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Interactions between the Arctic Ocean and the Siberian Hinterland during the Late Mesozoic and the Cenozoic and Their Impact on the Ice Covers

by Jörn Thiede*[1]

Abstract: The Cenozoic Arctic sea-ice cover owes its existence to the geographical polar position of the Arctic Ocean, its oceanographic isolation and its small solar seasonal insolation (at least during the winter) and hence cool to cold temperatures, as well as its interaction with the continental hinterlands. The major point of this paper will address the impact of paleophysiographic changes of the northern hemisphere (mainly in Siberia) on the history of its ice covers. The vagueries of the Cenozoic Arctic ice-cover history require intensified future studies, but have the potential of contributing to our understanding of future environments on the Northern Hemisphere. This may have its implications for the socioeconomic conditions for the societies inhabiting high northern latitude land areas, probably beyond that even on a global scale. Climatic conditions during the young geologic past were sometimes warmer than today; the climate has a "memory", and as such reconstructed conditions might offer analogues for what is in store for the future for all of us.

Zusammenfassung: Die känozoische arktische Eisbedeckung verdankt ihre Entstehung und ihre Veränderungen der geographischen polaren Position des Nordpolarmeeres, seiner ozeanographischen Isolation und der relativ kleinen und saisonal stark schwankenden Sonneneinstrahlung und daher kühlen bis kalten Temperaturen. Die Wechselwirkung mit dem angrenzenden kontinentalen Hinterland (in diesem Falle hauptsächlich Sibirien) spielt dabei eine große Rolle. Die Unsicherheiten der Geschichte der arktischen Eisbedeckung erfordern große, künftige Forschungsanstrengungen, aber haben das Potential für wichtige Beiträge zum Verständnis der Umweltbedingungen in der Zukunft auf der Nordhemisphäre. Sie mögen große Auswirkungen für die sozioökonomischen Rahmenbedingungen für die Bewohner der Nordhemisphäre haben, wahrscheinlich darüber hinaus jedoch auch für den gesamten Erdball. Die Klimaverhältnisse in der jüngsten geologischen Vergangenheit waren zeitweise wärmer als heute. Klima hat ein „Gedächtnis" und die rekonstruierten Szenarios bieten mögliche Beispiele für zukünftige Entwicklungen der globalen Umweltverhältnisse.

INTRODUCTION

In this paper, I want to review briefly the physical frame of the paleoclimatic evolution on the northern hemisphere during the Cenozoic, because it covers a largely terrestrial dominated hemisphere hence of important consequences for human societies inhabiting these land areas, but possibly reaching the entire globe. It must be pointed out that the impact of these developments is by no means restricted to high northern latitude regions. The physical frames must consider:

(1) major plate tectonic events which influenced the paleogeography and -physiography of the Arctic Ocean and of its adjacent continents, much in a way as Köppen & Wegener (1924) considered the relationship of paleogeography and paleoclimate;
(2) the interaction of the Siberian continental hinterlands with the entire Arctic Ocean during the Cenozoic which had an enormous impact on the cooling of the northern hemisphere. The sedimentary sequences from the Arctic Ocean now reveal a much longer historic sequence of glacial events contradicttory to our previous understanding; and
(3) a paleoclimatic evolution of the northern hemisphere as examplified by the history of Arctic Ocean ice covers during the Late Mesozoic and the Cenozoic.

The onset of "glacial" climates at least since the middle Eocene on the northern hemisphere and ensuing eustatic sea-level changes resulted in the temporal emergence of its huge shelf seas and the repeated cut-off of some of the shallow connections of the Arctic Ocean to the world ocean (cf. Hopkins 1967). As a consequence of the climatic development during the Late Mesozoic and Cenozoic the Arctic Ocean acquired ice covers of highly variable nature, with temporal and probably at first only seasonal sea-ice covers over the ocean, but later (since middle Eocene times) also with glaciers and finally large ice sheets over North America, Greenland and northwestern Eurasia, as described below.

Finally, the modern Arctic Ocean is responding fast to the ongoing anthropogenically induced climate warming which causes a shrinking sea-ice cover, a shrinking Greenland ice sheet, rising global sea levels (and we do not know how far and how fast it will rise), and an instabilisation of large tracts of the land surface due to thawing permafrost (Haine & Torge 2017, AMAP 2017).

In this study, I will attempt to establish a relationship between the Cenozoic paleogeographic changes on the northern hemisphere, which controlled important properties of the hydrography of the Arctic Ocean water masses, and the resulting paleoclimatic changes, in a way following the philosophy of Köppen & Wegener (1924). In attempting to do so, one is facing major obstacles because:
(1) The Arctic Ocean paleoenvironmental record is still fragmentary, despite the highly successful attempts to drill the Arctic Ocean for long sediment sequences (Backman & Moran 2009, Myhre et al. 1995).
(2) The same applies to the history of the Siberian river systems, with the exception of its youngest part (Alekseev & Drouchits 2004), and

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(3) our poor understanding of the long-term development of the paleogeography and -physiography of NE Siberia (Diekmann et al. 2017).

