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Millions of Years of Greenland Ice Sheet History Recorded in Ocean Sediments

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Abstract: Geological records from Tertiary and Quaternary terrestrial and oceanic sections have documented the presence of ice caps and sea ice covers both in the Southern and the Northern hemispheres since Eocene times, approximately since 45 Ma. In this paper focussing on Greenland we mainly use the occurrences of coarse ice-rafted debris (IRD) in Quaternary and Tertiary ocean sediment cores to conclude on age and origin of the glaciers/ice sheets, which once produced the icebergs transporting this material into the adjacent ocean. Deep-sea sediment cores with their records of ice-rafting from off NE Greenland, Fram Strait and to the south of Greenland suggest the more or less continuous existence of the Greenland ice sheet since 18 Ma, maybe much longer, and hence far beyond the stratigraphic extent of the Greenland ice cores. The timing of onset of glaciation on Greenland and whether it has been glaciated continuously since, are wide open questions of its long-term history. We also urgently need new scientific drilling programs in the waters around Greenland, in particular in the segment of the Arctic Ocean to the north of Greenland.

Zusammenfassung: Tertiäre und quartäre terrestrische und marine Schichtenabfolgen belegen das Bestehen von Eiskappen, -schilden und Meereisdecken sowohl in den südlichen wie auch den nördlichen Polargebieten seit dem Eozän, etwa seit 45 Mio. Jahren. In dieser Arbeit behandeln wir die Vereisungsgeschichte von Grönland. Wir benutzen die Vorkommen von grobem, eisbergtransportiertem, terrigenem Detritus (IRD) in quartären und tertiären Tiefseekernen, die im Umfeld von Grönland geborgen worden sind, um Rückschlüsse auf das Vorhandensein von Gletschern und Eisschilden zu ziehen, von denen einst Eisberge kalbten. Tiefseekerne mit Vorkommen von IRD vor NE-Grönland, aus der Framstraße und vor Südgrönland lassen vermuten, dass Grönland während der letzten 18 Mio. Jahre – u.U. sogar viel länger – fast fortlaufend von Eis bedeckt war. Damit übertreffen sie den Zeitraum der jungquartären Geschichte des grönländischen Eisschildes, die mit den Eiskernen von Grönland belegt werden kann, um ein Vielfaches. Der Zeitpunkt und der genaue Ort des Einsetzens der Vergletscherung/Vereisung Grönlands sind ungelöste wissenschaftliche Fragen, denen man sich aber über neue Tiefseebohrungen im Umfeld von Grönland, vor allem im nördlich angrenzenden Nordpolarmeer nähern könnte.

INTRODUCTION

The Greenland Ice Sheet – a modern relict of the Late Quaternary glacial ice sheets

The modern climate system is characterized by steep temperature gradients between the tropics and the poles. The Antarctic and the Greenland ice sheets are some of its most prominent expressions. While polar regions of planet Earth were glaciated repeatedly in the long course of their geological history, the Cenozoic transition from a "greenhouse" to an "icehouse" produced a unique climatic scenario with bipolar glaciation, which is different from all previous well-documented glacial events. The Greenland ice sheet is a remnant of the giant Northern Hemisphere last glacial maximum ice sheets (in our region composed of the Greenland Ice Sheet with the adjacent Innuitian Ice Sheet to the West, which again was connected to the North American Laurentide Ice Sheet) and represents hence a spectacular anomaly. The future of these ice sheets is, because of political, socio-economic and scientific reasons, subject to intensive debate and much speculation (HUYBRECHTS et al. 2004). In the light of the ongoing discussion of its potential future instability it is of paramount importance for humanity on local (habitats on Greenland), regional (fisheries, fresh water export from Greenland) and global scales (potential for eustatic sea-level rise) to resolve the long-term natural variability of the Greenland ice sheet.

In this paper, therefore, we will briefly attempt to review the evidence of the history of the Greenland Ice Sheet based on Quaternary and Tertiary marine sediment cores and their ice-rafting record of coarse debris because they cover periods with substantially warmer and colder climates as compared to today and because we hope to be able to deduce how the ice on Greenland responded to different climate scenarios. A similar approach had been taken recently by ALLEY et al. 2010; they concentrated on much shorter time scales, but came to conclusions quite similar to our study. The emphasis of the present paper is mostly on longer Pleistocene and Tertiary records because the Greenland ice cores document without doubt that the Greenland Ice Sheet has existed continuously since pre-Eemian times (WILLERSLEV et al. 2007).

Geological records from Tertiary and Quaternary terrestrial and oceanic sections have documented the presence of ice caps and sea ice covers both in the Southern and the Northern hemispheres since Eocene times, approx. 45 Ma (THOMAS 2008). Deep-sea sediment cores with their records of ice-rafting from off NE Greenland, Fram Strait and to the south of Greenland suggest the more or less continuous existence of the Greenland ice sheet since 18 Ma (WOLF & THIEDE 1991), maybe much longer, and thus we need to investigate the history of the natural variability of the Greenland ice sheet over time scales far beyond those presently available from ice cores (VINTHER et al. 2010). The present situation illustrates that the other large northern hemisphere ice sheets vaned during interglacials (cf. VINTHER et al. 2009 for the present interglacial), thereby suggesting that Greenland was and is the main source of coarse terrigenous ice-rafted debris (IRD) during relatively warm climatic scenarios.

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The marine records suggest that the Greenland ice sheet has existed for many million years. The timing of onset of glaciation on Greenland and whether it has been glaciated continuously since are the wide open questions of its long-term history. While this has been well known in the case of Antarctica for some time, previous ideas about the onset of Northern hemisphere glaciation during Pliocene times (approx. 2.5-5 Ma) have been superseded by the dramatic findings of coarse IRD in Eocene sediments from Lomonosov Ridge close to the North Pole (St. John 2008). These appear to be slightly older than the oldest Antarctic records of ice-rafting (Thomas 2008). The histories of the onset of Cenozoic glaciation in high northern and southern latitudes remain enigmatic and are presently the subject of the planning for new international geological deep-sea drilling projects, which hope to reveal some of their secrets over the coming decades (Stein & Coakley 2009, Stein 2011).

The overall objective of this short study is to review the available data from ocean sediment cores and answer questions of the timing of initial Greenland glaciation as well its temporal and spatial variability and to what extent the ice sheet could have survived conditions of extreme interglacial warming at times beyond the ice core stratigraphies. Using published and new sedimentary records from deep-sea cores from offshore Greenland we will thus investigate the compositional variability and sources of ice-rafting as evidence of the Greenland Ice Sheet under past climate and ocean regimes ranging from severe glaciation to warming levels surpassing present conditions. However, it is also clear that the questions addressed in this paper require substantial new research.

Presently, the West-Antarctic and Greenland ice sheets are both subject to a rapid decline in response to the ongoing climate change. Their natural variability can be deduced from ice cores, mostly incomplete stratigraphic sections on land and the much more complete marine sedimentary records from their off-shore areas. The modern Greenland Ice Sheet extends from approx. 60 °N to just above 80 °N and hence is not in a polar position (Fig. 1). It must be considered an anomaly and probably would not exist if it was not supported by the peculiar physiography of the North Atlantic Ocean, with its extension into the Norwegian-Greenland Sea and the Labrador Sea / Baffin Bay area, as well as the orogeny of Greenland and the oceanographic and atmospheric boundary conditions which have developed around and over Greenland during the Holocene.

Modern patterns of atmospheric and ocean circulation over and around Greenland

The Cenozoic plate tectonic opening of the seaways connecting the Arctic Ocean with the main basin of the North Atlantic shaped the continental margins and the gateways for the ocean circulation around Greenland. As a result, cold waters of mostly Arctic origin surround this island, protecting it against the influence of temperate Atlantic waters entering the Labrador-Irminger Sea basin from the southeast on their way towards the eastern basins of the Norwegian-Greenland Sea (Macdonald et al. 2003). In contrast, its north coast is subject to the onslaught of Arctic sea-ice drift carried by the Beaufort Gyre and the Transpolar Drift (Fig. 1).

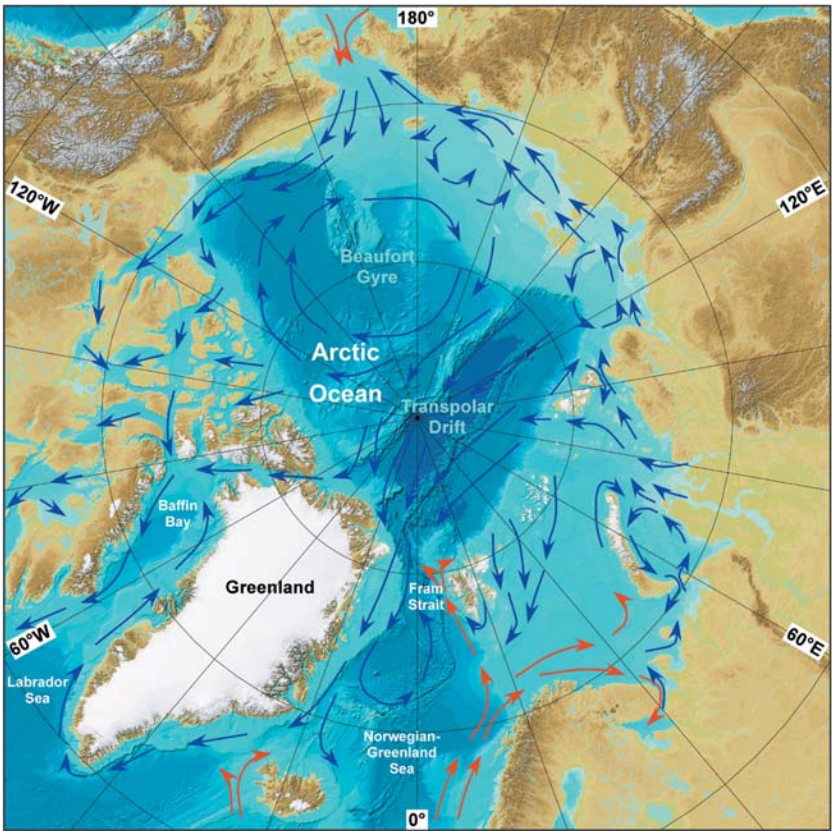

Fig. 1: Bathymetric map of the Arctic Ocean (from http://www.ibcao.org) with surface water circulation around Greenland and Arctic Ocean sea-ice drift (after http://www.amap.no). Blue arrows mark ice drift/cold surface currents; red arrows mark warm surface currents.

Abb. 1: Bathymetrische Karte des Arktischen Ozeans (von http://www.ibcao.org) mit Strömungsmuster der Oberfläche und Meereisdrift im Arktischen Ozean (von http://www.amap.no). Blaue Pfeile = kalte Oberflächenströmungen bzw. Eisdrift; rote Pfeile = warme Oberflächenströmungen.

