Middle Miocene ice sheet expansion in the Arctic: Views from the Barents Sea

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Revised core data from Ocean Drilling Program (ODP Leg 151, Hole 909C) and preglacial paleorelief and bathymetric reconstructions in the Barents Sea and the Arctic gateway region indicate that large-scale glaciations were already developed in the northern Barents Sea during the Middle Miocene Climate Transition (MMCT), ~15–14 million years ago. Our findings show that subsequent to an ice-free period during the Miocene Climate Optimum (MCO, ~17–15 Ma), glacially eroded materials from the uplifted northern Barents Sea were transported by iceberg flotillas toward the Fram Strait. The simultaneous opening of the North Atlantic–Arctic gateway provided pathways for iceberg transport from the north. The expansive ice growth is probably induced by both large-scale changes in ocean circulation due to enhanced flow of Atlantic water into the Arctic Ocean during opening of the gateway and concurrent global cooling during the MMCT.

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1. Introduction

Causes for intensive glaciations at the Earth’s poles during the Cenozoic are linked to opening of the polar gateways, namely the Fram Strait in the north and the Drake and Tasmanian passages in the south [Zachos et al., 2001]. The opening of the Drake Passage completed the oceanographic isolation of Antarctica. In conjunction with decreasing atmospheric carbon dioxide levels, opening and successive deepening of the Drake Passage possibly lead to the beginning of massive Antarctic glaciation ~34 Ma ago [e.g., Shackleton and Kennett, 1975; Kennett, 1977; Zachos et al., 1992; Scher and Martin, 2006]. The Arctic Ocean has been relatively isolated from global ocean circulation during most of its geological history [Moran et al., 2006]. This situation gradually changed during the mid-Neogene as the Fram Strait opened between Greenland and Spitsbergen. A complex system of fracture zones and mid-ocean ridges provided a link to the global ocean current circulation system, and consequently enabled an exchange of warm Atlantic and cold Arctic water masses [Jakobsson et al., 2007] (Figure 1). The opening of the gateway corresponded to enhanced deep-water mass exchange and eventually climate cooling in the Northern Hemisphere deduced from sedimentary records. This is inferred from the first
occurrences of ice-rafted debris (IRD) at ~14 Ma possibly reflecting the floating of icebergs in the central Fram Strait during the middle Miocene [Wolf-Welling et al., 1996]. However, fundamental questions and uncertainties exist concerning the origin of these icebergs, the potential pathways and the magnitude of potential regional glaciations in the circum-Arctic. Filling this gap in knowledge would help constrain the impact of the Middle Miocene Climate Transition (MMCT, ~14.2–13.8 Ma) on Northern Hemisphere ice growth in response to the commencing flow of Atlantic water toward the Arctic Ocean induced by the opening of the gateway prior to 15 Ma [Jakobsson et al., 2007].

Here we combine new plate reconstructions in the North Atlantic–Arctic gateway region with sediment core data from ODP Leg 151 Site 909 in order to address this area’s glacial inception. The results suggest that the opening of the gateway at the MMCT and intensification of water mass exchange between the Arctic and the North Atlantic, together with an elevated paleorelief of the NW Barents Sea area played a major role in Northern Hemisphere climate evolution. We hypothesize that these changes produced meridional heat and vapor transport that initiated large-scale ice growth on the emerged northern Barents Sea during climate deterioration and established the pathway for iceberg transport from the calving Barents Sea ice sheet (BSIS) to the Fram Strait.

2. Background

Very little is known about the Miocene glacial development in the Barents Sea, because adequate Neogene sedimentary records older than Late Pliocene have not yet been studied. The first major advance of the western BSIS is placed at ~1.6 Ma [Butt et al., 2000], and of the northern BSIS at ~2.7 Ma [Knies et al., 2002]. Older evidence for Barents Sea glaciations is not available from onshore or offshore studies.