PLATE TECTONIC EVENTS

There are two major plate tectonic events which influenced the hydrography of the Arctic Ocean and which happened both during the early or middle Paleogene. One occurred very close to the Arctic itself, namely the opening of Fram Strait, the first and only deep-water passage between the Arctic and the global oceans through the Norwegian-Greenland Sea, an extension of the Atlantic (Talwani & Eldholm 1977, Kristoffersen 1990, Piepjohn et al. 2016) to the North. The other one occurred very far from the Arctic, when the paleophysiography of the Eurasian Plate changed dramatically through reorienting the drainage pattern of rivers from the Siberian platform into the Arctic Ocean (Alekseev & Drouchits 2004) due to the built-up of the high plateaus and mountain ranges along its southern fringe. The eastern segment of the Siberian platform and its history are particularly important in this context, because the glacial ice sheets over North America and northwestern Eurasia were blocking intermittently fresh water drainage to the Arctic Ocean, while the region between the Taimyr Peninsula and the Bering Strait (Svendsen et al. 2004) remained largely unglaciated (except undated enigmatic indications of glacial erosion from the East Siberian continental margin).

The Opening of Fram Strait

The opening of Fram Strait is closely linked to the plate tectonic evolution of the Norwegian-Greenland Sea and the simultaneous establishment of the deep-sea basin (Eurasian Basin) between Lomonosov Ridge and the Eurasian Arctic continental margin (Fig. 1). The opening of both deep-sea basins began during magnetic anomaly 24 time or slightly earlier, some 56-60 ma ago (Talwani & Eldholm 1977). In the area between Greenland and Svalbard a complicated regime of transform movements first resulted in a collision of the Greenland and Svalbard margins and the establishment of the Tertiary fold belt in western Svalbard (Piepjohn et al. 2016), probably during post Eurekan-times approximately since 34 ma. Later the separation of the margins allowed for the opening of Fram Strait as a deep-water passage. The existence of the Yermak Plateau to the North of Svalbard and of the Morris Jesup Rise to the North of Greenland may have delayed an early opening of Fram Strait, and their poorly defined ages further complicate a better definition of the age of Fram Strait. A major change in the isotopic properties of the Lomonosov Ridge sediments recovered during the ACEX-expedition (Backman & Moran 2009) suggest an important change in the hydrography of the deep Arctic Ocean water masses occurred at 17.3 ma and may indicate that the onset of a deep-water connection between the Arctic Ocean and the Norwegian-Greenland Sea (Jakobsson et al. 2007, Haley et al. 2008) occurred at that time.