The atmospheric circulation driving the surface water currents, and in particular the Arctic Ocean sea-ice drift, is controlled by the position of the Icelandic Low and the Siberian High and seems to be able to fluctuate between a cyclonic and an anticyclonic mode for periods of several years in duration (Proshutinsky & Johnson 1997, Hutterli et al. 2007). Modern warming seems to impact not only the Arctic Ocean sea-ice cover, but also on the Greenland ice sheet. The recently published report of the Intergovernmental Panel on Climate Change (IPCC 2007) suggests that the former may disappear during the summer time towards the end of this century, whereas the latter will melt only slowly, thus adding within the coming century some 80-200 cm to the global sea level against the 7 m sea-level rise which is believed to be stored in the Greenland Ice Sheet. The Greenland Ice Sheet seems to be waning along its margins, in particular in regions of fast flowing outlet glaciers, whereas its central parts are fed by a sufficiently high annual snow precipitation, at least enough to slow down the lowering of the ice divide (Weidick 2009, Chen et al. 2006, Tedesco et al. 2008, Howat et al. 2007).

Hence, the existence and probably persistence of the Greenland Ice Sheet is related to a very special pattern of oceanic and atmospheric circulation patterns, which may have existed for a long time during the Cenozoic. The basic boundary conditions of these patterns, however, were substantially different before the opening of the Norwegian-Greenland Sea and particularly Fram Strait, which is believed to have occurred during Miocene-Pliocene times (Kristoffersen 1990, Jakobsson et al. 2007).

METHODOLOGY

The origin of the ice rafted detritus (IRD): Source regions and the dynamics of the Greenland Ice Sheet as reflected in the composition of the IRD records

Ice sheets reaching the ocean in fjords and along continental margins erode rock material from local basement and transport the erosional products via calving glaciers and icebergs to adjacent ocean basins, where it is deposited as IRD. By analysing such material in sediment cores by geochemical, mineralogical, isotopic, and biostratigraphical methods the provenance area(s) of the IRD can be determined and used for reconstructions of the extent and dynamics of former ice sheets. Over the past decades, provenance studies of upper Quaternary IRD deposited in the North Atlantic and Arctic Ocean have been widely used to reconstruct the dynamics of past Northern Hemisphere ice sheets (Andrews et al. 1998a, b, Knutz et al. 2002, Spielhagen et al. 2004). For example, Nd, Sr, Pb, and Ar isotopic data of IRD in Heinrich layers have been used to link these layers to periodic surges of ice streams from the Laurentide Ice Sheet in North America (Grousset et al. 1993, Hemming et al. 1998). To determine whether IRD material is indicative of isolated or more pervasive ice-rafting, or whether it occurred by sea ice or iceberg rafting, surface textures of grains, calculated mass accumulation rates of different grain size fractions, and bulk sediment trace element geochemistry of IRD-bearing strata can be used (Eldrett et al. 2007). Another provenance method that has been fine-tuned during the last few years is age determinations of zirconium minerals by U/Pb isotopic measurements (Frei et al. 2006). The iron-oxide trace element composition of coatings on ice-rafted sand grains can be used for a statistical provenance determination of potential IRD source areas (Bischof & Darby 1997). Glacio-marine sediments are mostly dominated by fine-grained silt and clay, which constitute the largest volume of glacier-eroded material. Therefore, bulk sediment X-ray diffractometry (XRD, mineralogical) analysis can for some purposes be advantageous and more time-efficient for IRD provenance analysis (Vogt et al. 2001, Moros et al. 2004, Spielhagen et al. 2004, Stein et al. 2010) and will be supplemented in the near future by X-ray fluorescence (XRF, geochemical) analysis. By the combination of several of the above mentioned provenance determination methods, statistical uncertainties in the identification of specific source areas can be narrowed down.

The polar and sub polar deep-sea floors are covered in general by fine to coarse-grained sediments of dominantly terrigenous origin (e.g., Lisitzin 2002). There is a variety of processes which transport such sediments from the adjacent continents into the ocean: aeolian transport provides only relatively fine-grained materials which size-wise, though not composition-wise, mix into the background signals of all other fine-grained marine sediments. Sea ice picks up fine-grained clays and silts, but sometimes smaller amounts of sand and coarser pebbles during its formation (Pfirman et al. 1990, Reimnitz et al. 1998, Nürnberg et al. 1994, Dethleff 2005, Dethleff & Kuhlmann 2009). Icebergs, which originate from glaciers and ice sheets can transport coarse terrigenous debris out into the oceans where they shed this material when melting. Because of their size and lithologies these coarse components are relatively easily identified, and under special conditions their lithologies allow them to be linked to specific source regions on the adjacent continents (Stein 2008, Darby et al. 2006). Icebergs are relatively scarce in the central Arctic Ocean at present, but they are found around Greenland in large numbers. During the glacial maxima of the Quaternary, active parts of the ice sheets must have dumped large amounts of icebergs into the oceans in the vicinity of Greenland, as revealed by frequency and size of the IRD as well as sediment horizons enriched in ice-rafted debris (Wolf & Thiede 1991). Ice-rafting records are hence ambiguous and therefore not easy to interpret.

Available sedimentary records from the seas around Greenland and the adjacent Arctic Ocean

We are dependent on the availability of large numbers of sediment cores. For the Quaternary part of this review we actually had access to numerous sediment cores, which have been collected by many expeditions over the past decades (Fig. 2). The stratigraphic distribution of the IRD in numerous cores around Greenland, however, has yet to be mapped in sufficient detail. They contain relatively easily datable upper Quaternary sediments and hence offer the possibility to identify its sources and their stratigraphic variability aiming at a definition of timing and spacing of the iceberg production around Greenland. Because of the scope of this study we have added detailed data from one Quaternary core. For the Tertiary time slices we had to rely on sites drilled around Greenland since the late seventies (Fig. 2) by the Deep-Sea Drilling Project (DSDP), the Ocean Drilling Program (ODP) and the Inte-

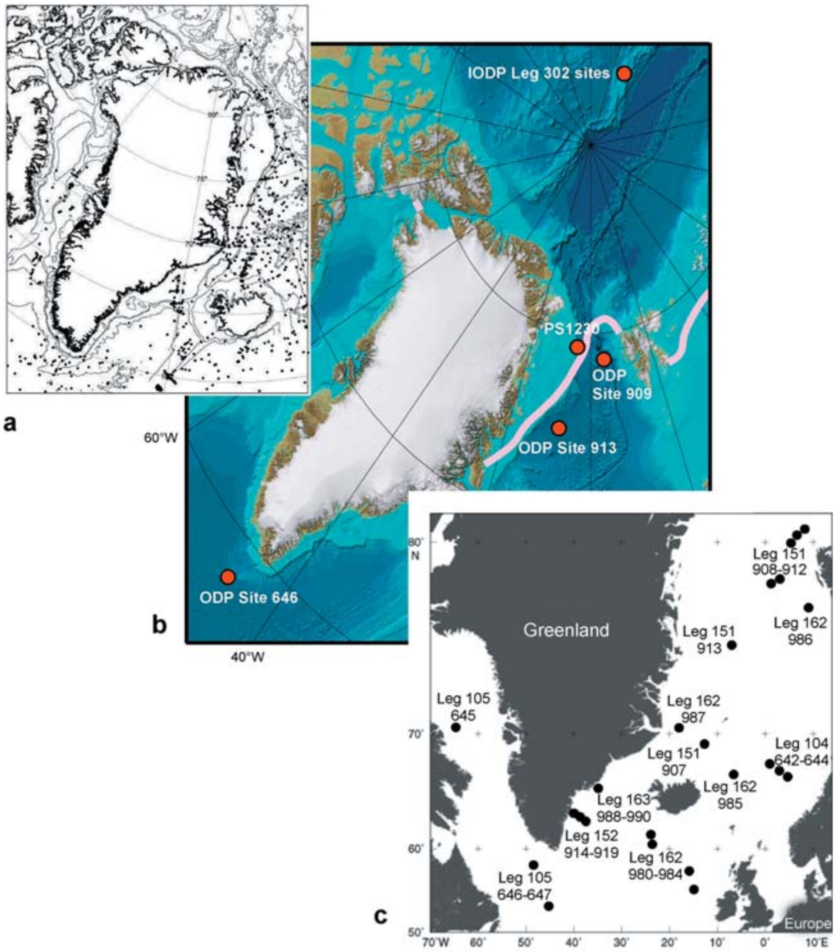

Fig. 2: Sediment cores available from the seas around Greenland.
a) Existing gravity and piston cores around Greenland with additional core sites from west Greenland according to the GEUS core repository (source: http://www.ngdc.noaa.gov).
b) Locations of sediment core PS1230 and ODP drill sites, which are discussed in detail in this paper.
c) Distribution of DSDP and ODP sites around Greenland (Source: DSDP and ODP expedition reports). In addition drill sites of IODP Expedition 302 (ACEX) on Lomonosov Ridge close to the North Pole have to be considered; for location see Fig. 2b.

Abb. 2: Sedimentkerne aus den Seegebieten um Grönland.
a) Schwere- und Kolbenlotkerne aus der Nähe von Grönland nach http://www.ngdc.noaa.gov und zusätzliche Kernlokationen westlich Grönlands nach Angaben des GEUS Kernlagers.
b) Positionen des Sedimentkerns PS1230 und der ODP-Bohrungen, die in dieser Arbeit im Detail diskutiert werden.
c) Verteilung aller DSDP- und ODP-Bohrungen aus dem unmittelbaren Seegebiet um Grönland (Quelle: DSDP und ODP Expeditionsberichte). Zusätzlich werden die Bohrungen der IODP-Expedition 302 (ACEX) auf dem Lomonosov-Rücken in unmittelbarer Nähe des Nordpols diskutiert (vgl. Abb. 2b).

grated Ocean Drilling Program (IODP). DSDP has visited the western North Atlantic Ocean during its Leg 12 and the Norwegian-Greenland Sea during Leg 38, producing the first indications that northern hemisphere glaciations were older than the Quaternary. The ODP visited the Labrador Sea and Baffin Bay as well as the Norwegian-Greenland Sea area during Legs 104, 151, 152 and 162 and recovered long records of Tertiary ice-rafting. Later the IODP succeeded in entering the central Arctic Ocean to determine the earliest onset of ice-rafting on the northern hemisphere around 48 Ma.

Except for one Quaternary sediment core (see below) we are mainly relying on published sediment records from the DSDP, the ODP, and IODP. They can be treated in consecutive order because each of them contributed important new data and insights to the problem we are addressing. While reviewing the available data from all relevant sites, we are concentrating on evaluating new data from a Quaternary sediment core as well as the ODP sites 646, 909, 913, 914-919 and IODP Expedition 302 sites because of their relevant locations, the availibity of sufficiently detailed stratigraphies as well as information on IRD lithologies (Fig. 2).