The potential location of major glaciations around the Arctic Ocean can be inferred by mapping the source areas of Neogene glaciomarine sediments, as has been accomplished from Plio-Pleistocene sediment core data. For instance, glacial erosion and ice sheet expansion toward the shelf edge has been proposed for the northern Barents Sea region on the basis of simultaneous high input of IRD, kaolinite, illite, and reworked organic matter, which pointed undoubtedly to the Barents Sea as the most probable source region [Knies et al., 2002]. This potential fingerprint of glacially eroded, exposed Mesozoic sediments in the Barents Sea has not been considered for localizing the prospective source region for the icebergs in the Fram Strait during onset of the MMCT so far. Instead Winkler et al. [2002] used the increase in primary clay minerals (illite + chlorite) at the expense of smectite, together with IRD pulses between 15–13 Ma as an indicator for a general circum-Arctic colder and/or dryer climate concurrent with the MMCT. Here, we use clay mineralogy together with Rock Eval pyrolysis, kerogen microscopy, and IRD data from Site 909 to identify the source of glacially eroded sediments in the Fram Strait during the middle Miocene. Our data suggest the existence of glacial ice in the central northern Barents Sea about ~12 million years earlier than previously inferred [Solheim et al., 1998].

A detailed description of the methodology of the multi proxy data set is outlined by Knies and Mann [2002] and Winkler et al. [2002]. The chronostratigraphic framework for ODP Site 909 was adopted from Myhre et al. [1995], Wolf-Welling et al. [1996] and Hull et al. [1996]. We note that some uncertainties exist for the age model due to the
fact that it is based on linear interpolation between two age tie points (10.83 Ma at 838.5 mbsf; 16.15 Ma at 1016.15 mbsf) [see Myhre et al., 1995; Wolf-Welling et al., 1996; Winkler et al., 2002]. However, biostratigraphic data have assigned the latter undoubtedly to represent the early to middle Miocene (17–13 Ma) [Myhre et al., 1995; Hull et al., 1996; Poulsen et al., 1996; Kaminski et al., 2005]. The oldest sediments recovered from Hole 909C are regarded to be earliest Miocene on the basis of the occurrence of the calcareous nanofossil Heliocystis carteri [Myhre et al., 1995], middle Miocene (Langhian-Serravallian, ~16–11.6 Ma) sediments have been constrained to occur between ~1020 and 758 mbsf [Poulsen et al., 1996].

3. New Evidence for the Onset of Barents Sea Glaciation During the MMCT

[7] The depositional environment in the central Fram Strait prior to the MMCT was mainly influenced by riverine input of terrestrially derived, fresh organic matter from the Hovgård Ridge microcontinent and the Spitsbergen Platform/ uplifted Barents Sea. This is inferred from input of large particles of plant material (vitrinite/huminite) indicating a proximal source origin with a dense vegetation cover and fluvial sediment supply from adjacent hinterland (Figure 2) [Knies and Mann, 2002]. Vitrinite reflectance values (Ro) from 0.3% Ro to 0.5% Ro and Rock Eval Tmax values of ~16.50°C indicate that the terrestrial organic material is largely immature (Figure 2), vitrinite reflectance histograms to measure the maturity degree of selected samples. Wolf-Welling et al. [1996] and Winkler et al. [2002] published the applied age model. A biostratigraphic fixpoint at ~16.15 Ma [Wolf-Welling et al., 1996] is indicated by a red star.

