# Deep-water sedimentary systems of Arctic and North Atlantic margins: An introduction

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The conference "Deep-water sedimentary systems of Arctic and North Atlantic margins" held in Stavanger, Norway from October 18th - 20th 2004 illustrated the wide temporal and spatial variability of Upper Mesozoic and Cenozoic deep-water sedimentary systems developed in this region. Particularly, Late Neogene high-latitude systems stand out as very different from pre-Neogene systems because of glacial control on sediment supply and source type. The high rates of sediment supply, steep slopes and deep basin bathymetries in these systems led to a dominance of slope instability with debris flows as depositional processes. Also, the onset of deep-water currents since the Miocene, as a response to deepening in the North Atlantic following sea-floor spreading, has played a major role in shaping systems. Pre-Neogene systems tend to be smaller and dominated by turbidity current deposits in contrast to younger systems. Evidence of continuous basinal and along-slope currents is rare, supporting the view that basins were shallower and smaller than in the Neogene.

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## Introduction

The conference "Deep-water sedimentary systems of Arctic and North Atlantic margins", organized by the Geological Society of Norway, was held in Stavanger from October 18-20, 2004. The aim of the conference was to illustrate how deep-water sedimentary systems vary spatially and temporally throughout the North Atlantic and Arctic regions and basins as a response to changing control mechanisms.

Fifty submitted papers (cf. Martinsen 2004), presented over three days and including 37 oral and 13 poster presentations (Fig. 1), showed a wide variability between Lower Triassic coarse-grained delta slope and canyon-related sediments in a rift setting in East Greenland (Surlyk & Noe-Nygaard 2004), to Recent deep-water instability and contourite deposits offshore western Ireland (e.g. Øvrebø et al. this volume). The papers covered all North Atlantic regions (Fig. 1; see Martinsen, 2004 and references therein) while the Arctic papers (Fig. 1) covered aspects of deep-water sedimentation on the North Slope of Alaska (e.g. Posamentier et al. 2004; Morris et al. 2004), and the large-scale fill of the Nansen and Amundsen sub-basins in the Eurasia Basin (Kristoffersen 2004). Overall, the conference provided the first overview of Mesozoic to Recent deep-water sedimentation in this vast deep-water region and illustrated successfully changes in space and over time.

Five full-length papers are included in this volume, of which four were presented at the conference and one is a later addition with relevance to the theme of the conference. The papers range from regional controls on Cretaceous turbidite systems in the Norwegian Sea (Lien this volume), to the development of various depositional systems of Neogene age both on the eastern and western side of the North Atlantic. Piper (this volume) describes the spatial development of Late Cenozoic deep-water systems of the continental margin of eastern Canada, while Øvrebø et al. (this volume) describe the temporal and spatial development of Late Quaternary slope sedimentation of the Rockall Trough. Laberg et al. (this volume) present sedimentation in a linked canyon and basin floor system offshore Andøya, north Norway, while Dahlgren & Lindberg (this volume) present Miocene and Pliocene cold-water coral reefs from deep-water areas in the Norwegian Sea.

A point of major importance that was well illustrated at the conference is the difference between particularly high-latitude, Late Neogene deep-water systems (see e.g. Prior this volume) and more typical submarine fan deposits (*sensu* Reading & Richards 1994) characteristic of lower-latitude Neogene margins and all margins in pre-Neogene time (Weaver et al. 2000; Martinsen et al. 2005; Lien this volume). The former characterize Pliocene-Pleistocene development on northern margins, while the latter are normally those sought for in hydrocarbon exploration. Large-scale controls changed substantially in the Late Paleogene-early Neogene, heralding the development of quite different