New data from a Quaternary sediment core

Gravity core PS1230-2 was obtained in summer 1984 from RV "Polarstern" during expedition ARK II (AUGSTEIN et al. 1984) from the East Greenland continental margin in the Fram Strait (78°52.2' N, 4°50.6' W, 1249 m water depth). Visual inspection of the core did not reveal any evidence of sediments deposited from downslope transport processes. The 489 cm long core was sampled every 4 cm in 2 cm intervals. The samples were freeze-dried, washed with deionized water through a 63-μm mesh, dried, split into several fractions and weighed. Total numbers of planktic foraminifers were counted on a representative split (>300 grains) of the 125-500 μm fraction. For oxygen and carbon isotope measurements 25 specimens of planktic foraminifers *Neogloboquadrina pachyderma* (sin.) were picked from the 125-250 μm fraction. Isotope measurements were performed on a Finnigan MAT251 mass spectrometer at the Leibniz Laboratory for Radiometric Dating and Isotope Research of Kiel University. Results are expressed in the ∂-notation referring to the PDB standard and are given as ∂^{18}O and ∂^{13}C values. The external analytical reproducibility is 0.08 ‰ and 0.04 ‰ for ∂^{18}O and ∂^{13}C, respectively.

Stratigraphy of core PS1230-2 is based on correlation to the oxygen isotope stack record of MARTINSON et al. (1987) and to the Arctic Ocean and Fram Strait records presented by SPIELHAGEN et al. (2004). Coarse fraction and planktic foraminifer abundance records of SPIELHAGEN et al. (2004) were also used for correlation. Published results including ^{14}C datings from the box core (48 cm length) obtained at the same station (PS1230-1, DARBY et al. 2002) confirm the position of the marine isotope stage (MIS) boundaries 1/2 and 2/3. MIS boundaries older than MIS 7 are tentatively assigned and must be regarded as somewhat questionable.

The Deep-Sea Drilling (DSDP) records

The "Glomar Challenger" and the "Joides Resolution" have visited the North Atlantic Ocean including the Labrador Sea, Baffin Bay and the Norwegian Greenland Sea repeatedly (DSDP legs 12, LAUGHTON et al. 1972; 38, TALWANI et al. 1976; ODP legs 104, ELDHOLM et al. 1987; 105, (SRIVASTAVA et al. 1987; 151, MYHRE et al. 1995; 152, LARSEN et al. 1996; 162, JANSEN et al. 1996). IODP Expedition 302 (BACKMAN et al. 2006) was executed using one of the European Consortium of Ocean Research Drilling's (ECORD) mission specific platforms when visiting the Lomonosov Ridge in 2004.

We have relied on the published lithostratigraphies, the assumed stratigraphic ages and the lithologic composition of the IRD, when available. Because of our intention to elucidate the age of the Greenland Ice Sheet we have put most emphasis on the drill sites close to the Greenland continental margin because of the higher probability to relate this material to icebergs with a Greenlandic origin. We have used a variety of advanced methodological approaches on available and mostly published sediment core material from ocean waters around Greenland (Fig. 2).

AVAILABLE STRATIGRAPHIC RECORDS AND RESULTS

Quaternary Sediment Core PS1230-1

Located off NE Greenland Core PS1230-1 covers approximately the past 300,000-500,000 years. Coarse fraction contents (Fig. 3) vary between 0 and 50 weight-%. Correlation of values (n = 123) for the >63 µm and >500 µm fractions is 0.82. Coarse fraction values are lowest in interglacial substages MIS 1, 5e and 11(?) while highest values are found in sediments from glacial terminations I and II. Planktic foraminifers are abundant in most analysed samples from the upper 300 cm of the record (i.e., the last ca 300,000 years). Below this they are present but in significantly lower amounts. The core interval between 370 and 418 cm is very fine-grained (<1 % coarse fraction) and contains only few planktic foraminifers; the origin of this particular core interval is doubtful, but it may represent a time span without deposition of ice-rafted materials.

Because sea-ice transport is almost entirely restricted to fine-grained particles (NÜRNBERG et al. 1994), the biogenic-free >500-µm-fraction in high-latitude hemipelagic deep-sea sediments is generally accepted as a useful measure for iceberg transport (BISCHOF 2000). Although there are considerable numbers of planktic foraminifers in the coarse fraction of core PS1230-1, biogenic components dominate the 125-500 µm fraction in only very few samples from early MIS 9(?) (290-298 cm) and from the early Holocene. In the other samples lithogenic particles make up more than 50 % of this fraction (average 78 %). The strong correlation (0.82) of the >63 µm

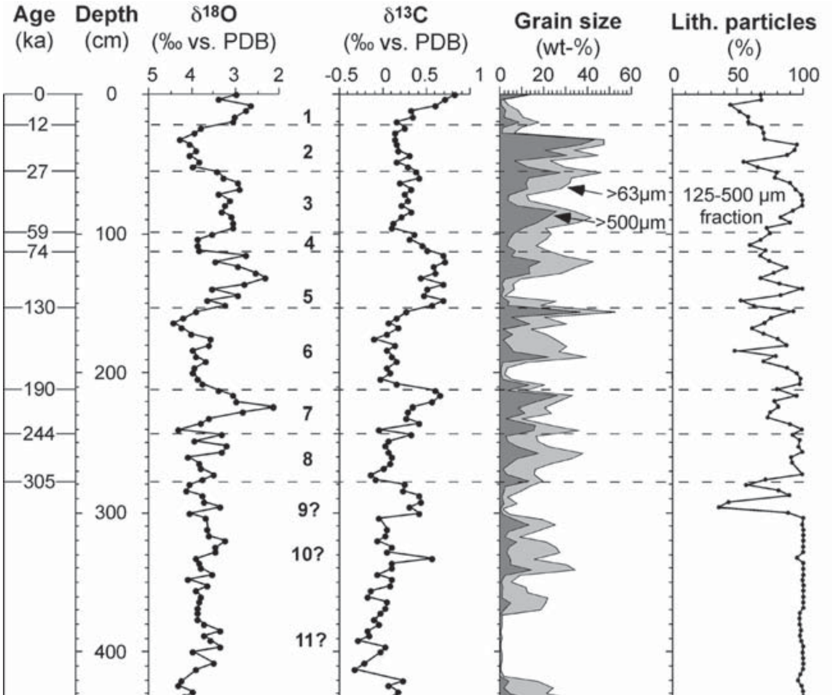

Fig. 3: Data of sediment core PS1230-2 (78°52.2' N, 4°50.6' W, 1248 m water depth) from the East Greenland continental margin in the Fram Strait (see Fig. 2b). High coarse fraction contents throughout the core reflect continuous deposition of IRD, maybe with the exception of a short interval during the interglacial of marine isotope stage (MIS) 11. Biogenic particle contents (%) can be seen as the non-lithogenic fraction adding up to 100 % (right column).

Abb. 3: Daten des Sedimentkerns PS1230-2 (78° 52,2' N, 4°50,6' W, Wassertiefe 1248 m) vom ostgrönländischen Kontinentalrand in der Framstraße (vgl. Abb. 2b). Hohe Gehalte grober terrigener Sedimentkomponenten im gesamten Kern sind das Ergebnis eines kontinuierlichen Eintrags von IRD möglicherweise abgesehen von einem Zeitabschnitt während des marinen Isotopenstadiums (MIS) 11. Der Biogengehalt (%) ergibt sich als der nicht-lithogene Anteil von 100 % (rechte Kurve).

and the >500 µm fractions supports the assumption that rafting by icebergs was the dominant sediment transport process on the East Greenland continental margin in the Fram Strait. Composition analyses of the >500 µm fraction reveal up to 50 % of detrital carbonates (i.e., calcite and dolomite) (SPIELHAGEN 1991) which most likely have their provenance in the Ellesmerian (Early Paleozoic) foldbelt of North Greenland and the adjacent Canadian islands (cf. PHILLIPS & GRANTZ 2001). The continuous presence of IRD from this area in the PS1230-1 record (with the exception of one interval possibly relating to MIS 11) is evidence of a long-lasting sedimentation of iceberg-rafted debris during the last 300,000 years and more. Furthermore it indicates an equally long history of glaciation in this area which was sufficiently large to have glacier outlets at the northern coast so that icebergs with a load of lithic particles from the above mentioned source could eventually reach the western Fram Strait. Hence this core offers evidence for glaciation and iceberg production in the region for most of the past 500,000 years.

DSDP Leg 12

DSDP Leg 12 was one of the first deep-sea drilling efforts devoted to the structural and depositional history of the main basin of the North Atlantic Ocean (LAUGTHON et al. 1972). Its drilling program established a transect from the continental margin off Newfoundland to locations to the south off Greenland, on Reykjanes Ridge, Rockall Plateau and in the Bay of Biscay. The sites were not continuously cored and hence not much detailed information on stratigraphy of the Neogene sediment sections was obtained. However, the Leg 12 scientists detected that the Pliocene-Pleistocene sections (Sites 111, 112, 113, 114, 119) comprised evidence for glaciations on the adjacent continents and linked the IRD partly to the Greenland ice sheet (DAVIES & LAUGTHON 1972, BERGGREN 1972). Despite their scarce evidence they also concluded that northern hemisphere glaciation reached back into the Pliocene (BERGGREN 1972).

DSDP Leg 38

Despite substantial exploration activities in the North Sea and along the Norwegian continental shelf DSDP Leg 38 brought for the first time a scientific drill ship into the Norwegian-Greenland Sea (TALWANI et al. 1976). Like Leg 12 it was of a generally exploratory nature, as many of the legs of the early DSDP when the project was still young. One of its scientific goals was to identify the initiation of northern hemisphere glaciation. The sites of Leg 38 were spread widely over the Norwegian-Greenland Sea and only spot cored so that no detailed stratigraphic records were obtained. Strangely enough none of the synthesis chapters of the Leg 38 Initial Reports (TALWANI et al. 1976) deals with the question of the initiation of northern hemisphere glaciations even though many cores, for example at Site 344, suggested an onset of glaciation earlier than known at that time.

ODP Leg 105

It was almost ten years later that the “Joides Resolution” visited again North Atlantic waters in the vicinity of Greenland, this time entering the Labrador Sea and even Baffin Bay (SRIVASTAVA et al. 1989). The three sites drilled during this leg contain a lot of information on the influx of ice-rafted materials, with excellent stratigraphic coverage even though dating of the sediments was not very sophisticated. The problem of its provenance and timing was related for the first time to the Greenland Ice Sheet.

The Leg 105 scientists explored extensively the origin of the ice-transported materials. CREMER & LEGIGAN (1989) approached the problem by studying the surface texture of quartz grains, mainly from Site 645 in the central Baffin Bay. They observed also the occurrences of coarse ice-rafted pebbles in the early Pliocene to Quaternary sediments, but did not specify their lithologies. Parallel striations and grinding features on the surface of quartz grains were interpreted by them to be of glacial origin, and based on seismic evidence (SRIVASTAVA et al. 1987) related them to a Greenlandic origin. Only in their lithostraphic Unit I (Quaternary) they mention the occurrence of IRD composed of carbonates and mafic rocks, similar to those observed in the carbonate-rich tills on Baffin Island. Based on a compilation of IRD findings (SRIVASTAVA et al. 1987), clay mineral analyses (THIEBAULT et al. 1989) and organic carbon data, STEIN (1991, 2008) reconstructed the onset of continental glaciation in the sediment source areas to be 9 Ma and an intensification for ca 3.4 Ma (Fig. 4).

