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Impact of glaciations on basin evolution: data and models from the Norwegian margin and adjacent areas—Introduction and summary

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1. Background

The present publication arose from a workshop held at the Glacier Museum in Fjærland on the west coast of Norway during May 30 to June 2, 1994, as a part of the European program "Late Cenozoic Evolution of the Polar North Atlantic Margins" (PONAM). PONAM was initiated in 1989, and approximately 70 scientists from seven European countries have been active in the program. The basic theme has been climatic changes during the last 5 million years on the margins at both sides of the Norwegian–Greenland Sea, the East Greenland Margin and the Svalbard–Barents Sea margin. As part of PONAM, a sub-project, "The Svalbard Traverse; effects of interglacial–glacial variations", was organized particularly to study the effects of glaciations on the sedimentary regime in the Barents Sea and the Svalbard margin.

The theme of the workshop in 1994 was "Glacial Cycles—Effects on the Physical Environment", and the idea was to bring scientists from both the glacial geological community and the petroleum industry together, in order to discuss effects of glacial cycles with particular reference to basin evolution and petroleum potential. Most of the contributions to this publication were presented orally or as posters during the workshop.

2. The Barents Sea experience

The exploration drilling for hydrocarbons in the Barents Sea and the Mid-Norwegian shelf, which was initiated in the early 1980s resulted in major oil and gas discoveries in Mesozoic structural traps located below the Neogene wedges of the Mid Norwegian shelf. In contrast, the Barents Sea shelf, where Cenozoic erosion prevailed, has yielded only gas discoveries. As a rule, structural traps in this area show evidence of late spillage and leakage of hydrocarbons. The amount of Cenozoic erosion of the Barents Sea and its impact on preservation of hydrocarbons in structural traps have therefore been a topic of discussion in the oil industry for more than ten years (Nyland et al., 1992).

While early stages of the debate mostly were concerned with an erosion that was assumed to predate the glacial period, Eidvin and Riis (1989) suggested that a surprisingly large part (> 50%) of the sedimentary wedge on the southwestern margin

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of the Barents Sea was of Plio-Pleistocene age and had a glacial origin. The ages proposed by Eidvin and Riis (1989), which were later supported by Eidvin et al. (1993), Mørk and Duncan (1993) and Sættem et al. (1994), combined with simple mass balance calculations, indicated that several hundred meters of sedimentary rocks were eroded from the Barents Sea, transported to the shelf edge and redeposited as large clastic wedges during the last 2.5 million years. Parallel to this, there was a growing general acknowledgement in the exploration industry that glaciers and glacial erosion have a major impact on the evolution of sedimentary basins.

On the other hand, the glacial history of Svalbard and the Barents Sea had been an important issue for glacial geologists for a number of years. The new results caused explorationists and Quaternary geologists to join efforts to study and quantify the processes which affected the Barents Sea and Mid-Norwegian shelves during the period of major glaciations. Large amounts of seismic and well data were made available for this research. Basin modelling techniques were applied on glacial depositional systems, and this also added a new dimension to the study of glacial margins.

The papers presented in this publication focus on the different lines of research which have been integrated to study the impact of glaciations, and to a large extent, the present state of knowledge is summarized. The Barents Sea–Svalbard region is used as a case study where different methods are applied. New data and models are presented concerning the *recent glaciations, the Plio-Pleistocene depocenters* and the *eroded shelves*. The quantification of glacial erosion based on regional studies can be compared with studies *of processes and mechanisms of glacial erosion*. Possible consequences *for subsurface fluid motion and basin modelling in general* are discussed in the last set of papers. We are convinced that the results derived from the studies presented here will be important for the study of other glaciated shelves, where less data may be available.