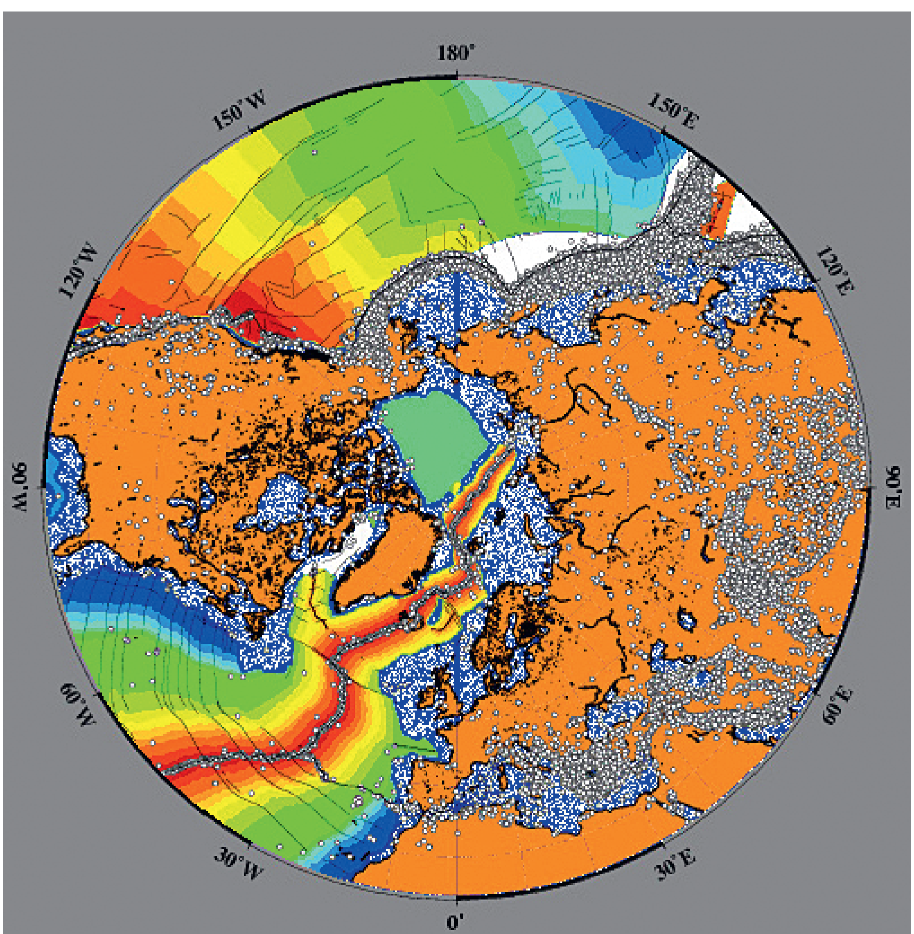

Fig. 1: The opening of Fram Strait (the deep-water passage between Greenland and Svalbard) is related to large Cenozoic transform movements of the continental margins to the East of Greenland and West of Svalbard which first led to tectonic deformation of both margins and later to the opening of Fram Strait. The precise age of the formation of the Canada and Makarov basins between the Amerasian continental margins and Lomonosov Ridge is unknown (dark green). The color code from yellow (oldest = Early Tertiary) to orange (youngest = Quaternary) along the Midocean Ridge in the Norwegian-Greenland Sea and the eastern Arctic Ocean (= Eurasian Basin, along the presently active Gakkel Ridge) has been deduced from the seafloor spreading related magnetic anomalies and reflects the ages of the ocean crust which was formed since approx. 56 ma (Figure via pers. comm. of D. Müller, Sydney; cf. Fig. 2 for its relation to geological age).

Abb. 1: Die Entwicklung und Öffnung der Fram-Straße zwischen den Kontinenträndern von Svalbard und NE Grönland wurde durch Transform-Bewegungen ausgelöst, die zur tektonischen Überprägung beider Kontinentränder und später zur Öffnung der Fram-Straße führten. Das genaue Alter der Entstehung der Canada und Makarov Becken zwischen den Eurasischen Kontinentalrändern und dem Lomonosov Rücken ist unbekannt (Dunkelgrün). Die Farbkodierung von Gelb (Frühtertiär) zu Orange (Quartär) spiegelt das geologische Alter der Bildung der ozeanischen Kruste wider, ist vom Verlauf der magnetischen Anomalien entlang des mittelozeanischen Rückens im Europäischen Nordmeer und im Eurasischen Becken abgeleitet worden und spiegelt ihre plattentektonische Entwicklung seit etwa 56 ma wieder (Abb. persönlich von D. Müller, Sydney; Verhältnis zu den geologischen Altern vgl. Abb. 2).

Changes of the paleophysiography of the Eurasian Plate

The idea of seeking a relationship between tectonism to the origin and history of continental drainage systems and Arctic climate is by no means new (MOLNAR & TAPPONIER 1975, RUDDIMAN & KUTZBACH 1989, Hayes pers. comm. 1996) even though the available stratigraphies and the chronology of events have completely changed over the past 20 years. The timing of this evolution is still highly disputable, as can be demonstrated by BRINKHUIS et al. (2006) who have published a paleogeographic map for the Eocene Arctic Ocean, when the occurrence of *Azolla*-microspores in the ACEX drill-cores (in the sections deposited approximately 48-49 ma) from Lomonosov Ridge suggested substantially warmer temperatures than later. In modern times *Azolla* is a floating fresh-water fern, mostly living in subtropical fresh water environments.

During the Eocene, the Arctic Ocean was connected to the world ocean only through shallow seaways. The Turgay Strait across western Siberia linked the Arctic Ocean with the Tethyan system further to the South (BRINKHUIS et al. 2006) suggesting that the Siberian platform at that time was not tipping to the North. The plate tectonic events further to the South at that time (Fig. 2) resulted in an East Siberian river system draining into the Arctic Ocean (as schematically indicated on Fig. 1). The tectonic evolution of this development is still disputed because the tectonic events in Southern Asia are very difficult to date. CAVES et al. (2017) assumed in their analysis of the Late Miocene tectonic uplift of tectonic units in southern Siberia that the entire Central Asian climate system was reorganized.

The deposition of the *Azolla*-rich sediments (approx. 48-49 ma, BRINKHUIS et al. 2006) preceded the onset of ice-rafting in the ACEX-cores and it is tempting to link the onset of northern hemisphere glaciation to the plate tectonic processes occurring at the southern margin of the Eurasian Plate (Fig. 2). They resulted in the generation of a northward flowing drainage system emptying into the Arctic Ocean, which was and is essential in maintaining the brackish surface water layer in the Arctic Ocean in supporting the sea-ice cover; and this is the major point of this paper.

LATE MESOZOIC AND EARLY CENOZOIC ARCTIC ICE COVERS?