KORSTGAARD & NIELSEN (1989) presented a relatively sophisticated description of ice-rafted pebbles which have been found frequently in the lower Pliocene to Quaternary sediments drilled during ODP Leg 105. The bulk of their data concern Baffin Bay Site 645, but they made some interesting statements on nature and origin of the IRD also in sites 646 (Labrador Sea close to Greenland) and 647 (central southern Labrador Sea) where IRD is smaller and less frequent than at Site 645. They discerned igneous, metamorphic and sedimentary dropstones and were able to relate dropstone assemblages to provenances from Greenland (mainly igneous and metamorphic rocks) and from the Canadian Arctic Islands (mainly sedimentary, calcareous rocks). For the Baffin Bay site high occurrences of dolomites at 160-330 mbsf seem to indicate an Early Pleistocene to Early Pliocene active source from the Canadian Arctic archipelago. The dropstone assemblages of Site 646 close to southern Greenland are related exclusively to a Greenlandic source regions, whereas the Site 647 dropstones seem to come sporadically from alternating source region both on Greenland and the Canadian Arctic islands. No detailed data on dropstone compositions from the latter two sites have been supplied by KORSTGAARD & NIELSEN (1989); the authors conclude that their dropstone occurrences suggest increasing glaciation since the Early Pliocene/Late Miocene (approx. 8 Ma), but that the onset of major northern hemisphere glaciation is restricted to the last 2.5 Ma (Quaternary).

WOLF & THIEDE (1990) have revisited the history of terrigenous sedimention at Site 646 (Fig. 5), in particular by studying the accumulation rates of the coarse fractions and of other sediment components as well as the records of the IRD. It was important to note that there is no evidence for hiata at this site. Rock fragment frequencies fluctuated at relatively low levels in sediments between 9.5-4 Ma, with a secondary maximum

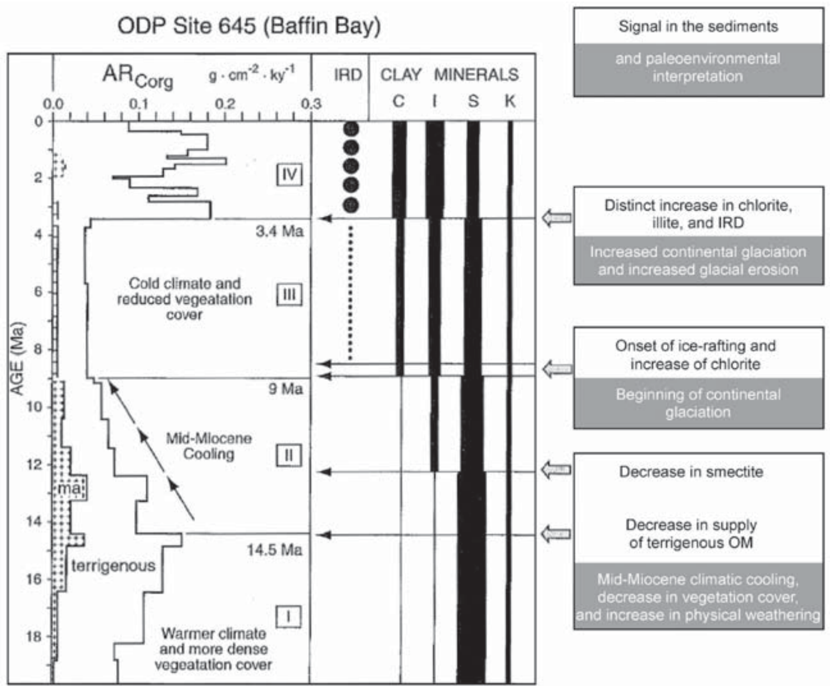

Fig. 4: Summary plot of accumulation rates (AR) of marine and terrigenous organic carbon (C_{org}) and clay mineral composition (C = chlorite, I = illite, S = smectite, K = kaolinite) at ODP Site 645, and paleoenvironmental interpretation (ma = marine). Figure modified from STEIN (2008).

Abb. 4: Zusammenfassende Darstellung der Akkumulationsraten (AR) von marinem und terrestrischem organischem Kohlenstoff (C_{org}), der Tonmineralverteilung (C = Chlorit, I = Illit, S = Smektit, K = Kaolinit) sowie der Paläoumwelt-Interpretation (ma = marin) an ODP-Bohrpunkt 645 (verändert nach STEIN 2008).

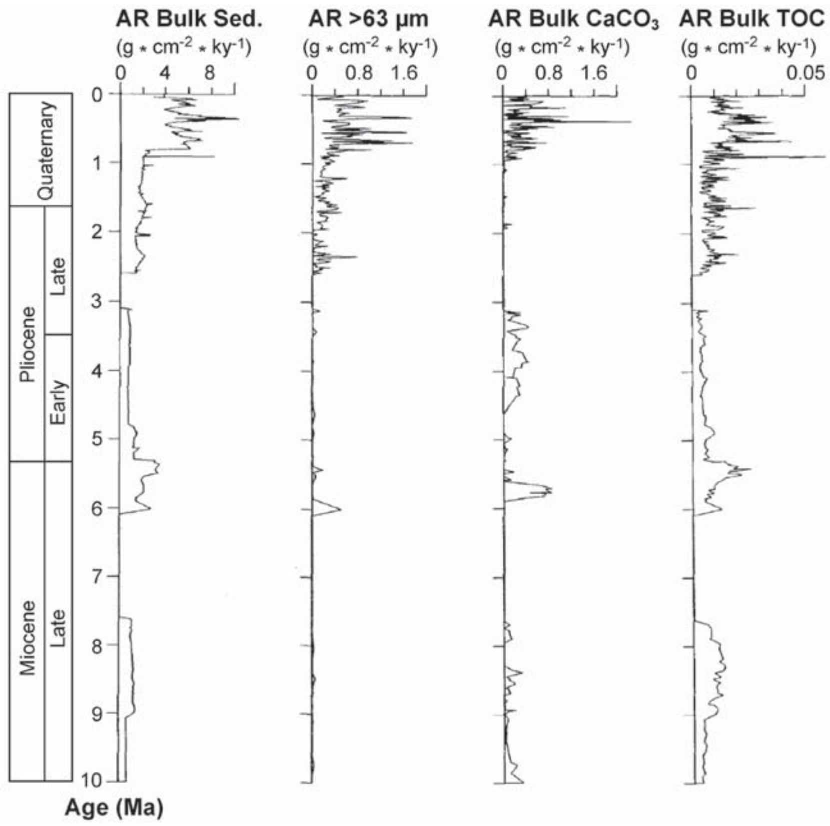

Fig. 5: IRD sedimentation at ODP Site 646 to the south of Greenland since 10 Ma, with stratigraphic record of IRD and sediment composition; AR = Accumulation rate, TOC = total organic carbon. (modified from WOLF & THIEDE 1991).

Abb. 5: IRD-Ablagerung an ODP Site 646 südlich Grönlands seit 10 Ma mit stratigraphischer Verteilung des IRD und Sedimentzusammensetzung; AR = Akkumulationsrate, TOC = gesamter organischer Kohlenstoff. (verändert nach WOLF & THIEDE, 1991).

between 9-7 Ma. Since 3 Ma rock fragments increased to approximately 20 % of the coarse fraction, and their distribution is subject to strong fluctuations. A correlation of their occurrences to the oxygen isotope data from the same site suggest that major pulses of the influx of ice-rafted materials are linked to transitional periods between glacials and interglacials.

ODP Leg 151

ODP Leg 151 was part of a drilling program devoted to unravel the history of the North Atlantic-Arctic gateways (Myhre et al. 1995). It brought the "Joides Resolution" into very high northern latitudes where it – accompanied by the icebreaker "Fennica" drilled locations on the Yermak Plateau, thus entering as a scientific drill ship the true Arctic Ocean for the first time. The drilling programme of this leg consisted of a transect of sites on the Iceland Plateau, in Fram Strait and on Yermak Plateau, and – particularly interesting for the topic of this study – a site very close to the central East Greenland continental margin (Site 913). All of the sites contained sequences with abundant ice-rafted debris of various origin and composed of varying proportions of sedimentary, metamorphic and igneous rocks. It was the first time that detailed data of the stratigraphy and composition of the IRD was collected and related to their possible source regions.

The reports on Site 907 do not contain any detailed information about the IRD; the site has been revisisted during ODP Leg 162 (Jansen et al. 1996), but again no detailed information is provided on the nature and frequency of the IRD. The cluster of sites in Fram Strait (sites 908, 909) and on Yermak Plateau (sites 910, 911, 912) have been analyzed in great detail for their stratigraphic and compositional records of IRD. They comprised frequent pebbles of several centimetres in diameter and their dominance seemed to be restricted to Pliocene and Quaternary deposits (Myhre et al. 1995). The pebble assemblages have a composition, which seemed similar for all of these sites and were dominantly composed of sedimentary rocks (sandstones, silt and clay stones, sometimes coals, very few carbonates, quartzites), occasionally also of igneous and metamorphic rocks. Thiede et al. (1998) and Winkler et al. (2002) calculated the accumulation of the IRD at Site 909 and were able to demonstrate that ice-rafting occurred without major interruptions (at least at the available stratigraphic resolution) since 18 Ma (Fig. 6), with distinct pulses of IRD deposition at 14.5-13.5, 9.5-9, 7.5-7, 3-2.5, and 1.5-1 Ma. This represents a substantial part of the Miocene, the entire Pliocene, and the Quaternary and covers the entire stratigraphic record available from this site. The composition of the IRD for this grouping of sites is suggesting mainly a Eurasian source, the large dominance of sedimentary components being the major difference to the pebble assemblages of Site 913.