3. Timing of glacial events, erosional and sedimentary cycles

A good age control is a prerequisite for correlations and for the calculation of rates of erosion and deposition. Despite the extensive amount of seismic data along the margins of the Barents Sea and Svalbard, chronostratigraphic control is still a problem, and age estimates for the major fans along the continental margin are discussed in several of the papers e.g. in *Faleide et al.* and *Kuvaas and Kristoffersen*. The combination of biostratigraphy and radiometric dates from deep wells and shallow borings on the Senja Ridge (Eidvin et al., 1993) and west of Bjørnøya (Mørk and Duncan, 1993; Sættem et al., 1994), respectively, indicate that the base of the glacial part of the fans can be dated to 2.3–2.6 Ma. Downlap of fan sequences on Plio-Pleistocene oceanic crust (*Fiedler and Faleide*; *Faleide et al.*) give a maximum age of 5 Ma, but *Faleide et al.* argue that this is probably too old. Based on paleoclimatic data from the Vøring Plateau, *Mangerud et al.* estimate the onset of the major glaciations of Scandinavia and the Barents Sea–Svalbard area to 2.5–2.8 Ma. Hence, an age range of 2.3–2.8 Ma for the base of the glacial fan deposits seems to be accepted by all the contributors discussing the Barents Sea, although *Laberg and Vorren* note that this age can be debated. *Faleide et al.*, on the other hand, do not exclude the possibility of glacially affected sediments, derived from smaller, more local glaciations, also below their deepest glacial reflector. This is in accordance with a significantly earlier onset of ice rafting in the Norwegian–Greenland Sea, as evidenced by recent drilling (ODP Leg 151 Shipboard Scientific Party, 1994).

Mangerud et al., in their regional review of the glacial history of northwestern Europe, put the age estimates into the context of global climatic change. As noted by Eidvin et al. (1993), there is a correlation between the onset of sedimentation in the fans off the Barents Sea shelf and the global cooling and increase in ice volumes at 3–2.5 Ma. *Mangerud et al.* point to the mid-Pleistocene climatic shift which is recorded at 1.2–0.8 Ma, involving a change in the cyclicity of the climatic variations. This is documented in records of ice-rafted detritus (IRD) from the Norwegian Sea (Jansen et al., 1988; Jansen and Sjøholm, 1991) as well as in global oxygen isotope records (Shackleton et al., 1984; Raymo et al., 1989; Ruddiman et al., 1989). *Mangerud et al.* place this transition at 0.9 Ma in the present paper. Between 2.8 and 0.9 Ma, ice volumes changed predominantly in 41 k.y. cycles, while later the 100 k.y. cycles were predominant. *Mangerud et al.* suggest that as a consequence, one should expect the ice sheets to be centred at higher latitudes prior to 0.9 Ma than afterwards. An important part of the erosion from the Barents Sea could therefore have taken place at 2.8–0.9 Ma.

Although the age of the onset of fan deposition seems to be relatively well defined, chronostratigraphic control of the internal sequence boundaries of the Plio-Pleistocene fans is scarce. *Faleide et al.* describe a regional seismic stratigraphy and interpret the main sequence boundaries of the major Bjørnøya, Storfjorden and Svalbard fans (Fig. 1). A significant sequence boundary within the fans is correlated with the mid-Pleistocene climate shift, which *Faleide et al.* tentatively place midway in the transitional period, at approximately 1.0 Ma. Based on correlation to a shallow borehole (Sættem et al., 1992), *Faleide et al.* estimate the uppermost main sequence boundary is to be younger than 440 ka. The more detailed studies by *Fiedler and Faleide* (Bjørnøya fan), *Hjelstuen et al.* (Storfjorden fan) and *Solheim et al.* (western Svalbard margin) (Fig. 1) indicate that the highest sedimentation rates took place at 1.0–0.44 Ma, and that the northernmost fans are slightly older than the Bjørnøya fan. According to *Laberg and Vorren* the main depositional/erosional phase took place prior to 1.0–0.6 Ma, and glaciofluvial processes may have been significant at this stage.

Solheim et al. interpret the seismic stratigraphy of the central western Svalbard continental margin,