The question arises when the first Arctic sea-ice covers developed. There are data sets, which seem to suggest that the Arctic was completely ice-free during the Late Mesozoic and earliest Cenozoic, supported by observations of Eocene lower

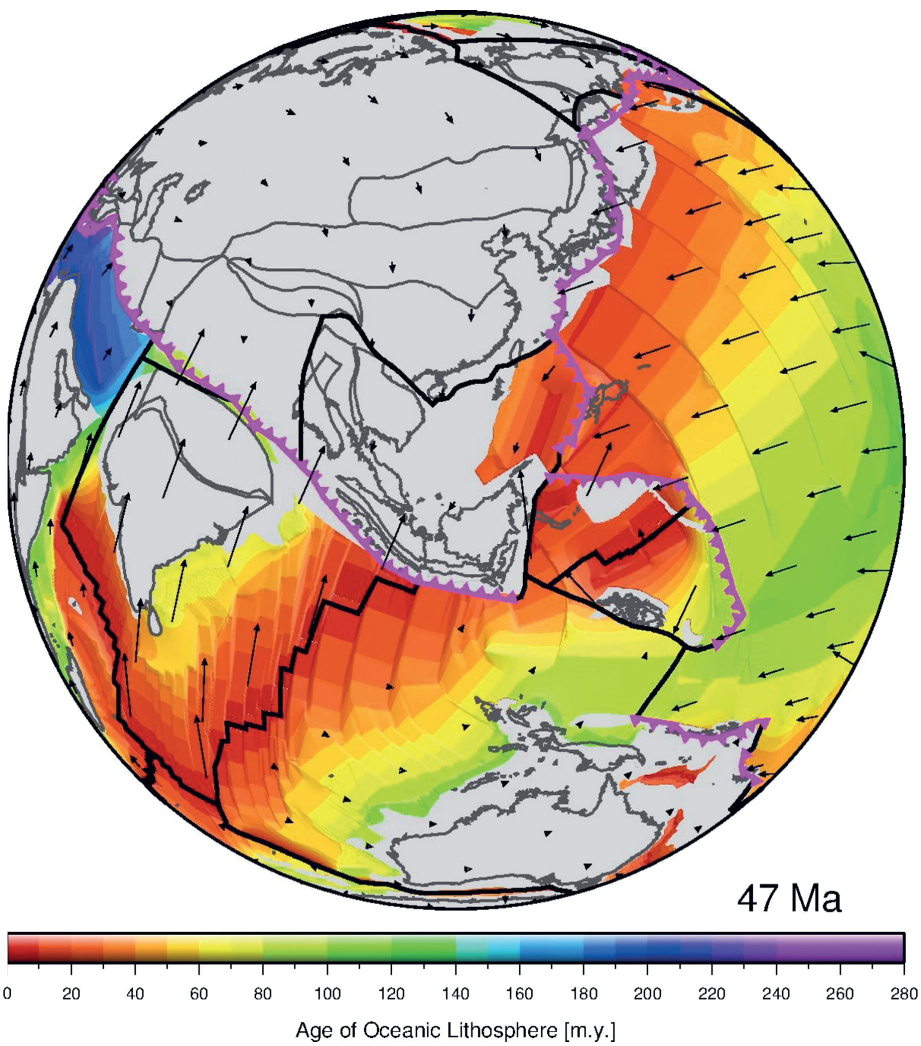

Fig. 2: The late Mesozoic and early Cenozoic plate tectonic development of the Indian Ocean resulted in the collision of the Indian subcontinent with the Southern Eurasian plate margin approx. 48 ma with important consequences for the physiography of the Siberian platform. Since that time, a river system developed almost exclusively draining into the Arctic Ocean (Figure via pers. comm. of D. Müller, Sydney), as schematically indicated in Fig. 1. The age distribution of the deep ocean floors can be deduced from the distribution of well-dated magnetic anomalies related to seafloor spreading, which have been mapped in the global ocean and which allow to trace its plate tectonic evolution. The time slice shown on the figure corresponds to mid-Paleogene (Eocene, some 48 ma), roughly coinciding with the onset of important ice-rafting in the central Arctic Ocean.

Abb. 2: Die spät-mesozoische und früh-känozoische plattentektonische Entwicklung des Indischen Ozeans führte zur Kollision des Indischen Subkontinents mit dem südlichen Kontinentalrand der Eurasischen Platte vor ca. 48 ma, die wichtige Folgen für die Physiographie der Sibirischen Plattform hatte. Seit dieser Zeit haben sich östlich des Urals Flusssysteme entwickelt, die in das Nordpolarmeer abfließen (Abb. persönlich von D. Müller, Sydney), wie schematisch auch in Abb. 1 gezeigt. Die geologischen Alter der ozeanischen Kruste können aus dem Verlauf gut datierter magnetischer Anomalien, die entlang aktiver mittelozeanische Rücken bei deren Spreizung durch Veränderungen des globalen Magnetfeldes entstehen, abgeleitet werden. Die hier gezeigte Zeitscheibe entspricht dem mittleren Paläogen (Eozän, ca. 48 ma), als im zentralen Nordpolarmeer erstmals größere Mengen eistransportierten Materials in pelagischen Sedimenten beobachtet werden.

vertebrates (lizards, turtles, alligators) from Ellesmere Island, Canadian Arctic Archipelago (ESTES & HUTCHINSON 1980) or signs of mangroves in the lower Eocene sediments from the New Siberian Islands (SUAN et al. 2017). CREBER & CHALONER (1985) studied patterns of tree growth during Mesozoic and Early Tertiary times in high northern latitude localities and suggested large seasonal differences. KEMPER (1987) described the occurrence of glendonites and mollusc faunas adapted to cool temperatures in Arctic regions during Mesozoic times, suggesting that the polar regions were cold, probably seasonally ice covered even during climatic warm phases (cf. also ROGOV et al. 2016). SPIELHAGEN & TRIPATI (2009) found evidence (glendonites and erratics) in Svalbard Paleogene sediments for near freezing temperatures.