Site 913 is extraordinary in several aspects. It covers a very long time span, from Middle Eocene to Quaternary sediments, but because of various reasons in part with relatively poor core recoveries. Frequent dropstones were initially recorded in the Miocene to Quaternary sections, with highest abundances in the lower Quaternary and Pliocene sections, but decreasing towards the uppermost sediments. Thiede et al. (1995) compared the composition of the dropstone assemblages in the Neogene sections of Site 913 with the northern group of sites of Leg 151 and found major differences. Whereas the northern sites contained 67-79 % sedimentary dropstones, their propor-

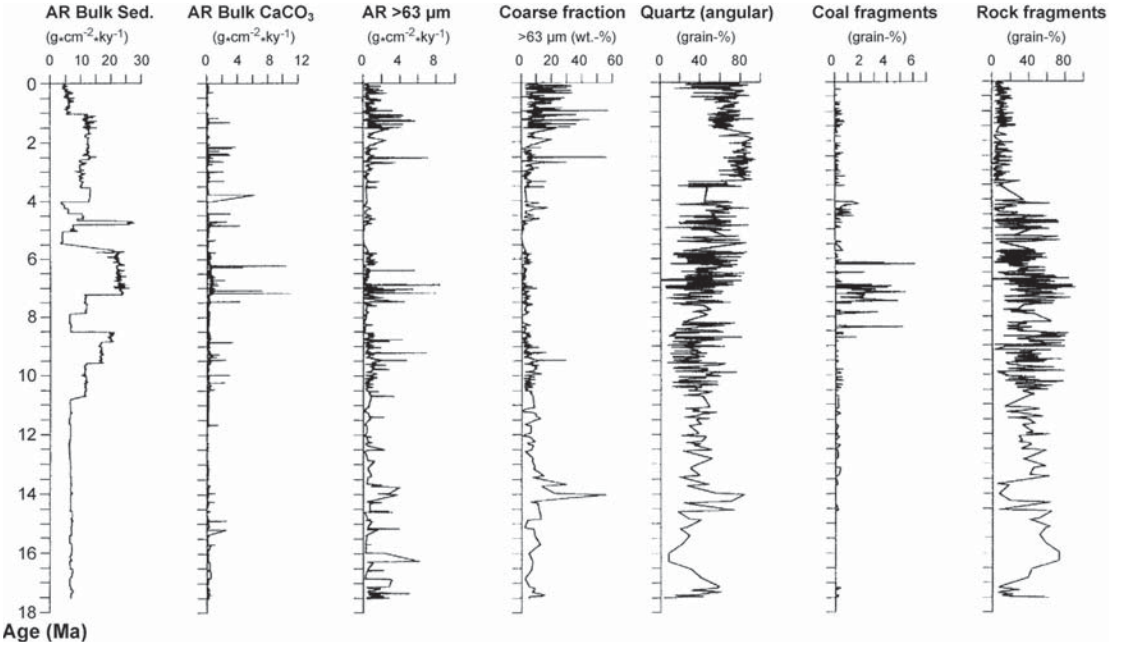

Fig. 6: Accumulation rates (AR) of various sediment components including IRD at ODP Site 909 in the central Fram Strait since 18 Ma (modified from Thiede et al. 1998).

Abb. 6: Akkumulationsraten (AR) verschiedener Sedimentkomponenten einschließlich IRD in der ODP-Bohrung 909 in der zentralen Framstraße seit 18 Ma (verändert nach Thiede et al. 1998).

tion is reduced to 19 % at Site 913, igneous (38 %) and metamorphic (41 %) dropstones making up the dominant remainder. This suggested a completely different source region for the dropstones in the Pliocene to Quaternary sections of Site 913, in all probability Greenland, which is located in the close vicinity.

At the time of the initial studies no IRD older than Miocene to Quaternary had been detected. However, core site 913 was revisited later by TRIPATI et al. (2008) (Fig. 7). They claim that the ice-rafted debris has been found in Middle Eocene to Lower Oligocene sediments (approximately 30 to 44 Ma), the proportions of components >500 µm is very small, but the authors have interpreted them as true dropstones, potentially deposited from icebergs. Assuming the same source region one will have to accept that some of the Greenland ice/glaciers are potentially much older than hitherto believed. However, this conclusion may be in contradiction to the results presented by ELDRETT et al. (2009).

ODP Leg 152

ODP Leg 152 drilled a suite of sites along a transect across the SE Greenland continental margin (LARSEN et al. 1996), which because of their locations were considered particularly suited to address the question of the age of the Greenland Ice Sheet. The major objectives of this leg were oriented towards understanding the tectonic and magmatic processes related to the early opening of this part of the North Atlantic and of the deeper structure of the continental margin. However, seismic reflection data of the shallow parts of the penetrated stratigraphic sequences leave no doubt that the tills and glaciomarine deposits originated from Greenland (LYKKE-ANDERSEN 1998) and it is a pity that the origin and stratigraphy of the glacial materials did not receive the attention they deserved.

Several of the initial site descriptions contain important details on stratigraphic distribution and composition of the glacial materials in these sites, and we will make as much use of them as possible. The drilling programme of the leg started with a grouping of locations on the shelf where large amounts of dropstones were found and even tills (diamictons) were part of the stratigraphic sequences. Sites 914, 915 and 916 were located in water depths of less than 1000 m and the presence of overconsolidated tills must indicate that the Greenland ice sheet extended far out onto the shelf during the time of their formation. Stratigraphic information is scarce and they are listed mostly as Quaternary. Some oriented fabric of the tills is listed as the result of the plowing effect of the grounded glacier generating these deposits (LARSEN et al. 1998). The dominant share of the pebbles from the tills are igneous in origin (granites, gabbros, basalts).

A questionable diamicton has also been reported from Site 917, which is located in approx. 508 m water depth. The Shipbord Scientific Party (1996) summarized the shelf sites and documented the presence of coarse clasts composed of igneous, metamorphic, and to a minor degree sedimentary rocks in the various mostly Quaternary lithostratigraphic units/subunits. The large proportion of basaltic clasts represents a major difference from Site 913 located close to Greenland, but substantially further north than these sites. They linked the occurrence of the diamictons to a larger Greenland ice sheet, assumed to be correlated to MIS 6.

Site 918 of this leg is located in 1868 m water depths and has produced an almost 600 m long record of dropstones of dominantly igneous composition (basalts, granites, dolerites, gabbro) but with some metamorphic and sedimentary rocks. The number of dropstones is highly variable, but they seem to extend into the late Miocene. Site 919 is located in 2088 m water depths and penetrated into a regularly stratified and

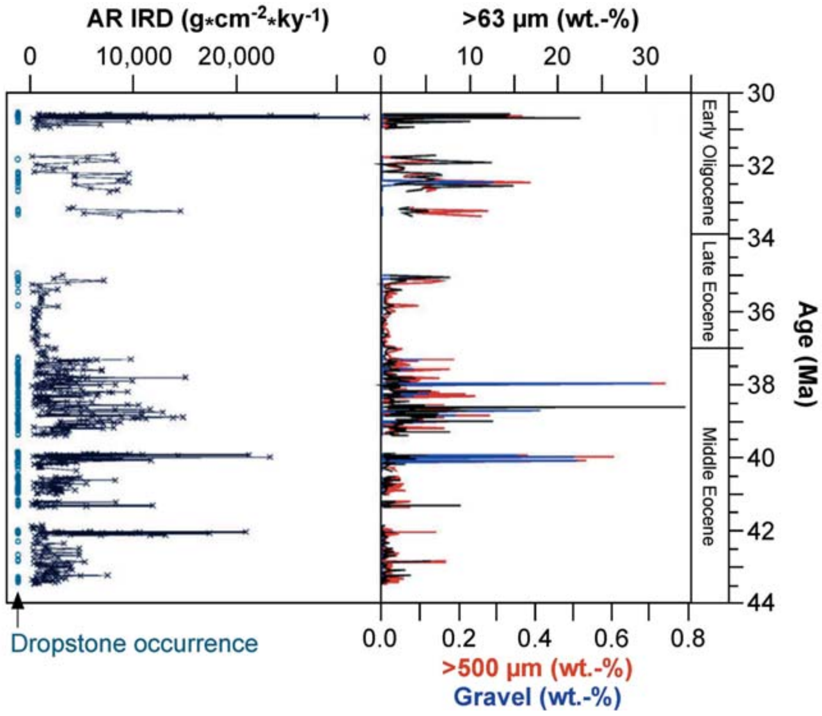

Fig. 7: Accumulation rates (AR) and grain size distribution of IRD at ODP Site 913 off East Greenland during 44-30 Ma (modified from TRIPATI et al. 2008).

Abb. 7: Akkumulationsraten (AR) und Korngrößenverteilung des IRD in der ODP-Bohrung 913 vor Ostgrönland in mittel-eozänen bis unter-oligozänen (44-30 Ma) Sedimenten (verändert nach TRIPATI et al. 2008).

undisturbed sedimentary sequence with dropstones composed of gneiss, other metamorphics, basalt, dolerite, gabbros and few sedimentary rocks. The oldest dropstone was reported from Pliocene sediments.

The Shipboard Scientific Party speculated in its summary of the cruise results on the onset of glaciation in Greenland (LARSEN et al. 1996). They related the occurrence of the oldest dropstones at Site 918 to an early glaciation, which began during Late Miocene time, but with a maximum developed during the Pliocene. The composition of the ice-rafted clasts could be related to sources in central East and Southeast Greenland. The Neogene dropstones did not occur continuously; the sequences comprising dropstones has been interpreted to reflect the results of three major glaciations of Southeast Greenland between 2.0 and 5.3 Ma because the dropstone occurrencs were separated by marine sediments devoid of them (LARSEN et al. 1996), potentially to be correlated to a late Pliocene relatively warm climatic phase over Greenland (FUNDER 1989). Coring had been difficult at these sites off south-eastern Greenland, recovery and stratigrapic resolution were limited and hence we are missing many of the details of the temporal evolution of the Neogene development of the Greenland Ice Sheet, but the unquestionable link of the glacial materials in the cores from these sites give this data set great weight for this study.

ODP Leg 162

ODP Leg 162 also belonged to the drilling programme devoted to the history of the North Atlantic – Arctic Gateways. Major emphasis was directed to the Southern gateway across the Greenland-Scotland Ridge and one site (Site 987) is located close to the East Greenland continental margin off Scoresby Sound, actually on the northeastern flank of the Scoresby Sound glacial fan (JANSEN et al. 1996). It penetrated Miocene to Quaternary sequences and was planned to establish the history of the Greenland Ice Sheet, but the stratigraphic record was disturbed by the occurrence of numerous turbidites. The presence of droptones is mentioned in many of the core descriptions. As at Site 913, the dropstone assemblages seem to have been dominated by igneous and metamorphic rocks. No systematic attempt has been undertaken to quantify their composition as well as their stratigraphic distribution. The oldest dropstone was listed in the Miocene cores. As in the case of Site 913, there is little doubt that the dropstone assemblages of Site 987 – located off Scoresby Sound, Greenland's largest fjord – have their origin in Greenland.

IODP Expedition 302 (Arctic Coring Expedition - ACEX)

Unravelling the history of the northern hemisphere progressed substantially when ECORD (European Consortium of Research Drilling) managed to organize the ACEX (IODP Leg 302) to a location on Lomonosov Ridge very close to the North Pole. By means of seismic reflection profiling Jokat et al. (1995) had detected here an apparently undisturbed sedimentary sequence conformably covering the ridge crest. It was hoped to comprise a complete record of the Cenozoic paleoceanographic history of the Arctic Ocean. This spectacular expedition (BACKMAN et al. 2006, BACKMAN & MORAN 2009) was conducted during the late summer 2004 when an armada of three ice-breaking vessels (the Swedish "Oden" and the Russian "Sovietsky Soyuz" in support of the drilling platform "Vidar Viking") entered the central Arctic Ocean. They succeeded to core an approximately 450 m thick sedimentary sequence documented in the seismic reflection profile from the top of the Lomonosov Ridge. Even though interrupted by long hiata (BACKMAN & MORAN 2009), the sedimentary sequences collected at the IODP Expedition 302 drill sites offer important insights into the transition of the Arctic Ocean paleoenvironments from a temperate to warm to glacial climatic conditions. ST. JOHN (2008) has analysed the contents of IRD in these cores (Fig. 8) and came to the unexpected and highly surprising conclusion that ice-transported materials including pebbles were reaching the central Arctic Ocean as early as approximately 47.5 Ma, overlying marine sediments representing the PETM (Paleocene-Eocene Thermal Maximum) and the obviously fresh-water influenced deposits of the "Azolla"-event (BRINKHUIS et al. 2006, BACKMAN & MORAN 2009), which are believed to represent times with no ice cover in the Arctic Ocean. The accumulation rates of IRD are small, their grains size is usually relatively small and it is difficult to speculate about their origin and source region, but BACKMAN & MORAN (2009) suggest that Greenland and potentially also Svalbard have acted as places where early ephemeral glaciers developed.