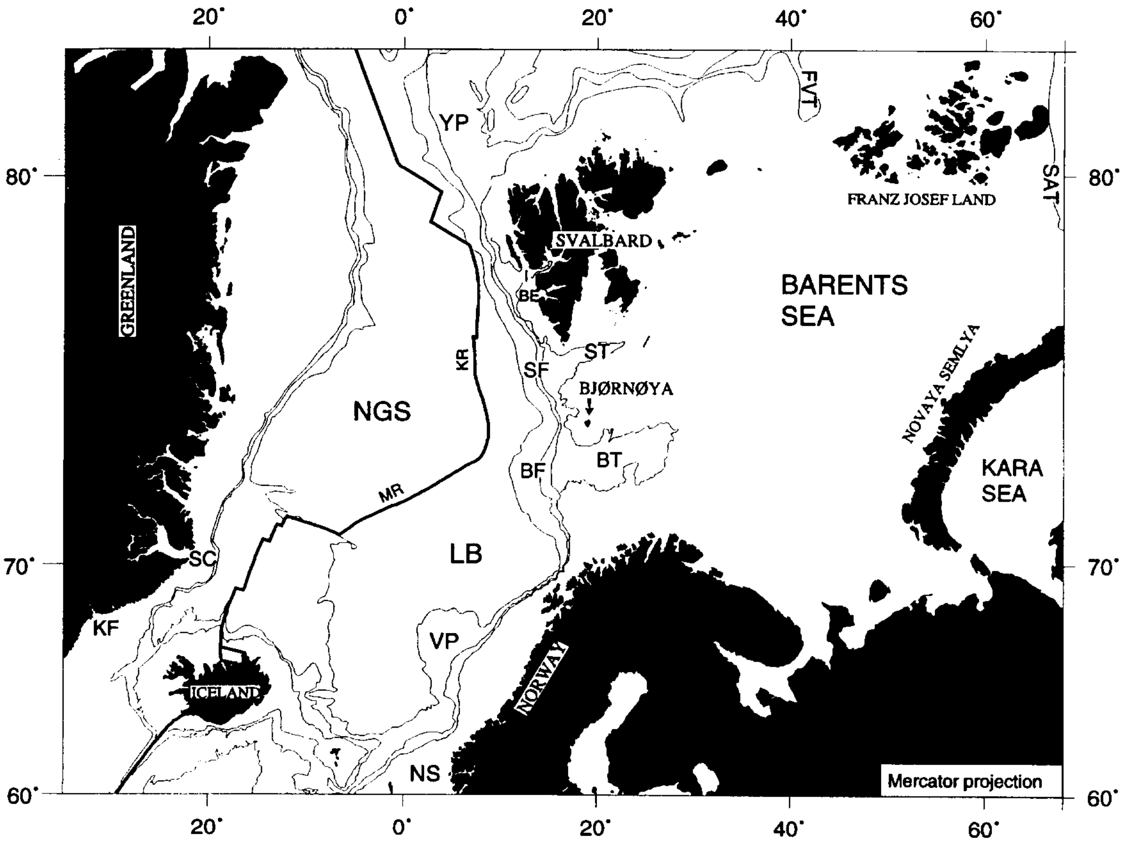

Fig. 1. Map of the area covered by the contributions presented in this volume. *BE* = Bellsund, *BF* = Bjørnøya (Bear Island) Fan, *BT* = Bjørnøya Trough, *FVT* = Franz Viktoria Trough, *I* = Isfjorden, *KF* = Kanguerlussuaq Fjord, *KR* = Knipovich Ridge, *LB* = Lofoten Basin, *MR* = Mohns Ridge, *NGS* = Norwegian–Greenland Sea, *NS* = North Sea, *SAT* = St.Anna Trough, *SC* = Scoresby Sund, *SF* = Storfjorden Fan, *ST* = Storfjorden Trough, *VP* = Vøring Plateau, *YP* = Yermak Plateau.

based on single channel high resolution data. The upper parts of the glacial section are interpreted in detail. Significant changes in the erosional and depositional patterns of the outer shelf may be related to changes in the glacial dynamical conditions as well as the subsidence history. At least 15 glacial advances are interpreted to post-date the proposed 1.0 Ma sequence boundary of *Faleide et al.*, which seems to represent a major change in glacial regime and style of deposition. This detailed stratigraphy cannot be linked to absolute dates with the presently available chronostratigraphic information.