To define the times of these cold spells during otherwise warm climatic phases is difficult because of stratigraphic problems, but it is clear that the polar regions of the high northern latitudes experienced large seasonal differences and cold winters, even during times of globally warm climates. The paper of SUAN et al. (2017) highlights this problem because they observed indicators for mangroves in lower Eocene sediments from the new Siberian Islands which is highly interesting in the context of the *Azolla*-occurrences in the ACEX-cores.

DAVIES at al. (2009) restudied old sediment cores (CESAR-6 and Fl-437) with laminated biosiliceous Upper Cretaceous deposits (diatom oozes of probably Late Campanian age) suggesting temperate surface water temperatures; the composition of the diatom floras allowed them to differentiate between spring blooms and summer productivity with indications for a strongly layered water column. To their surprise, they also detected thin layers of fine-grained terrigenous materials, which they took for evidence for sea-ice rafting and hence for the formation of sea ice during the cold and dark winter months.

STICKLEY et al. (2009) unraveled the details of the initial formation of seasonal sea ice approx. 46 ma by analyzing a 2 m long segment of the ACEX-cores (approx. 45-48 ma in age) from the Lomonosov Ridge in the central Arctic Ocean (BACKMAN & MORAN 2009), cf. Fig. 3. They found evidence for the presence of fragile sea-ice diatoms and they were able, based on studies of grain texture, to discern between sea ice and iceberg rafted terrigenous debris (IRD). They argued for the existence of small icecaps or glaciers in higher Arctic elevations already during the middle Eocene. So, there exists a large discrepancy between some of the ocean sediment-core-derived data and the onshore evidence (SUAN et al. 2017).