The stratigraphic continuity of the IODP Expedition 302 sites is interrupted by several long lasting hiata of unknown origin. For this study are the Eocene to Miocene (18.2-44.4 Ma) as well as the Miocene (9.4-11.6 Ma) interruptions of the sedimentation relevant, and nothing can be learned on whether the central Arctic Ocean was ice-covered during these time spans or not. However, as documented by ST. JOHN (2008), the early accumulation rates of IRD rose very quickly from modest values beginning at approximately 47.5 Ma to values comparable to the Neogene input of IRD already in Eocene times (Fig. 8). STICKLEY et al. (2009) have analysed the diatom content of these sediments and found extraordinary abundances of fossil diatoms belonging to *Synedropsis* spp., which are dependent of sea-ice. Hence they have interpreted the record of the ice-rafted materials related to the presence of sea ice rather than large iceberg producing glaciers on the continents surrounding the Arctic Ocean.

The paper of STICKLEY et al. (2009) picked up an idea and observations, which had been published by DAVIES et al. (2009). They have restudied the Upper Cretaceous laminated CESAR-6 core from the Alpha Ridge, which for a long time had been thought to document an ice-free, relatively warm Arctic Ocean. However, by restudying this and other similar cores they found thin layers of poorly sorted fine-grained terrigenous sediment, linked to the layers formed during the spring diatom bloom. They concluded that seasonal sea-ice could have formed as a consequence of substantially colder winter temperatures than assumed hitherto.

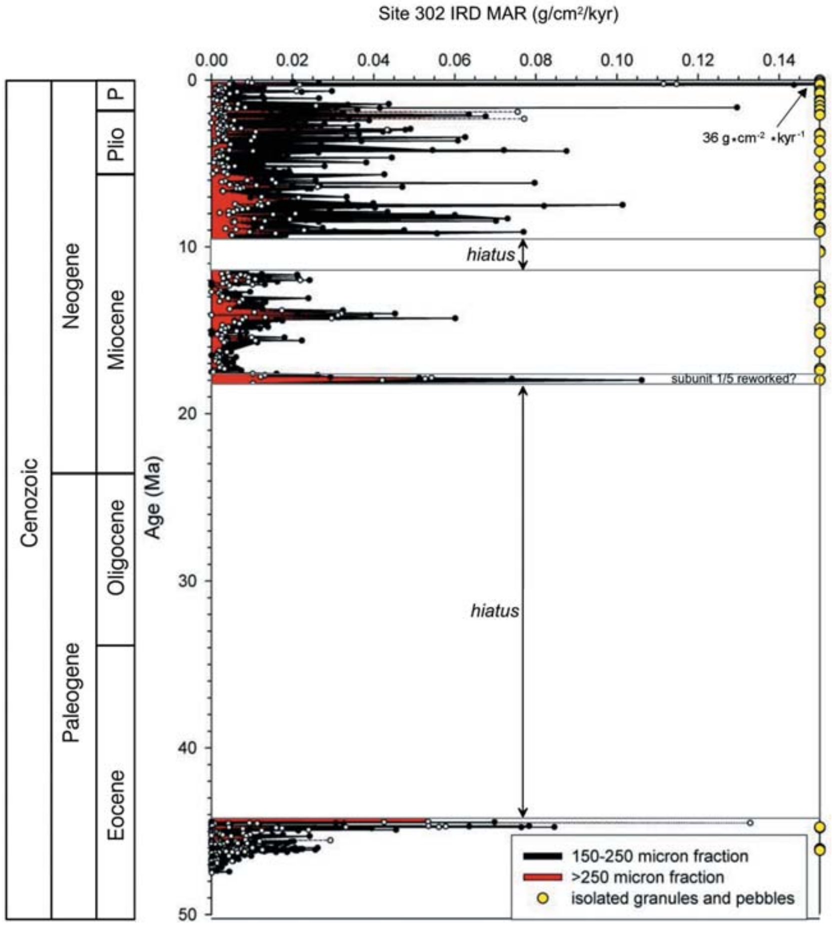

Fig. 8: Accumulation rates (AR) of IRD on the Lomonosov Ridge in the central Arctic Ocean (IODP Leg 302; modified from St. John 2008).

Abb. 8: Akkumulationsraten (AR) des IRD auf dem Lomonosov-Rücken im zentralen Arktischen Ozean (IODP Leg 302; modifiziert nach St. John 2008).

HISTORY OF THE GREENLAND ICE SHEET DURING SELECTED TIME INTERVALS

Pleistocene and Holocene shelf records and onshore evidence

By virtue of the physical properties of ice, and the processes controlling the dynamics of the turnover of the ice sheets, only relatively young records of glacial ice caps on Antarctica and on Greenland have been preserved, on Greenland with ice probably not older than 150-200 kyr and on Antarctica potentially as old as 1.5-2 Ma. The modern Greenland Ice Sheet is a small rest of the northern hemisphere Last Glacial Maximum ice sheets. The ice cores drilled in central and northern Greenland have proven that the ice sheet existed during the entire Holocene, through the last Glacial and at least during the younger part of the last interglacial (LIG, Eemian) period (North Greenland Ice Core Project Members 2004, see also Colville et al. 2011). The extent of the Greenland ice sheet has, however, fluctuated substantially over this time as could be shown by classical geological mapping of Quaternary deposits exposed around the fringes of Greenland (see Funder et al. 2011 for a review). Onshore and shelf data provide evidence for periods when the ice extended over all or parts of the shelves, in particular during the glacial periods (e.g., Andrews et al. 1998a, Jennings et al. 2002a, Dowdeswell et al. 2010, Larsen et al. 2010, Funder et al. 2011). There is substantial uncertainty about the extent of the ice sheet during warm climatic phases like the early Holocene and in particular during the LIG when the global sea level was higher by 1.6-2.2 m (Colville et al. 2011). For the LGM, widespread evidence has been found for the Greenland ice sheet to have extended at least onto the continental shelf while inland ice would have covered most areas where presently only local glaciers are found (Funder et al. 2011). Deglaciation started around 17 kyr BP, but was diachronous in the various shelf areas, probably owing to variable influences like sea-level change, ocean warming, bathymetry etc. (Funder et al. 2011).

Stratigraphy and the pollen records from marine sediment cores

The identification of the timing of ice-rafting required extensive stratigraphic studies of available sediment cores. Pollen assemblages from marine sediments have been used for palaeoenvironmental reconstruction in several continental margin regions. In this case the interpretation of these assemblages and identification of the source area has often been difficult as pollen may be exotic and derived from long-distance transport. Long-distance atmospheric transport normally leads to enrichment of *Pinus* pollen grains. On the other hand, detailed studies in continental margin settings demonstrated that most of the pollen in marine sediments originate here from fluvial input from adjacent land areas and are thus indicative of terrestrial vegetation changes in these areas. For example, based on pollen material from ODP Site 646 in the NE Labrador Sea, DE VERNAL & HILLAIRE-MARCEL (2008) could confirm the existence of a boreal coniferous forest in southern Greenland some 400 kyr ago. These conclusions support the previously reported finding of a forested southern Greenland by WILLERSLEV et al. (2007). The latter study found evidence for the occurrence of *Alnus, Populus,* and other typical northern boreal vegetation species different from today's Greenland environment. Thus, by using pollen assemblages from marine sediments, major variations in Greenland inland ice extent have been documented for the past million years.

Upper Pleistocene and Holocene marine records

Information about upper Pleistocene deposits on the extensive shelf areas around Greenland is limited. However, a number of sediment cores have been collected off East Greenland and in the West Greenland Disko Bay area (e.g., JENNINGS et al. 2002b, KUIJPERS et al. 2001). Cores from the continental slope off East Greenland reveal continuous Upper Pleistocene to Holocene sediment records, reflecting the waxing and waning of the ice sheet both on the continental shelves and inland (e.g. NAM 1997). The shifting focus of sediment delivery during each cycle, varying from inner fjords to the continental shelf break and upper slope, is reflected in the marine records from these environments (DOWDESWELL et al. 1998). Marine IRD records of the last two glacial-interglacial cycles along the continental margin of East Greenland reveal major advances and retreats of glaciers beyond the coastline (NAM 1997, NAM & STEIN 1999). Most of the major IRD peaks correspond to periods of cooling of air temperatures over Greenland. Proxies from Greenland ice cores and North Atlantic marine sediment cores of the late Pleistocene document repeated abrupt climate swings of a few decades to millennia, including massive ice-rafting (Heinrich / Dansgaard-Oeschger) events, which disrupted ocean circulation, resulting in severe cooling (BOND et al. 1992, NAM & STEIN 1999).

Fjords are known to be important sedimentary traps during both deglaciation events and ice-free periods. During glacial advances, glacial erosion causes these sediments to be removed and transported further offshore. Consequently, the many large fjord systems of Greenland host thick marine (or glaciomarine) sediment successions of late Glacial to Holocene age, with a potential for preserving high-resolution records of environmental changes and climatic variability. Records from the Greenland fjords both identify local-scale response of the Greenland Ice Sheet to climate forcing, as well as close oceanographic links between Greenland and broader North Atlantic oceanography (e.g., LLOYD et al. 2007). Proxy records of Holocene climate history on East Greenland are internally consistent at multi-century to millennial resolution (e.g., ANDREWS et al. 1997). Holocene records show that, once deglaciation was complete, the climatic proxies follow the broad trends indicated by the solar insolation, such that early to mid-Holocene warming was followed by Neoglacial cooling beginning between 6 and 4 cal. ka (e.g., KOC et al. 1993). Records of IRD from several shelf cores show that between 8 and 6 cal. ka there were rare intervals of IRD delivery, whereas in the last 6 cal. ka the IRD was pervasive (ANDREWS et al. 1997). Recent studies of upper Holocene records from West Greenland have revealed a long-term climate see-saw pattern of this region as compared to the Northeast Atlantic including western Europe (SEIDENKRANTZ et al. 2008). This can be explained by a North Atlantic Oscillation type long-term atmospheric circulation pattern.

