minimum and maximum values of 1 and 560 × 10^3 km^2 (0.38 and 216 × 10^3 mi^2), has been estimated for the paleo–Ormen Lange system (Figures 9, 12). This estimate is in good agreement with onshore geomorphological remnants of ancient fluvial systems (Figures 10, 14) and provenance data from the fan.

- Such estimates will have implications for the sediment distribution system in poorly known depositional systems, allowing characteristics such as discharge ratio, as well as volume and lateral extent of potential reservoir bodies to be inferred. For the Ormen Lange system, it is, for example, suggested that the rivers had a peak/average water discharge ratio of 100–1000, which is indicative of the frequency-magnitude characteristics of the system, and thus the timing and mode of sediment delivery to the fan.
- Estimations can be made in terms of the number and configurations of catchments feeding a part of the coastline, which again has implication for the prospectivity and the location and spacing of sediment sources in the region. Along the Møre margin, catchments were relatively closely spaced (~40–80 km [~25–50 mi]), suggesting that several smaller catchments may have contributed sediments to the Ormen Lange Fan (Figure 14).
- Such estimates may also provide information on the paleotopography and bathymetry in a source-to-sink system, as the segments in nonglacial, siliciclastic margins with a distinct shelf-slope-basin floor configuration are generically related, so that the flattening and heightening of the catchment occur in concert with the flattening and deepening of the slope and basin floor as a system develops. For the Ormen Lange system, a catchment height of approximately 2500 m (~8202 ft) (ranging between 900 and 4200 m [2952 and 13,779 ft]) and water depths of about 1800 m (~5905 ft) (ranging between 600 and 3200 m [1968 and 10,498 ft]) are suggested for the Maastrichtian–Danian (Figure 17).
- The scale of the data set allows for first-order predictions but is below the resolution of local basin variations such as complicated tectonics and local climate variations; a good geological understanding of the basin will therefore significantly increase prediction accuracy and may help identify outliers that deviate from the main trends and that have to be treated with special care.
- Shelf morphology is conditioned to the prevailing eustatic sea level trend at the time of deposition; shelf widths and water depths at the shelf edge in ancient systems are therefore expected to be very different from those of the Pliocene–Holocene, which have experienced eustatic fluctuations that are unprecedented compared to the remaining Mesozoic and Cenozoic. Extrapolating Pliocene–Holocene shelf characteristics to ancient systems should therefore be done with caution.

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