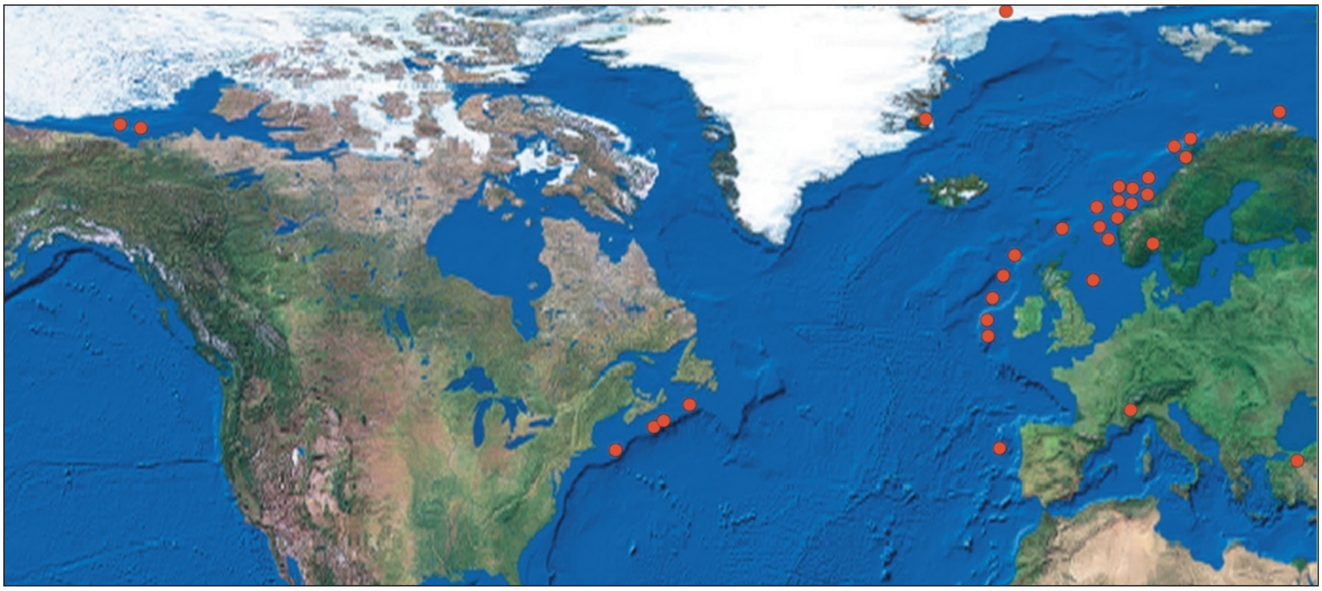

*Figure 1: Location of the study areas of the papers presented at the conference, covering both western and eastern North Atlantic margins, as well as examples of Arctic regions in Alaska and the Eurasia basin (see Martinsen 2004 for details).*

deep-water sedimentary systems and deposits in addition to classic submarine fans.

The aim of the present introductory paper is to review the control mechanisms of Mesozoic and Cenozoic deep-water sedimentation in the North Atlantic and Arctic deep-water regions. Papers presented at the conference exemplify these spatially and temporally variable controls. Where and to what extent glaciations played a vital role in determining the type of system developed is discussed, as well as the control exerted by temporal variability in tectonic influence as a response to North Atlantic rifting and subsequent sea-floor spreading.

## Controls on deep-water sedimentary system development - a North Atlantic and Arctic perspective

A number of factors control the resulting shape of deep-water sedimentary systems (Table 1), but there are some key controls that are more important than others in shaping the resulting North Atlantic and Arctic systems. To illustrate these differences, the systems are grouped into two general classes (Table 2): (i) Late Neogene high-latitude systems where the dominant control is glacial influence, and (ii) Neogene low-latitude and pre-Neogene systems where the dominant controls on their shape have been basin rugosity and processes related to rifting and subsequent sea-floor spreading. Weaver et al. (2000) have illustrated spatial variability in system morphology for Pleistocene and Holocene systems along the eastern North Atlantic margin, and Martinsen et al. (2005) showed variability between Late Jurassic to Paleogene systems in the North Sea and Norwegian Sea Basins. No authors have previously compared the late Neogene high-latitude systems and the Neogene low-latitude and pre-Neogene systems. This variability was captured to a large extent at the conference (see Martinsen 2004 and abstracts therein). The division is broad but captures the main differences in the nature of the sediment delivery systems, the depositional processes and basin tectonics (Table 2).

### *Deep-water sedimentary systems understanding: evolving models*

Over the last 35 years, our understanding of deep-water sedimentary system development has evolved from composite facies and depositional models (Mutti & Ricci Lucchi 1972; Normark 1978; Walker 1978) through an increasing understanding of the role of the hinterland and shallow-marine source system (e.g. Wetzel 1993; Reading & Richards 1994), to studies where controls along the entire depositional dip profile from source to sink are considered (e.g. Martinsen et al. 2005). There is an increasing consideration of extrinsic processes such as climate and tectonics on sediment delivery and basin physiography, bathymetry and accommodation in deep-water settings (Wetzel 1993; Reading & Richards 1994; Mienert & Weaver 2003; Martinsen et al. 2005). Nevertheless, the major controls change spatially and temporally as a response to changing tectonic regime, climate and eustatic sea level (Martinsen et al. 2003). The North Atlantic and Arctic regions are no exception (Weaver et al. 2000; Piper this volume). Two major processes, operating over widely variable time spans and with great differences in rates of influence, though sometimes in concert, are considered