Although some age information exists that can be used to date the seismic stratigraphy, there is clearly a need for better age constraints in order to quantify the change in rates of deposition and erosion, and to study the relations to climatic change, in particular to the mid-Pleistocene climate shift discussed by *Mangerud et al.*

4. Glacial history of the Barents Sea / Svalbard from field evidence and models

The results of *Faleide et al.*, *Fiedler and Faleide*, and *Hjelstuen et al.* indicate that Plio-Pleistocene sediment thicknesses in the major fans outside the Bjørnøya- and Storfjorden Troughs exceed 4 km. The Bjørnøya Fan contains sediment volumes comparable to the Amazon- and Mississippi Fans, although the drainage areas of the two latter fans are 5–10 times greater than that of the Bjørnøya Fan. Estimated glacial erosion varies from approximately 500 m in the southwestern part of the Barents Sea, to more than 1500 m in the northwest.

Fiedler and Faleide and *Hjelstuen et al.* calculate average Plio-Pleistocene depositional rates ranging from 0.25 to 1.8 m/k.y., based on the stratigraphic framework of *Faleide et al.* Their mass balance calculations indicate corresponding average rates of erosion of the Barents Sea shelf of between 0.1 and 1.1 m/k.y. The main uncertainty in all calculated rates from this area relates to the lack of age control discussed above. Estimating the drainage areas and their variation through time, however, forms another significant problem in the calculation of erosion rates.

Knutsen and Larsen present data from the northernmost exploration well in the Barents Sea. Core lithology and high resolution seismic data from the cored interval, provide indications for possible glaciations in adjacent areas. However, no absolute diagnostic evidence for large scale Pliocene glaciation of the western Barents Sea is found in the data.

The last glacial period, the Weichselian, is the best known, and can be used to "calibrate" interpretation of more scarce or indirect evidence for glacial fluctuations further back in time. Important questions are whether the Late Weichselian glaciation did erode and transport sediments in amounts comparable with the rates deduced for the last approximately 2.5 Ma, and whether the volume and extent of the last ice sheet can be compared with previous glaciations.

The distribution of the Late Weichselian glaciation (maximum at 18–20 ka) has been an issue of debate, with views ranging from a major, thick ice sheet covering the entire Barents Sea, Svalbard and the Kara Sea, to no ice at all. There is still a debate on the exact timing, extent and thickness of the Late Weichselian Barents Sea ice sheet. *Lambeck* summarizes the debate and concludes that most indications and views point to a Barents Sea region which was covered by grounded ice out to the shelf edge. This is supported by modelling results in which Lambeck uses a glacio-isostatic rebound model to reconstruct the maximum ice extent and the deglaciation pattern of the Late Weichselian Barents Sea ice sheet, based on known shoreline displacement curves from the land areas and islands surrounding the Barents Sea.

Siegert and Dowdeswell use a glaciological ice sheet model in order to identify the dynamic evolution of ice sheets from different bedrock topographic conditions; a pre-Quaternary subaerial topography (low-land except for Svalbard) and the largely submarine morphology of the present day. They note that under subaerial conditions, formation of ice streams and deepening of the troughs were essential to maintain the ice velocities and erosional capabilities needed to form the large sediment fans along the margin.

Rasmussen and Fjeldskaar use an isostatic model and input data on the sediment volumes of the Cenozoic depocenters, as well as present day topography to calculate the pre-glacial topography and thus estimate the amounts of erosion in the Barents Sea. Their results appear to be in good agreement with calculated sediment volumes in the fans along the western and northern margins of the Barents Sea presented by *Faleide et al.*, *Fiedler and Faleide*, *Hjelstuen et al.* and *Vågnes*. *Rasmussen and Fjeldskaar* conclude that the northwestern part of the Barents Sea was elevated to 500–1500 m prior to the main glaciation.

Thus, the models indicate that the Late Weichselian ice sheet indeed covered large areas in the Barents Sea, but that it may not have been representative of the whole period of late Cenozoic glaciations because the topography has been lowered. The pre-glacial and early glacial topography remains an important, but not well constrained, parameter. The present topography of Spitsbergen suggests a major uplift of a surface where Neogene lavas were deposited. Better age constraints on the Neogene lavas could possibly constrain the timing of uplift of the pre-glacial surface in the north-western Barents Sea (Prestvik, 1978; Hjelle and Lauritzen, 1982; B.L. Skjelkvåle, pers. comm., 1992, in Vågnes and Amundsen, 1993).