Figure 2. Results of organic/sedimentological bulk analyses and kerogen microscopy in ODP Hole 909C versus age (Ma) [Winkler et al., 2002; Knies and Mann, 2002]. Photomicrographs showing typical maceral compositions of whole rock samples from MCO and during MMCT. (top left) Small and well-rounded vitrinite particles in a light crystalline matrix (at ~14.8 Ma). (bottom left) Large (>200 μm) dark vitrinite/huminite particle (at ~17.1 Ma). (middle) IRD, ice-rafted debris (>0.5 mm g cm⁻² ka⁻¹); illite/kaolinite (rel. %), the relative amounts of the clay minerals illite and kaolinite; Tmax, temperature of maximum pyrolysis yield (in °C). (right) Reflection in oil (Ro%), vitrinite reflectance histograms to measure the maturity degree of selected samples. Wolf-Welling et al. [1996] and Winkler et al. [2002] published the applied age model. A biostratigraphic fixpoint at ~16.15 Ma [Wolf-Welling et al., 1996] is indicated by a red star.
mature (>0.9%Ro), small-sized and well-rounded (Figure 2) suggesting long transport distance of most probably glacially reworked fossil organic matter. The latter may be further confirmed by elevated Rock Eval Tmax values (>450°C) subsequently to the MCO (Figure 2) indicating erosion of organic-rich bedrocks, most probably Mesozoic sediments outcropping in the central/northern Barents Sea [Birkenmajer, 1989]. Indeed, concurrent highs of IRD, kaolinite and illite between ~15 and 12 Ma (Figure 2) indicate glacially derived sediment transport from the Barents Sea. While the illite peaks were formerly interpreted by Winkler et al. [2002] to be indicative for a colder and/or dryer climate in the study area, the highs in kaolinite content parallel to IRD maxima point unequivocally to the northern Barents Sea as the main source for the detritus supply (Figure 2). IRD supply from northern Canada and/or northern Greenland may be ruled out due to the lack of detrital dolomite in middle Miocene sediments Hole 909C [Chow et al., 1996], which is the source indicator for glacial erosion in these regions [e.g., Suryk and Hurst, 1984; Stemmerik, 1996; Bischof and Darby, 1999]. On the other hand, detrital dolomite is abundant beginning at ~2.7 Ma [Chow et al., 1996], which is consistent with synchronous ice sheet development in the high latitudes [Flesche Kleiven et al., 2002]. Hence, proxy data in the Fram Strait suggest that the uplifted northern Barents Sea was ice covered already during the middle Miocene and that glacial erosion, calving of icebergs along the coastline and subsequent transport via Transpolar Drift was the determining processes for the supply of detritus to the Fram Strait. Given the reconstructed preglacial relief of the Barents Shelf (Figure 3) [Rasmussen and Fjeldskaar, 1996], exiting icebergs from a protruding BSIS to the southwest may be another possibility for transport of glacially eroded material to the central Fram Strait. However, Hjelstuen et al. [1996] envisaged a fluvial drainage system along the western Barents Sea shelf during the Miocene reducing the possibility of iceberg transport from this region.

Taking all the information from ODP Hole 909C into account, we conclude that, contemporary to the global cooling at the Middle Miocene Climate Transition at ~15–14 Ma, the existence of a calving ice sheet in the northern Barents Sea is
more than likely (Figure 3). From ~15–12 Ma, illite concentrations follow the highs of kaolinite, and IRD, while supply of reworked (mature) organic matter dominates (Figure 2) implying not only the persistence of cold conditions in the circum-Arctic [Winkler et al., 2002] but also the irregular release of icebergs from a protruding BSIS. Other evidence for ice sheet development in the Northern Hemisphere contemporaneous to the MMCT is scarce. However, evidence is clear in a broader time window for the Gulf of Alaska (~15 Ma) [Marincovich, 1990] and Scandinavia (~12.6 Ma) [Fronval and Jansen, 1996], the latter based on first IRD pulses in the Norwegian Sea. Accordingly, storage of ice in both hemispheres during MMCT is possibly larger than previously thought, a fact that is consistent with enhanced abundance of ice-derived material in central Arctic Ocean sediments at ~14 Ma [Moran et al., 2006].

4. Plate Kinematics and Paleorelief

[10] To explain the transport of IRD-laden icebergs from the northern Barents Sea in the Fram Strait, paleo ice drift patterns as existing today must have already developed by the MMCT [Jakobsson et al., 2007]. A prerequisite for this assumption is the opening and deepening of the Atlantic-Arctic gateway during the MMCT. It has been suggested that the deep-water connection to the Arctic Ocean was probably not established before 13.7 Ma while the opening of the gateway and formation of a narrow strait was already established at about 17.5 Ma [Jakobsson et al., 2007]. The exact age of the oceanic crust that floors Fram Strait proved to be difficult to be interpreted, mainly because Knipovich ridge propagated slowly into the Arctic region and the plate boundary might have been readjusted several times [Crane et al., 2001]. As detailed knowledge of the evolution of plate boundary can be inferred from detailed magnetic data from north and south of the Fram Strait area, we have constructed a kinematic model for the opening between Greenland and Svalbard by using Eurasia-Greenland rotations inferred from Gaina et al.’s [2002] data set and a new model for microcontinent evolution. The mid-Miocene paleoage grid of oceanic crust in the Fram Strait area has been converted to paleobasement depth using a thermal subsidence model (see auxiliary material Table S1 and Figure S1)1.