Table 1. Forcing factors for deep-water sedimentary system development

| Major factor | Subordinate factors |
| --- | --- |
| Tectonics | Sediment supply/drainage system, basin relief, basin rugosity, slope gradients, accommodation, slope stability, shelf width |
| Climate/vegetation | Sediment supply/drainage system, glaciations |
| Sea level | Accommodation (particularly shelfal) |
| Oceanic currents | Internal waves, tides, along-slope currents |
| Gravitational processes | Flow mechanics, rheology |

to have a key impact on the development of deep-water sedimentary systems in the region:

- Opening of the North Atlantic ocean, from the Early Jurassic onwards, and related pre-drift extensional tectonics in peripheral basins
- Glaciations, at least from the Pliocene onwards

Of these two processes, the former is apparently the more important because of its long-term and widely variable effect over at least the last 150 million years (Færseth & Lien 2002; cf. review of Neogene effects by Stoker et al. 2005; Lundin & Doré 2005), but the latter is also extremely significant because of the huge sediment volumes that have accumulated in various deep-water basins (e.g. Sejrup et al. 1996). In the following, the local and regional effects of these inter-regional processes are discussed.

*Rifting and sea floor spreading: major controls on basin bathymetry and rugosity*

Initial seafloor spreading occurred in the central Atlantic in the earliest Jurassic and propagated northwards to reach the Labrador Sea by the Late Cretaceous and the Norwegian Sea at the Paleocene-Eocene transition (Ziegler 1988). Prior to sea-floor spreading in the Jurassic, the development of continental and marine rift basins caused the development of local differential bathymetry that led to (i) locally accumulations of salt, such as on the Scotian shelf (Hogg & Enachescu 2004), but (ii) even more importantly, to the formation of small, deep-water basins where small, sand-rich turbidite systems developed (Surlyk & Noe-Nygaard 2001; 2004). The salt on the Scotian shelf has been a key factor in localizing basin development and in controlling the structuring of overlying Cretaceous and Cenozoic stratigraphy (Hogg & Enachescu 2004).

In the Norwegian Sea basins and in the North Sea, extension and deep bathymetry developed in the latest Jurassic, set up a basin physiography of local half-grabens that persisted and deepened into the Early-early Late Cretaceous (Færseth & Lien 2002; Martinsen et al. 2005; Lien this volume). As renewed rifting commenced in the Campanian (Færseth & Lien 2002), a more complex basin bathymetry was created limiting the deposition of turbidites to areas closer to the source areas in contrast to Cenomanian-Santonian systems (Lien this volume).

From the Eocene, the structural template created by sea-floor spreading has been instrumental in controlling both the location and nature of deep-water sedimentary system development by (i) creating deep, abyssal plain areas, above oceanic crust, which ultimately became sinks for gravity-controlled flows (Stoker et al. 2005), (ii) by increasing the gradients through increased subsidence of already existing slopes inherited from the previous rift stage (Stoker et al. 2005), and thereby setting up a favourable regime for large submarine slides, and (iii) setting up a deep bathymetric template favourable for the formation of contour and along-slope currents, at least since the Miocene (Stoker et al. 2005).

The Iceland-Faroes volcanic ridge, considered to be a failed arm of North Atlantic rifting (Lundin & Doré 2005), probably cooled and subsided to abyssal depths by the Late Eocene, therefore allowing deep-water circulation between the central and northern parts of the North Atlantic (e.g. Stoker et al. 2005). In addition, the closing of the Panama seaway was probably also instrumental in allowing deep-water circulation in the North Atlantic in the Neogene (Stoker et al. 2005 and references therein).

*Neogene glaciations*

Climatic deterioration from the Middle Miocene probably brought about northern hemispheric glaciations, at least from the Middle Pliocene (Eidvin et al. 2000), and had two major effects on the development of North Atlantic and Arctic deep-water sedimentation:

- Bottom current enhancement, causing further reshaping and moving of previously deposited sediments in the form of contourite drifts (these currents initially started due to the deep bathymetry formed by sea-floor spreading - see above).
- High-latitude glaciated margins received sediments at a greatly increased rate and over wide areas. This changed deposition in deep-water areas dramatically.

While deposits from continuous, along-slope, deep-water currents are common in the Neogene record, they are rare in pre-Neogene deposits. In the northern North Atlantic, contour drifts are common in Miocene and younger deposits, and in many places are the rule rather than the exception (Stoker et al. 2005; Øvrebø et al. this volume).