Beyond sediment cores there is naturally substantial other evidence that the Greenland Ice Sheet extended much further offshore than at present, at least for the LGM. DOWDESWELL et al. (2010) using geophysical observations were able to prove that the ice sheet extended for about 200 km across the shelf off East Greenland (off the Kangerlussuaq Fjord). LARSEN et al. (2010) have demonstrated the same for the area off northernmost Greenland. The long debate of an ice sheet covering the entire Arctic Ocean has found a continuation in the paper of JAKOBSSON et al. 2010 who collected information on overconsolidated sediments and erosional features related to thick ice from many of the marginal plateaus and from Lomonosov Ridge. They argue now for the development of an ice shelf, much like in Antarctica, in many of the marginal areas during MIS 6; the question if this ice shelf may have covered the entire central Arctic Ocean is left open.

Mid-Brunhes Transition

The implications of the Mid-Brunhes Transition (MTB), which is a marked climate boundary marking the beginning of a mode of four large-amplitude 100 kyr glacial-interglacial cycles having been operating until today, are unclear for the Greenland Ice Sheet development. Antarctic interglacials prior to the MBT displayed less warming but lasted for a longer time (e.g., RAYNAUD et al. 2005). Prior to the MBT, the average position of interglacial ocean-fronts both north and south of the Equator had probably been displaced about five degrees more to the north, reflecting increased interhemispheric climatic asymmetry during interglacials (JANSEN et al. 1986, KUIJPERS 1989). These conditions may have favoured atmospheric and ocean circulation patterns over and around Greenland, leading to significant retreat of the ice in southern Greenland during this period as recently suggested by WILLERSLEV et al. (2007). This conclusion is supported by pollen data from a marine sediment core south of Greenland, revealing that the exceptionally warm interglacial period (Stage 11: 424-374 kyr BP) was characterised by much higher spruce pollen concentrations, supporting widespread coniferous foresting of southern Greenland during that period (DE VERNAL & HILLAIRE-MARCEL 2008). However, there are ice-rafted pebbles in the corresponding marine sediments suggesting at least a partial ice-cover over Greenland.

Mid-Pleistocene Revolution (MPR)

Another major, global shift in large-scale patterns of ocean and atmospheric circulation occurred between 900 and 650 ka and is known as the Mid-Pleistocene Revolution (BERGER & JANSEN 1994, MASLIN & RIDGEWELL 2005). The MPR is characterized by an increase in mean global ice volume and a change in the dominant orbital period from 41 to 100 kyr. High latitude North Atlantic seismic records, not only from the Greenland shelf but also from other areas (e.g., Faroe Islands), document a major shift in (shelf) sedimentation patterns, which for Greenland can be assumed possibly to imply a significant change in inland ice coverage. There is, however, clearly IRD in the corresponding ocean sediments, in particular off northern Greenland. Sediment cores from the Amerasian Basin of the Arctic Ocean reveal a transition to increased IRD deposition in MIS 16 and thereafter, according to preliminary data and stratigraphic correlations (STEIN et al. 2010). Since the IRD largely consists of carbonate rocks (dolomite, calcite), a source area in North Greenland and/or the Canadian islands can be assumed (STEIN et al. 2010), which experienced intensified glaciation after the MPR.

Quaternary Greenland Ice Sheet variability

During late Quaternary glacial inceptions, rapid ice-sheet growth is demonstrated by many studies to have first occurred in North America, presumably NE Canada. Formation of a semi-permanent atmospheric high pressure centre over this early glaciated region must have led to increasing polar air flow over Baffin Bay and adjacent landmasses including West Greenland. Thus, after glacial inception particularly western Greenland may have been already strongly glaciated at an early stage, as also suggested by some marine sediment core data. IRD from the Baffin Bay region may include characteristic detrital carbonate from geological formations of the Ellesmere Island area as well as basalt from the surroundings of Disko Bugt. In contrast, during the beginning of Greenland deglaciation, with major ice sheet dynamics concentrated around the eastern mountain ranges, IRD from this source area can be characterised by abundant plutonic and metamorphic rock as well as dolerite, with only sparse sedimentary rock (LINTHOUT et al. 2000, KUIJPERS et al. 2003).

Major fluctuations of the Greenland Ice Sheet have been documented for the past one million years, but still a large uncertainty exists with regard to the maximum ice sheet extent during extreme glaciation and possible virtually total elimination of the ice sheet during extreme (interglacial) warming episodes. This uncertainty is even larger for the earlier history and timing of initial glaciation of Greenland. It is evident that significant ice sheet reduction has major implications for our understanding of past sea level change under (natural) interglacial warming.

Late Pliocene intensification of glaciation

It is thought that the Northern Hemisphere experienced only ephemeral glaciations from the late Eocene to the early Pliocene (about 38-4 Ma) and that the onset of extensive glaciations did not occur until about 3 Ma (MASLIN et al. 1998, KLEIVEN et al. 2002, BARTOLI et al. 2005). Several explanations for this climate transformation have been suggested; from tectonically-driven closure of the Panama seaway (e.g., HAUG & TIEDEMANN 1998), a diminished northward heat transport by the North Atlantic Current (NAAFS et al. 2010), the loss of a more permanent El Nino state in the late Pliocene (PHILANDER & FEDOROV 2003), to the uplift of the Rocky Mountains and Himalaya forcing cooler air masses and increased moisture to the incipient Greenland ice sheet (RUDDIMAN & KUTZBACH 1989). The CO_2 hypothesis states that lowering of atmospheric CO_2 concentrations during the late Pliocene led to cooler melt-season temperatures and decreased ablation (LUNT et al. 2008). The question remains as to whether some of these forcing mechanisms acted together as a priming mechanism for inception, triggered by orbital variations (LISIECKI & RAYMO 2005). Modelling studies constrained by an expansion of the IRD record and detailed seismic stratigraphy studies from Greenland continental margins may hold the clues to solving this issue (cf. SARNTHEIN et al. 2009).

Kap København Formation – Late Pliocene warming

Onshore sediment records of the Plio-Pleistocene transition are found in a few places in northern and eastern Greenland. The most notable is the Kap København Formation in Peary Land, northern Greenland, from which rich and diverse floras (including larger tree stems) and faunas of marine and non-marine environments have been described (e.g., BENNIKE 1990, FUNDER et al. 2001). The sediments have been dated to about 2.3 million years and as glacial tills are found below and above the formation, it is considered as the earliest known interglacial record from onshore Greenland. During this period the inland ice may have melted totally away. However, the corresponding marine sediments in ODP-cores (see discussion above) do contain IRD (Figs. 5, 6, 8). The Pliocene high latitude warming may have been caused by an intensified North Atlantic Drift, which could bring warm water from equatorial regions northwards (e.g., HAYWOOD et al. 2000). Even if the East Greenland Current is active, it would not bring really cold water south, since the Arctic Ocean is then relatively warm. Estimates of Pliocene atmospheric CO_2 based on stomatal parameters of fossil leaves suggest only a slight increase. Thus enhanced thermohaline circulation was probably the main reason for the reduced equator-to-pole temperature gradient during the Pliocene.

Middle Eocene to Early Oligocene greenhouse to icehouse transition

The glaciation of Greenland during the Cenozoic greenhouse to icehouse climate transition probably led from ephemeral glaciations to the onset of extensive glaciations. Until quite recently it was widely believed that widespread northern hemisphere glaciation was a phenomenon of the late Cenozoic (SHACKLETON et al. 1984, BINTANJA & VAN DE WAL 2008). However, after DSDP, ODP and IODP have repeatedly visited the northernmost extensions of the North Atlantic (Labrador Sea, Baffin Bay, Norwegian-Greenland Sea) and more recently the central Arctic Ocean, it is now clear that iceberg-producing ice sheets or glaciers calving onto shelf regions must have existed for much longer. After WOLF & THIEDE (1991) had described ice-rafted materials in upper Miocene and younger deposits, ODP Leg 151 results from the central Fram Strait discovered ice-rafting in lower Miocene deposits (Site 909, MYHRE et al. 1995). ELDRETT et al. (2007) revisited ODP Leg 151 Site 913 and detected IRD in Eocene-Oligocene deposits off East Greenland. Finally ST. JOHN (2008) described the hitherto earliest onset of ice-rafting in the central Arctic Ocean in Eocene sediments 47-48 Ma (see Fig. 8, from ST. JOHN 2008), hence older than the oldest indicators for Antarctic glaciation (Fig. 9), much to everybody's surprise.

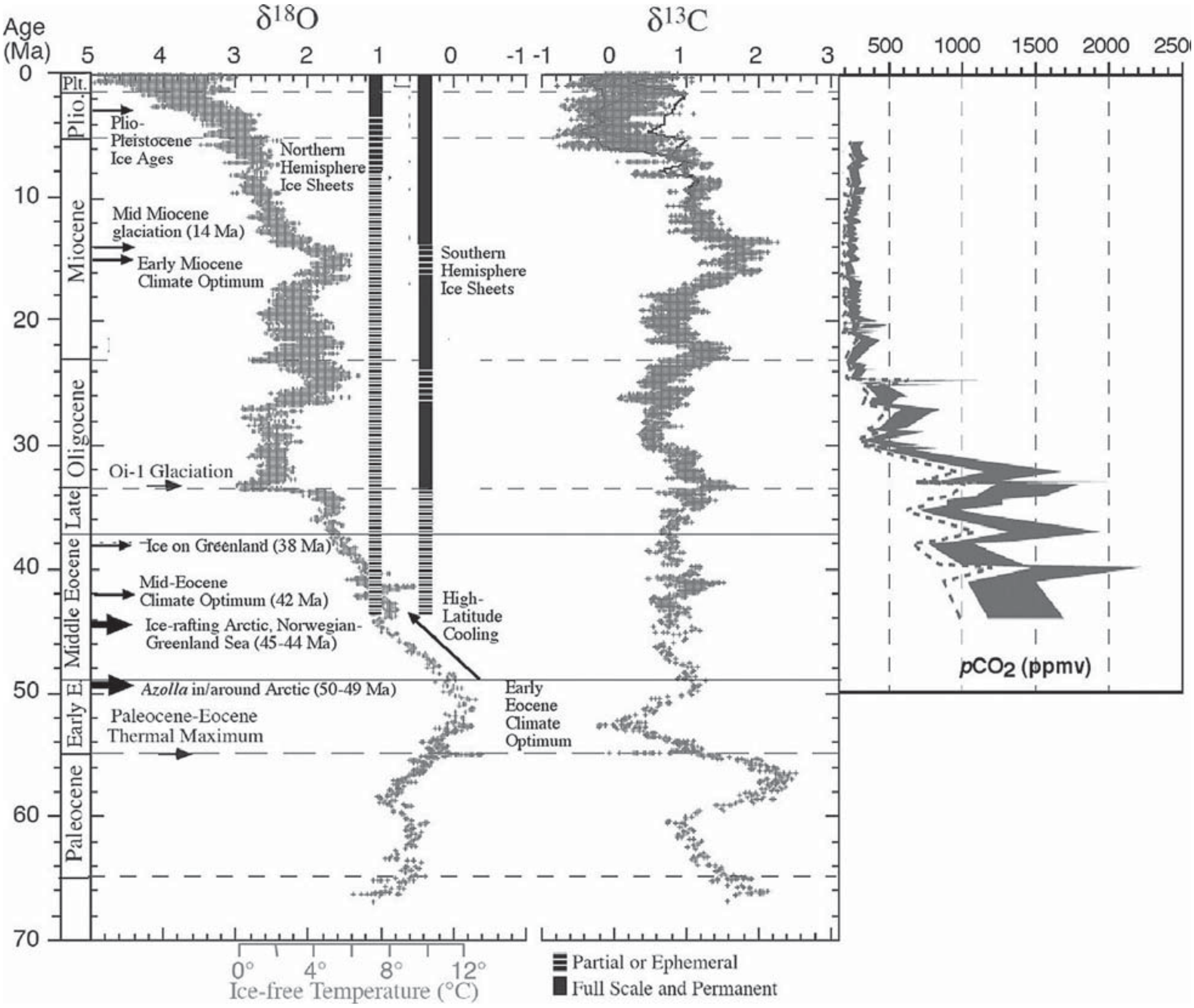

Fig. 9: Summary of climatic development on the northern and the southern hemispheres since 65 Ma and the occurrence of glaciers and/or ice sheets as documented through the occurrence of IRD in deep-sea drilling cores (from THOMAS 2008).