The northern Barents Sea margin represents an important "unknown" in the total evaluation of the Tertiary evolution of the Barents Sea region. Mainly because much of this area is usually accessible only to ice breakers, this part of the margin has a very sparse coverage of seismic and core data. In particular this is the case for the northeastern areas, where main drainage of ice and sediment to the Arctic Ocean probably follow the Franz Viktoria and St. Anna Troughs (Fig. 1), as well as the Voronin Trough even further to the east. In an attempt to estimate sediment volumes adjacent to these troughs, *Vågnes* uses the present-day bathymetry of the Nansen Basin in isostatic modelling of the sediment thickness outside the St. Anna and Voronin Troughs. The conclusion is that these sediment wedges are comparable in size to the fans off the Bjørnøya and Storfjorden Troughs. This shows the need for more data from this region to discuss fully the Late Cenozoic evolution of the Barents Sea and adjacent areas.

In addition to the Barents Sea case studies, two contributions deal with the uplift history and depositional regime off Mid Norway. In this region, Plio-Pleistocene fans were deposited on the shelf, while the deeply eroded area is located along the coast and onshore in the uplifted Scandinavia. *Henriksen and Vorren* present a detailed seismic stratigraphy for the Late Cenozoic of the mid Norwegian continental shelf. Based on seismic stratigraphy combined with well data, these authors relate changes in the depositional regime to significant events in the glacial history of the continental shelf as well as the Late Cenozoic uplift history for Fennoscandia. *Reemst et al.* focus on a pronounced inversion of the seismic velocities found at the base of the Plio-Pleistocene sedimentary wedge. They relate this inversion to the effect of rapid, glacially influenced deposition and overpressuring of the underlying sediments.

5. Glacial sedimentary processes

One important aspect of bringing together people from industry and the glacial geological community, has been to include realistic glacial sedimentary processes in the often large scale models of glacial impact on the offshore regions. On the other hand, the regional settings derived from seismic interpretation represent new boundary conditions for the glacial geologists. It is a challenge to match the rates of deposition along the Barents Sea margin, estimated from seismic studies, with rates derived from studies of glacial processes. A wide range of processes and environments have influenced the sediments which were deposited in the offshore sedimentary basins and in the deep sea. Glaciers erode the substratum in a number of different ways, move and redeposit sediments in many steps before they may reach the continental margin.

Hallet et al. review data on glacial erosion rates and modes of sediment evacuation by glaciers. They compare regions of different glacial and tectonic regime and discuss changes in erosional rates and isostatic uplift as a function of climatic change. Measured rates of erosion by glaciers vary by more than two orders of magnitude, and the high rates observed in Alaska exceed the calculated maximum average rates from the Barents Sea with one order of magnitude.

Hooke and Elverhøi use Holocene sedimentation rates in Isfjorden, Svalbard, combined with accumulated sediment volumes on the continental margin, to discuss rates and modes of erosion and sediment evacuation from this high arctic fjord and its drainage basin. They conclude that sediment evacuation by subglacial till deformation played a major role. The basic idea that sediments released in fjords are effectively trapped in the fjord basin until other mechanisms, such as glacial evacuation, remobilize them, is further discussed by *Syvitski et al.*, from a fjord in East Greenland. These authors investigate depositional processes and calculate sedimentation rates along the fjord and find at least one order of magnitude difference between sedimentation rates of the inner shelf and the average rates for the fjord.

During large scale glaciations, when marine based ice sheets cover the continental shelf areas, dynamic processes at or near the base of the glaciers may greatly alter the deposits of the continental shelf. Glacitectonic processes can have an important impact on both older glacial deposits and preglacial sediments of the continental shelf. Sættem (1991) showed how glaciotectonism may enhance glacial erosion through a process where large bodies of underlying pre-glacial bedrock can be moved relatively undisturbed by glacial advances, before they are further disintegrated and incorporated in subglacial till. Glaciotectonism may be enhanced by permeable lithologies and fluid overpressure (Sættem, 1994). Such observations are important to constrain models of fluid flow below the glaciers, as discussed in the papers by *Boulton et al.* and *Forsberg*.