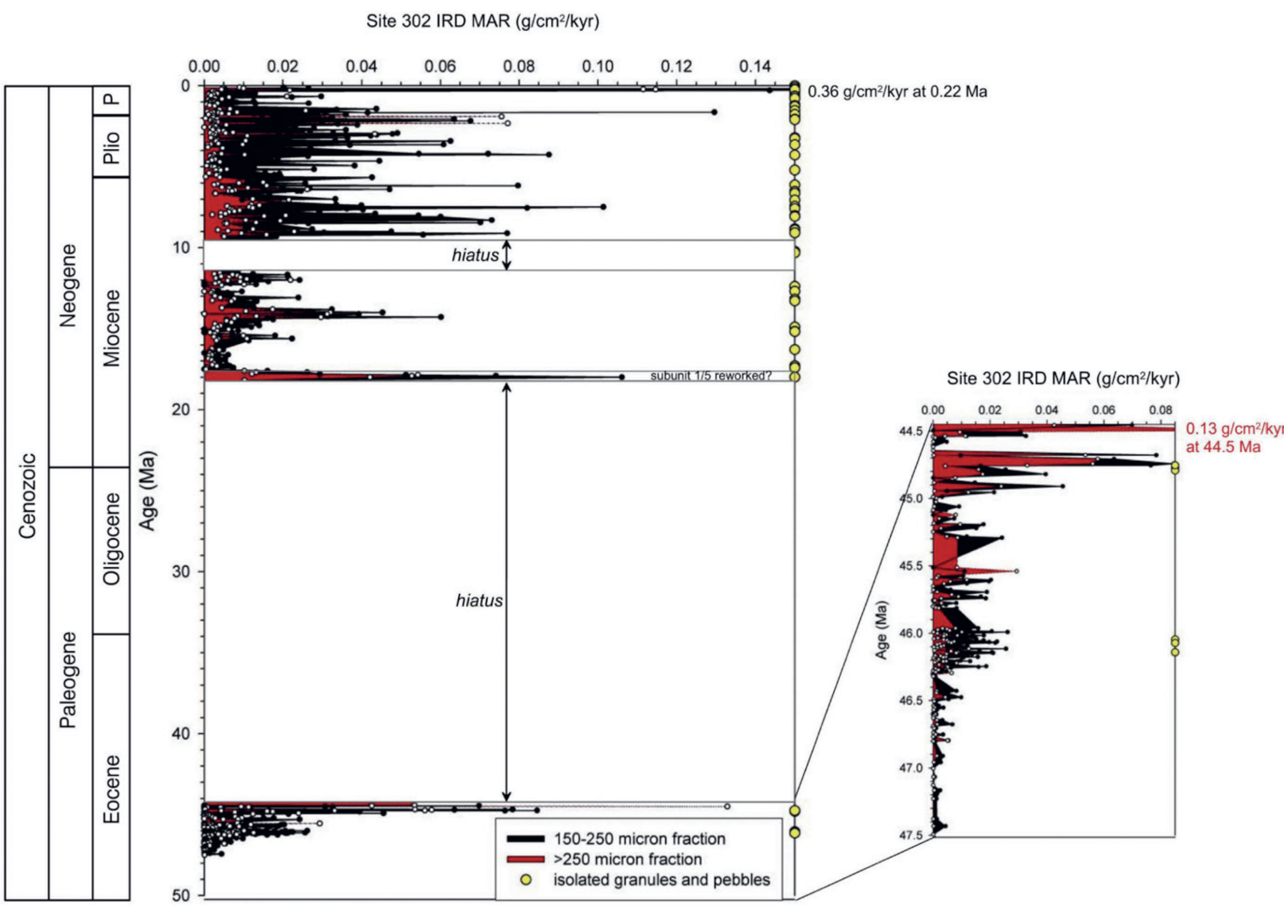

Fig. 3: The Lomonosov Ridge ice-rafting record from Eocene through Quaternary times deduced from terrigenous sediment components (ST JOHN 2008) in the IODP ACEX cores. The yellow circles mark the occurrence of relatively coarse terrigenous deposits, possibly indicative of ice-bergs. Age scales on the left; a hiatus marks a missing sediment record. Regarding the stratigraphic position of the mid-Tertiary hiatus see CHERNYK & KRYLOV (2017).

Abb. 3: Geschichte des Eintrags eistransportierten Materials in das zentrale Nordpolarmeer seit dem Eozän, abgeleitet aus der Verteilung der terrigenen Sedimentkomponenten (ST JOHN 2008) in den IODP ACEX Sedimentkernen. Die gelben Punktsymbole markieren das Auftreten relativ grober Gerölle, die vermutlich durch Eisberge transportiert worden sind. Altersskalen links; ein Hiatus markiert eine Schichtlücke. Bezüglich der stratigraphischen Position des mittel-tertiären Hiatus siehe CHERNYK & KRYLOV (2017).

THE LATE PALEOGENE AND EARLY NEOGENE ARCTIC ICE COVERS

Since DSDP Leg 38 to the Norwegian-Greenland Sea (Talwani, Udintsev & Shipboard Scientific Party 1976) and earlier observations of Tertiary sections on land (Köppen & Wegener 1924) it had become clear that Northern Hemisphere glaciations were not restricted to the Quaternary (Thiede 2017), but that they extended quite a bit further back in time (Thiede et al. 2011a, b), as documented by the occurrences of IRD in many high latitude deep-sea drill cores. Extensive deep-sea drilling programs in the Norwegian-Greenland Sea (Thiede et al. 1996) and to the South and West of Greenland before the famous ACEX-expedition to the central Arctic Ocean had long proven that iceberg derived ice-rafting had occurred in high northern latitude regions since Oligocene times, requiring the existence of ice caps or glaciers reaching the coastal regions of the ocean basins. It remains open though, where these could have been located, or if these occurrences of ice-rafted terrigenous debris possibly can be explained by other mechanisms, for example by transport of river or coastal ice.

There is also quite a bit of a dispute if the occurrence of the fine- and coarse grained IRD in the mid-Tertiary Arctic and sub-Arctic deep-sea sediments means that the Arctic Ocean was frozen over throughout the year, or if proxies like the IP25 or the alkenone-based summer sea-surface temperatures of >4 °C suggest only a seasonal sea-ice cover for the central Arctic Ocean (Stein et al. 2016, cf. also Stein et al. 2017a).

THE PLEISTOCENE ARCTIC ICE COVERS

Detailed information on the nature and extent of the Arctic Ocean ice covers during the Pleistocene is essentially only available for the stratigraphic intervals of marine isotope stages 1-7 (Spielhagen et al. 2004). The first reconstructions of the central Arctic Ocean ice cover were almost entirely based on existing knowledge of the LGM ice sheets over North America and NW Eurasia while virtually no information from the Arctic deep-sea basins was involved (Figs. 4 and 5).