Abb. 9: Übersicht der Klimaentwicklung in den südlichen und nördlichen Polargebieten seit 65 Ma und das Vorkommen von Gletschern und/oder Eisschilden, deren Existenz durch das Vorkommen von IRD in Tiefseebohrkernen belegt wird (aus THOMAS 2008).

How this development on the Northern Hemisphere relates to the global cooling during the Eocene-Oligocene climate transition (with a substantial build-up of ice in Antarctica), remains quite enigmatic (LIU et al. 2009).

Until recently, the oldest IRD documented in the North Atlantic and Pacific was found in sediments that were up to 18 million years old (MYHRE et al. 1995). New scattered IRD findings back to the middle Eocene from both the Antarctic region, the Nordic Seas (TRIPATI et al. 2008), and the Arctic Ocean (ST. JOHN 2008) reveal evidence indicating that glaciers extended to sea level in the region, allowing icebergs to be produced despite the global climate curve (see Fig. 9). This suggests substantially warmer conditions world-wide (see ST. JOHN 2008, ELDRETT et al. 2007). IODP Leg 302 sites revealed a relatively quick onset and intensification of ice-rafting approx. 47-48 Ma (ST. JOHN 2008), but presently we do not know the locations of the early glaciers or ice sheets. Yet constraints on the first occurrence and extent of glacier ice from the distribution of IRD are extremely limited because most sediment cores from the sub-polar oceans in the Northern Hemisphere that are Oligocene or older in age are riddled with hiatuses due to strong bottom current activity and erosion.

ONSET AND ORIGIN OF NORTHERN HEMISPHERE GLACIATION

There is substantial evidence that the Arctic was relatively warm during the Early Eocene (SLUIJS et al. 2006, WELLER & STEIN 2008, EBERLE et al. 2009), but then changes started to occur at a dramatic rate. As illustrated in Figures 8 and 9 the transition from a relatively warm climate over Greenland and the Arctic Ocean happened over a relatively short time span and ice-rafting began when the global climate was substantially warmer and when atmospheric carbon dioxide was higher than today. The important and unresolved problem is the quest for precise timing, location and reason for the appearance of the first glaciers or ice sheets on the Northern Hemisphere sub-polar landmasses. It is too early to speculate about reasons for the onset, nature and place of the earliest Cenozoic glaciations on the northern hemisphere. The Arctic Ocean was without doubt filled by relatively warm waters during the Paleocene and early Eocene (STEIN 2008 cum lit.). The mid-Eocene *Azolla*-event (BRINKHUIS et al. 2006), marked by the massive appearance of spores of a fresh water fern, can only be explained by dramatic flooding of the Arctic Ocean basin from the adjacent continents.

It is tempting to speculate that this may be related to a reorganisation of Siberian drainage patterns as a result of the tectonic changes subsequent to the collision of the plate carrying the Indian subcontinent northwards, once it collided with the southern margins of the Eurasian plate. According to CLEMENTZ et al. (2011) the collision between Asia and India began 53.7 Ma, but it took several millions years until India was firmly locked into the southern Asian continental margin. The reorganized Siberian drainage pattern may have resulted in an increase of the influx of freshwater and would then also have produced a brackish water lid over the Arctic Ocean. This could, after some cooling and possibly related to dropping carbon dioxide levels in the atmosphere, have supported the earliest sea-ice covers and potentially even glaciers on mountain ranges adjacent to the Arctic Ocean (on Greenland?), which then could produce icebergs introducing the first IRD into upper Eocene sediments. It should be noted that there is intermittent sedimentological and geochemical evidence for sea ice as early as the Paleocene-Eocene in the Central Basin on Svalbard (SPIELHAGEN & TRIPATI 2009), which was then connected to NE Greenland.

Widespread evidence has been found that orography is a crucial factor in the initiation of ice sheets. Higher mountains allow earlier glaciation, while the height-mass balance feedback is the most effective process to turn local ice caps into large ice sheets (OERLEMANS 2002). Modelling the disappearance of the Greenland ice sheet due to greenhouse warming has shown that its last (ca 7 %) remains will be found in the easternmost mountain ranges (RIDLEY et al. 2005). Isostatic response of the crust will notably affect the orography and ice sheet evolution, which applies to both glacial inception and elimination. For glacial inception, model studies show that changes in insolation (orbital parameters) are crucial, with precession being the most important factor (KUBATZKI et al. 2005). Reduction in CO_2 favours global cooling but cannot initiate ice-sheet growth itself. These studies have further demonstrated that changes in vegetation and ocean circulation are other crucial factors in the glacial inception process.

RESEARCH NEEDS AND DISCUSSION

The questions raised in this review can be addressed by a variety of methods and data, namely through tracing the glacial morphology on the seafloors surrounding Greenland (almost impossible to date), shallow seismic reflections lines (not available in sufficient number), investigating strata outcropping on land (very incomplete time series) and ocean sediment cores. Here we consider the latter, both because a substantial number of (gravity and piston) cores has already been taken and dated and because we see the chance to acquire new cores relatively soon. The second source of samples are the cores of DSDP, ODP and IODP; new drilling cannot be expected immediately (COAKLEY & STEIN 2009).

Major fluctuations of the Greenland Ice Sheet have been documented for the past one million years, but still a large uncertainty exists with regard to the maximum ice sheet extent during extreme glaciation and the possible virtual total elimination of the ice sheet during extreme (interglacial) warming episodes. This uncertainty is even larger for the earlier history and timing of initial glaciation of Greenland. It is evident that significant ice sheet reduction has major implications for our understanding of past sea level change under (natural) interglacial warming.

Past conditions of a strongly reduced ice sheet should be studied by means of pollen analysis indicating the vegetational environment and climate conditions during past episodes of significant warming. These records should be supplemented by results from paleoceanographic studies of North Atlantic and Arctic thermohaline circulation changes, thus providing a better understanding of the link between Greenland ice sheet variability and ocean circulation since the initial development of the ice sheet.

Based on this review it is clearly important to investigate the evolution and the history of natural variability of the Greenland Ice Sheet from marine records in further detail. These records suggest that the Greenland Ice Sheet has existed for many millions of years and therefore over time scales far beyond those presently available from ice cores. Marine sediments carry large amounts of IRD, and based on their stratigraphy as well as their lithologies, we should be able to define iceberg-producing segments of the Greenland ice sheet/glaciers in both space and time. The timing of onset of glaciation on Greenland and whether is has been glaciated continuously or discontinuously since then, are wide open questions in its long-term history (cf. SARNTHEIN et al. 2009). This is important because the IPCC report of 2007 predicts a substantial contraction of the Greenland ice sheet due to the negative surface mass balance; if this is sustained for millennia, the report predicts the elimination of the Greenland ice sheet and a global sea-level rise of approx. 7 m, comparable to the last interglacial.

The dramatic decrease in extent and thickness of the Arctic sea-ice cover of the past decades has aroused much public and political interest because of the potentially dramatic consequences for the exploitation of living and non-living resources as well as the socio-economic, technical and comercial systems developed in the Arctic seas and in the permafrost-infested adjacent land areas. However, recent findings of possibly ice-rafted sand-sized lithogenic grains in the upper Cretaceous CESAR-6 core from the Alpha ridge (DAVIES et al. 2009) allow speculations about the possibility that an Arctic sea-ice cover may develop in winter despite relatively high surface water temperatures in the summer season. A complete (perennial) disappearance of the Arctic sea-ice cover in the region around northern Greenland can be expected to have major consequences for the adjacent Greenland ice sheet due to major changes in atmospheric conditions involved.

The fate of the Greenland Ice Sheet with its impact on global sea-level changes is one of the central unresolved problems. From archaeological investigations of remnants of early Innuits and from historic reports about the Nordic settlements in southern Greenland towards the end of the medieval climatic optimum it is well known that the extent of the Greenland Ice Sheet and the climate over Greenland can change rapidly.

CONCLUSIONS

- Deep-sea cores with their records of ice-rafting from off NE Greenland, Fram Strait and to the South of Greenland suggest the more or less continuous existence of the Greenland Ice Sheet for the past 18 Mio years, if not more. This material thus provides an unique and fantastic opportunity for a spectacular extension of the record of Northern Hemisphere glaciation back into times that never can be reached by the ice cores. Hence millions of years of Greenland Ice Sheet history are recorded in ocean sediments, which allow to trace the Greenland Ice Sheet history beyond the ice core horizon.

- The amount of available well-studied sediment cores extending beyond the Quaternary along the Greenland margin is quite limited. In order to get a more detailed view of the sediment deposition pattern around Greenland reflecting earlier glaciations (Tripati et al. 2008), it is suggested to retrieve new long sediment cores from selected sites.

- The interpretation of the ice-rafted materials in the oldest sediment cores (Eocene, cf. Tripati et al. 2008, St. John 2008) leaves many questions open. While the occurrence of pebbles points to an iceberg related transport mechanism, the co-occurrence of sea-ice diatoms (Stickley et al. 2009) with the relatively fine-grained ice-rafted material would rather point to sea ice as the transport agent.

- The overall objective of our review was to answer questions of the timing of initial Greenland glaciation as well as its temporal and spatial variability and to what extent the ice sheet could survive conditions of extreme interglacial warming at times beyond the ice core horizon. Using sedimentary records from deep-sea cores from offshore Greenland allows to investigate natural variability of the Greenland Ice Sheet under past climate and ocean regimes ranging from severe glaciation to warming levels surpassing present conditions, and far beyond the ice core horizon. We underline that this information is of paramount importance for mankind both on regional (Greenland onshore habitat, fisheries, North Atlantic ocean circulation) and global scale (potential eustatic sea level rise).

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