The continental shelf areas along Norway and in the Barents Sea have been repeatedly glaciated. In response to climatic conditions and the uplift and erosion history, the ice sheets may have had different dynamic characteristics. In particular the temperature regime may have changed, causing major differences in the impact on the substratum. *Sættem et al.* discuss well expressed changes in geotechnical properties of glacial sediments on the mid Norwegian shelf, and relate the variations in consolidation to effects of changes between frozen and pressure melting bed conditions of grounded glaciers. Such field evidence is of interest for basin modelling purposes since it is of importance to know whether the base of the glacier was frozen or at pressure melting conditions. Given pressure melting conditions, hydrostatic pressures will prevail, while overpressures could build up below a permanently frozen bed.

Sediments eroded and transported from the continental and marine based ice sheets of Fennoscandia and the Barents Sea, respectively, have mainly been transported to the major depocenters where they form large submarine fans along the continental margin. The contributions by *Kuvaas and Kristoffersen* and *Laberg and Vorren* discuss gravity driven sedimentary processes in the Bjørnøya Fan (Fig. 1), which forms the largest of these depocenters. Based on conventional multichannel seismic records, *Kuvaas and Kristoffersen* identify numerous slide and slump features, often bounded by listric faults, in the lower part of the glacial section of the Bjørnøya Fan. The mass movements, which are considered to have taken place in five stages prior to 0.5 Ma, are thought to result from glacial advances causing high sediment input and slope oversteepening. Based on single channel sparker records, *Laberg and Vorren* discuss mass movements at a smaller scale in the upper part of the Bjørnøya Fan. They map series of extensive debris flows and relate these to glacial advances to the shelf break, also with high sediment input and slope oversteepening as the main cause for the mass movements. These, however, apparently took place at different scales and different modes than in the slope failures described by *Kuvaas and Kristoffersen.*

6. Consequences for basin and crustal modelling, and the regional hydrocarbon prospectivity

The glacial loading and rebound effects from the last glaciation are discussed by *Lambeck* for the Barents Sea region. It is more difficult, however, to investigate whether repeated glaciations can cause more permanent crustal movements. The papers of *Riis* and *Stuevold and Eldholm* provide geological input to the crustal modelling by discussing the large scale uplift and erosion history of Scandinavia since the Cretaceous. The present elevation of Scandinavia can be explained by at least two separate phases of uplift in the Paleogene and the Neogene.

Riis discusses the pre-glacial morphology, the "paleic surface", which is related to Cambrian and Mesozoic peneplanation and Early Tertiary uplift. He concludes that the Early Tertiary relief was rejuvenated in the Neogene, mainly in the Plio-Pleistocene, when localized uplift in the order of 1000 m took place in South Norway, Lofoten and Svalbard. Uplift of southern Norway is related to the Mid Miocene and Base Pleistocene unconformities. The uplift is described as a tectonic event.

Stuevold and Eldholm suggest that the Neogene uplift phase was initiated in the Oligocene, but do not have precise age estimates. They estimate maximum uplift in the order of 1 km, which primarily took place during the Neogene, amplified by glacio-isostatic effects in the Plio-Pleistocene. Possible causal relationships between the uplift history and the paleoclimatic evolution are also discussed. In addition to glacio-isostatic effects, the Plio-Pleistocene glaciations had a major impact on the depositional regime along the margin, as also discussed in several other contributions to this publication.

A geological understanding and exact timing of the Neogene uplift is important for crustal modelling. Detailed age information and structural reconstruction of the Miocene, Pliocene and Pleistocene sequences along the coast seem to be the best way of refining the geological models. In addition, use of Apatite fission track (AFT) analyses, place new constraints on estimates of uplift and erosion (Cloetingh and Kooi, 1992; Rohrman et al., in press.)

The increasing body of information on glacial geological processes and Late Cenozoic climatic and tectonic evolution can be used as boundary conditions in modelling studies of direct glacial impact on the evolution of sedimentary basins and their petroleum reservoirs. The contribution by *Doré and Jensen* provides some of the reasons for the relatively recent increase in interest from the petroleum industry in glacial geology. *Doré and Jensen* focus on the uplift and erosion of parts of the Norwegian continental shelf, now interpreted to be intimately associated with the Late Cenozoic glaciations. The paper reviews the implications for petroleum exploration and note that positive as well as negative effects can result from uplift and erosion. *Doré and Jensen* point out that many known petroleum basins have been recently uplifted, and suggest that these could be useful analogues in further exploration of the Norwegian continental shelf.