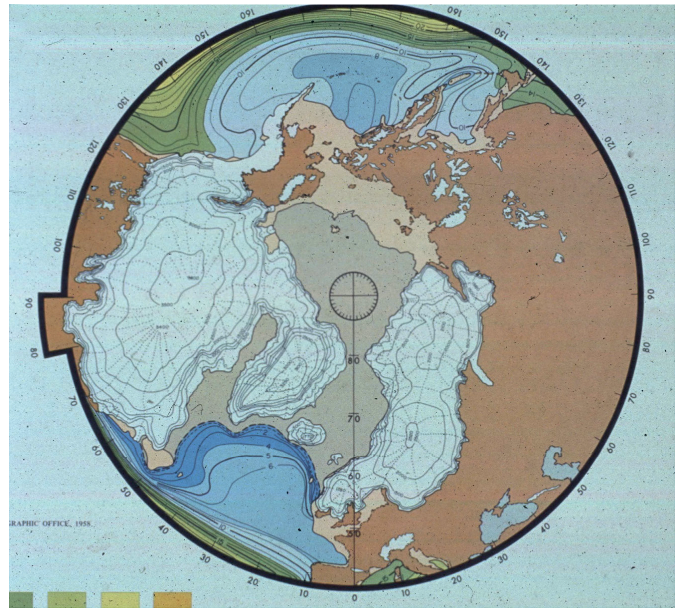

Fig. 5: The CLIMAP reconstruction (CLIMAP Project Members 1976; see also Cline & Hays 1977) of the Last Glacial Maximum (LGM) on the Northern Hemisphere. Contrary to Hughes et al. (1976) the central Arctic Ocean was considered sea-ice covered, even this could only be proven much later after expeditions of research ice breakers successfully reached the central Arctic Ocean (Spielhagen et al. 2004). Ocean water masses without ice are color coded according to surface water temperatures.

Abb. 5: Die CLIMAP Rekonstruktion (CLIMAP Project Members 1976; cf. Cline & Hays 1977) der Eisbedeckung für das letzte glaziale Maximum (LGM) auf der nördlichen Hemisphäre. Im Gegensatz zu Hughes et al. (1976) nahm diese Rekonstruktion an, dass das zentrale Nordpolarmeer damals nur von Meereis bedeckt war, obwohl dieses erst viel später nach Eisbrecherexpeditionen an gewonnenen Sedimentkernen nachgewiesen werden konnte (Spielhagen et al. 2004). Die ozeanischen Wassermassen sind farbkodiert nach Oberflächenwassertemperaturen.

In the sixties and up to the late seventies US American and Canadian researchers organized expeditions on ice islands in the central Arctic Ocean from where also sediment cores could be collected (Cannabis et al. 1965, Kristoffersen 1982, Jackson et al. 1985). Dating these cores was difficult at that time and no clear picture emerged. This changed only when heavy duty research ice breakers were deployed in the deep

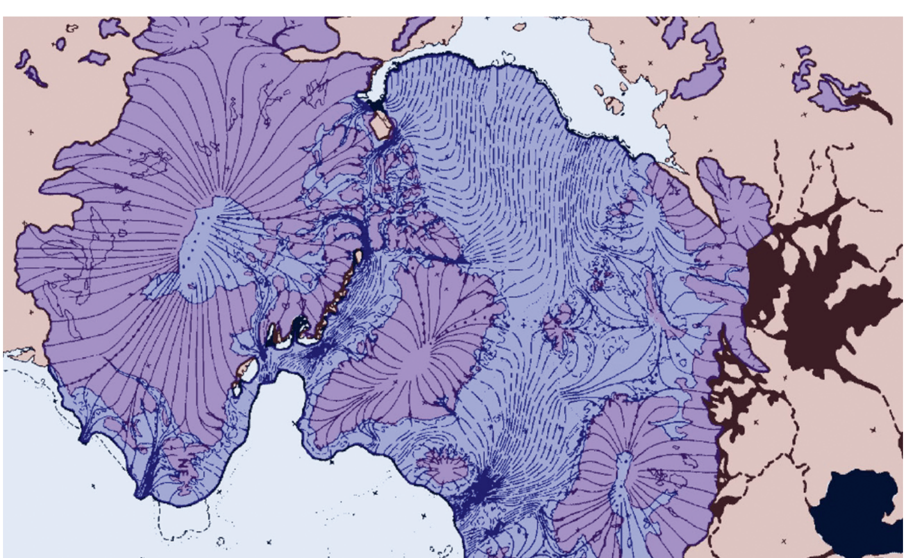

Fig. 4: Northern Hemisphere ice cover during the Last Glacial Maximum (LGM) according to Hughes et al. (1977) who assumed the existence of a thick ice shelf over the central Arctic deep-sea basins, connecting the glacial ice-sheets over North America, Greenland and Northern Eurasia.

Abb. 4: Die Eisbedeckung der nördlichen Hemisphäre während des letzten glazialen Maximums nach Hughes et al. 1977, die die Existenz eines mächtigen Eisschelfs über dem zentralen Nordpolarmeer annahmen, der die Eisschilde in Nordamerika, Grönland und im nördliche Eurasien verband.

Arctic having enough power on board to collect long sediment cores; a Swedish expedition on "Ymer" (Schytt 1983) succeeded to do so in 1980 (Boström & Thiede 1984). Since then research icebreakers have been traversing the central Arctic Ocean on a regular basis and a large number of well dated sediment cores with their variable record of ice-rafted debris allowed to define the paleoenvironmental history for the past 200,000 years when the ice cover consisted mostly of sea ice with variable amounts of icebergs (Spielhagen et al. 2004). Each time when northwestern Eurasia was covered by a large ice sheet (MIS 2, 4 and 6) the amount of IRD increased substantially. Once the glacial ice sheets collapsed during deglaciation (Zhuravleva et al. 2017) large amounts of fresh water entered the Arctic Ocean because the subglacial lakes suddenly were not barred from draining into the shelf seas (Mangerud et al. 2004, Spielhagen & Bauch 2015).