[11] In order to restore the paleotopography of the western Barents Sea, we have examined the models published by Dimakis et al. [1998] and Rasmussen and Fjeldskaar [1996]. The preglacial reconstructed topography by Dimakis et al. [1998] is confined to the western Barents Sea and used a set of sediment thickness/erosion maps and a simple Airy isostatic model to estimate preglacial topography. The model of Rasmussen and Fjeldskaar [1996] gives only a rough estimate of the preglacial topography of the Barents Sea by approximating the continental margin tectonic uplift due to rifting with isostatic corrections. Rasmussen and Fjeldskaar [1996] modeled contours have been used for the eastern Barents Sea and interpolated to match the more detailed calculations of Dimakis et al. [1998]. The modeled northwestern Barents Sea topography displays a high relief (more than 1500 m) due to extensional and transpressional uplift; the height decreases toward the southern part reaching elevations of only 100–200 m (Figure 3). The paleoelevation of the Spitsbergen area has been merged with the reconstructed paleobathymetry of the Fram Strait gateway at MMCT time (around 14 Ma) (Figure 3). The modeled depth of the Fram Strait passage is estimated to have reached by mid-Miocene time between 2500 and 2800 m.

[12] Besides the two microcontinents that border the NE margin of Greenland (Greenland and Hovgaard), Yermak Plateau represents an important barrier for the ocean circulation. Irrespective of the crustal type that underlies the Yermak Plateau, it is widely accepted that Oligocene-Miocene volcanism modified the shape and size of this plateau. Present-day bathymetry (Figure 1) [Jakobsson et al., 2003] shows that the Yermak Plateau is shallower than the surrounding oceanic floor by about 2000 meters. Oceanic (volcanic) plateaus appear to subside at the same rate as the lithosphere they are built on [Coffin, 1992]; therefore we roughly estimate that Yermak Plateau’s depth was shallower than the surrounding oceanic floor by the same amount as in the present-day situation. This assumption would imply that north of Spitsbergen, the Fram Strait gateway was already opened at 14 million years, with the Yermak plateau acting only as a shallow (~500–1000 m) barrier to the water circulation.

5. Paleoceanographic and Paleoclimatic Implications

[13] Our results suggest that iceberg flotillas in the Arctic Ocean derived from calving ice sheets in the
northern Barents Sea during MMCT were able to reach the Fram Strait and delivered their load upon melting (Figure 3). The establishment of a modern-like ice drift pattern in the gateway region by MMCT time suggests the onset of water mass exchange between the Arctic and the Nordic Seas, a scenario compatible with a prominent switch from biosiliceous to calcarous-rich sediment pattern in the Norwegian Sea [e.g., Bohrmann et al., 1990; Poole and Vorren, 1993] and the North Atlantic [Flower and Kennett, 1994] during the same period. A plausible reason for this coincidence might be the formation of an initial proto-thermohaline-like circulation in the Nordic Seas with southward flowing cold Arctic waters and northward intrusion of Atlantic water during the MMCT. This circulation pattern is consistent with the intensification of North Atlantic Deep Water (NADW) production during the middle Miocene [Wright et al., 1992; Woodruff and Savin, 1989]. The initiation of deep-water production and circulation from the Norwegian Sea into the North Atlantic must have started within the early Oligocene (~38–30 Ma) [Davies et al., 2001; Via and Thomas, 2006], concurrent to the development of continental ice in the Northern Hemisphere (Green-
land) [Eldrett et al., 2007] (Figure 4). The relationship between deep-water production and climate change during the middle Miocene may be an analogue to the early Oligocene. Peak production of proto-NADW around 17 Ma [Wright et al., 1992] is closely followed by the build-up of glacial ice in the northern Barents Sea (Figure 4). Thus we argue that the expansion of the Barents Sea glaciation began in response to the initial opening of the Fram Strait and onset of water mass exchange between the Arctic and the Nordic Seas coupled with a general global cooling trend during the MMCT. This scenario is (although stratigraphically less constrained) concurrent with Antarctic ice sheet expansion at ~14 Ma which was apparently triggered by a combination of low summer insolation and declining atmospheric carbon dioxide [Holbourn et al., 2005] and/or orbitally paced ocean circulation changes [Shevenell et al., 2004]. The generation of positive feedbacks in the ocean-atmosphere system has promoted the build-up of ice sheets in both hemispheres during middle Miocene global cooling; a scenario that is comparable with recent findings of ice storage in both hemispheres during the late Eocene to early Oligocene [Eldrett et al., 2007].

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