Because of the obvious erosive capability of glaciers and their wide lateral extent, glacially controlled deep-water sedimentary systems receive sediments over wide areas. A prime example is the Upper Pliocene sedimen-

Table 2. Some key characteristics of deep-water sedimentary systems in Arctic and North Atlantic areas

| **Characteristics** | **Neogene high-latitude systems** | **Neogene low-latitude and pre-Neogene systems** | **Example references** |
|---|---|---|---|
| Basin rugosity | Relatively little local rugosity but larger water depths due to sea floor spreading | Initial local rift-related bathymetry that was filled and onlapped. Basin rugosity increased during late Cretaceous rifting | Piper (this volume); Lien (this volume) |
| Tectonic influence | Long wavelength margin uplift and tilting. Sea floor spreading causes deep bathymetries | Initial local rifting followed by basin wide subsidence and renewed rifting | Farseth & Lien (2002); Stoker et al. (2005) |
| Dominant stratigraphic style | Margin progradation | Onlap of structural highs | Sejrup et al. (1996); Stoker et al. 2005; Martinsen et al. (2005); Piper (this volume) |
| Glacial influence | Yes | No | Piper (this volume); Weaver et al. 2000; Martinsen et al. (2005) |
| Drainage area and source characteristics | Very large with line source | Small to large with point sources | Sejrup et al. (1996); Mienert & Weaver (2003); Martinsen et al. (2005) |
| Shelf width | 10's to 100's of kilometres | 10's to 100's of kilometres | Piper (this volume); Weaver et al. 2000; Martinsen et al. (2005) |
| Sedimentation rate | Very high periodically | Low to medium | Sejrup et al. (1996); Mienert & Weaver (2003); Martinsen et al. (2005) |
| Slope gradient | High | Low to high | Piper (this volume); Øvrebø et al. (this volume); Martinsen et al. (2005) |
| Slope deformation | High | Low to high | Piper (this volume); Martinsen et al. (2005) |
| System elements | Closely spaced canyons and gullies, debris flow lobes, channels, contourite drifts | Single canyons, lobes, channel-levee systems, classic fan shapes | Laberg this volume; Piper this volume; Øvrebø et al. this volume; Martinsen et al. 2005 |
| System size | Large (~up to 1000's of square kilometres) | Relatively small to medium (~100's of square kilometres) | Piper (this volume); Martinsen et al. (2005); Lien (this volume); Laberg (this volume); Øvrebø et al. (this volume) |
| Processes | Debris flows and large slides dominate, but influence from turbidity currents. Along-slope currents/contour currents dominate in areas | Turbidity currents dominate pre-Neogene systems. Sliding is common in Neogene low-latitude systems | Stoker (1998); Piper (this volume); Martinsen et al. (2005); Lien (this volume); Laberg (this volume); Øvrebø et al. (this volume) |

tary wedge that envelops most of offshore Norway (Henriksen & Weimer 1996; Martinsen et al. 1999). Therefore, glacially controlled deep-water systems will differ in processes and plan-view shape from non-glacial systems, which often tend to be controlled by point sources (Wetzel 1993; Reading & Richards 1994).

Climatic changes cause significant changes in ice volume and extent on glacial margins (e.g. Mienert & Weaver 2003 and references therein). In cold periods, glaciers in some areas extended across continental shelves to shelf breaks, thus delivering enormous volumes of sediment to deep-water areas over short periods of time (Sejrup et al. 1996). In these periods, canyons and gullies on slopes were incised, and sliding was very common (Weaver et al. 2000; Piper this volume). Conversely, in warm periods, glaciers may only have existed in polar areas, such as at present, so that the same deep-water areas became inactive or other processes such as along-slope currents dominated (e.g. Weaver et al. 2000).

*Processes and systems: Temporally and spatially variable on North Atlantic and Arctic margins*

It is challenging to draw up general rules for the development of deep-water sedimentary systems in Arctic and North Atlantic basins. Spatial and temporal variability is high, but it is important to recognize local variability in the nature of the source, the shelf characteristics and configuration of the receiving basin. Table 2 summarizes semi-quantitatively some key characteristics of the two classes of deep-water sedimentary systems identified (see discussion above). The systems are in some respects intergradational, but are time- and latitude-dependent, as discussed by Weaver et al. (2000). However, the glacial control, which has been dominant in high-latitude systems from Late Pliocene at least, provided a major shift in the nature of feeder systems and in a much increased rate of sediment supply (Weaver et al. 2000; Mienert & Weaver 2003 and references therein) and, consequently, in slope steepness and processes. The pre-Neogene systems, in contrast, were generally subject to supply from smaller source areas and into smaller basins (Martinsen et al. 2005), although exceptions occur particularly for the Late Cretaceous systems of the Norwegian Sea (cf. Lien this volume), but with no glacial control. Future work needs to address these differences more clearly, but the conference abstracts (Martinsen 2004) and the papers included in this volume demonstrate this variability.

Even if analogues to high-latitude Neogene systems existed in the stratigraphic record in basins with petroleum potential, many would be unattractive as exploration targets due to the dominance of mass movement deposits such as debrites. This and the common lack of a clear differentiation of clean, sand-bearing elements such as channels and lobes would make accumulation of hydrocarbons in large, producible volumes unlikely.

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