Johansen et al. model the temperature distribution in the basin below a glacier, and conclude that subsurface temperatures can be significantly affected by cold-based glaciers with permafrost conditions, relative to temperate glaciers or the non-glaciated situation. Løvø et al. (1990) discussed the possibility of permafrost in the Barents Sea, and conclude that this is not likely for the last glaciation. However, the conditions may have been quite different in earlier periods of glaciation, when the Barents Sea at some point most likely was a subaerial platform. The same may be said about the North Sea, which is used as a test case by *Johansen et al.*

One aspect of glacial influence on sedimentary basins which cannot be readily measured is the effect on subsurface fluid flow. Quantification of the fluid flow is important in basin modelling efforts. *Forsberg* discusses groundwater flow beneath a theoretical glacier assumed to be representative of the Weichselian glaciations of the Barents Sea. Groundwater drainage is modelled under different geological and glaciological conditions. The ground water flow through a Jurassic sandstone acquifer may have affected the distribution of oil and gas contacts and caused spillage of hydrocarbons in the traps in the study area. *Boulton et al.* model groundwater flow under the Saalian and Weichselian glaciations over northwestern Europe. Field data from the present day are used as input parameters to this large scale (continent-wide) modelling. The model predicts large changes from the modern values, and effects on the geological environment are discussed. The authors claim that their model also can be readily applied to hydrocarbon reservoirs.

7. Conclusions

This publication presents data compilations and interpretations which, as a whole, is unique for glacial continental margins. In an integrated approach glaciologists, Quaternary geologists, geophysicists and petroleum geologists have joined forces to obtain the best possible understanding of this dynamic environment. The depositional history of the margin is placed in a paleoclimatic framework, and a complete, although coarse mass balance is documented for the Barents Sea and Svalbard margin, in which all the main depocenters are included. A discussion of processes responsible for the erosion and deposition, including crustal movements, as well as implications for basin evolution and petroleum prospectivity, are also parts of the effort. This study should also have several implications of interest for other regions characterized by rapid uplift and erosion.

The main conclusions can be summarized as follows:

- Scandinavia was close to sea level in the Cretaceous and was uplifted in two phases, in the Paleogene and in the Neogene.
- Prior to the glaciations, the northwestern part of the Barents Sea was a subaerial platform and the central parts were probably close to sea level. Although glacial erosion has played the major role in lowering the topography, significant erosion took place also prior to the glaciations. Intermittent depocenters may have existed in central parts of the Barents Sea.
- The glacial erosion of the Barents Sea shelf during the last approximately 2.5 m.y. seems to increase from an average of approximately 500 m in the south to 1500 m in the northwest. Average erosional rates of the sedimentary bedrock of the Barents Sea calculated for this time interval are between 0.2 and 0.6 m/k.y. As a result, the region was lowered from a subaerial platform to an epicontinental sea.
- The major shelf troughs have been occupied by ice streams which fed large submarine fans off the shelf edge. The deposition in the fans was mainly controlled by glacial advances.
- During interglacials and interstadials, sediments were deposited in fjord and shelf basins, before they were removed and redeposited by subsequent ice advances.
- The global mid-Pleistocene climatic shift to longer and more severe glacial periods of 100 k.y. cyclicity, centered at approximately 1.0 Ma, most likely had an important impact on the distribution and dynamics of glaciers, and therefore on the depositional regime along the margin. However, the age control is still unsufficient to verify this.
- Glaciers can affect generation, migration and trapping of hydrocarbons by speeding up erosional and depositional processes, by tilting of traps and by altering the hydrodynamic conditions of the basin.
- Abnormal pressures and temperatures can be created within the reservoirs in cases of subglacial permafrost.
- Glacial continental margins are highly dynamic depositional regimes. Three advances beyond the coast of western Svalbard are documented during the last 120 k.y., and at least 15 advances are estimated for the last 1 m.y. The time during which the ice sheet holds its maximum thickness and extent (e.g. the shelf edge) is short compared to the total length of the glacial–interglacial cycle.

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