This simplified picture changed when the traces of large ice shelves extending into the central Arctic Ocean were detected through glacial erosional features, first on Lomonosov Ridge, later also on several other structural highs in the Arctic Ocean (Jakobsson et al. 2016), indicating the existence of ice-shelves extending far into the central Arctic Ocean (however, see Stein et al. 2017b). The ice shelves have yet to be dated, but appear to be coeval with MIS 6, which represented the glaciation over northwestern Eurasia with an ice sheet substantially larger than the younger ice sheets, which had been mapped by Svendsen et al. (2004) as their contribution to the QUEEN project (Thiede et al. 2004).

DYNAMICS OF THE MODERN AND HOLOCENE ARCTIC SEA-ICE COVER

The Holocene and modern central Arctic Ocean ice cover consists largely of sea ice with occasional icebergs and ice islands (broken off pieces of ice shelves). Probably as long as it existed, it owes its existence to the small solar insolation because of its polar position and the influx of large amounts of fresh water from the continental hinterlands, which generate a cap of surface water with reduced salinities (cf. Stein et al. 2003, see also Gorshkov 1983). Since Fridtjof Nansen's famous expedition on "Fram" 1893-1896 it is known that the sea ice is of modest thickness and highly mobile due to the influence of the atmospheric circulation over the Arctic, but that it covers the entire central part of the Arctic Ocean. Fifty years prior to this expedition some scientists even speculated about an ice-free central Arctic Ocean (Koldewey 1871). In modern times and under the influence of a warming climate it is shrinking fast, both in extent and thickness (AMAP 2017, Polyakov et al. 2017, Haine & Torge 2017). Until recently relatively little was known about its potential variability during the most recent geological past, except for the time after the sixties, when Russian and US American submarine data became available and when remote sensing techniques were used to monitor the fate of the Arctic sea-ice cover.

There are several detailed studies available covering the Holocene period, when the Siberian margin has been flooded due to the postglacial sea-level rise. Bauch & Polyakova (2003) used the occurrence of diatoms to infer changing salinities of shelf waters and their implications for the fluvial drainage patterns. The Lena delta formation is also largely a phenomenon related to the high postglacial sea levels and has been addressed by a substantial number of detailed studies, originating from bilateral Russian-German studies (Schirrmeister et al. 2002, 2008, Siegert et al. 2009) and by efforts of Russian scientists (Bolshiyanov et al. 2015).

However, Funder et al. (2011) published a detailed study of the composition and ages of driftwood and beach ridges around northern Greenland. Since driftwood originating from Siberia consists largely of larch, but that originating from North America largely of spruce, he was able to document large variations of the main drift patterns of the Arctic sea ice, namely of the Transpolar Drift and of the Beaufort Gyre and related them to the large-scale atmospheric circulation such as the Arctic Oscillation and they were taken as indicators of the presence of multiyear sea ice and its travelling routes, whereas the occurrence or absence of beach ridges were taken as indicators of seasonally open waters.

AN OUTLOOK

Presently there are some major obstacles for further progress in resolving the history of Late Mesozoic and Cenozoic ice covers of the northern hemisphere:

- Future deep-sea drilling on southern segments of Lomonosov Ridge will probably complete the stratigraphic records recovered during the ACEX-expedition in 2004 (Backman & Moran 2009), cf. IODP drilling proposal ArcOP (2017).
- Further deep-sea drilling in the more distant future will have to aim at the Mesozoic and unkown older as well as younger sediment layers on Alpha-Mendeleev Ridge. We urgently need to understand how an euxinic and at least during the summer time relatively ice free Arctic Ocean "functioned".
- There is some enigmatic information of glacial erosional features from the East Siberian continental margin (Niessen et al. 2013) suggesting the repeated (?) existence of an ice cap or shelf. These glacial events have yet to be dated precisely (cf. also Jacobsson et al. 2016).
- We need to study the Cenozoic river histories of Eastern Siberia. Under the frame of a major effort of the Köppen-Laboratory of SPbGU we have organized several expeditions to the shores of the Lena River, the largest of the East Siberian rivers draining into the Arctic Ocean. The modern Lena is accompanied by large terrace systems whose age and origin is only slowly emerging (Savelieva et al. 2012, 2013) and which have to be related to Tertiary and Quaternary history of glaciation of central Eastern Siberia (Margold et al. 2016); two examples are given in Figs. 6 and 7 and dating is in progress.

CONCLUSIONS

- Two important plate tectonic events, namely the opening of Fram Strait during mid-Cenozoic times and the collision of India with the southern continental margin of Eurasia during the early Cenozoic reshaped the paleogeography and physiography of the northern hemisphere including the Arctic Ocean as well as the adjacent continents dramatically.
- Detailed micropaleontologic and petrographic studies of two Upper Cretaceous sediment cores, the occurrence of glendonites revealed that the Arctic Ocean experienced cold seasons, even during times of globally warm climates.

Fig. 6: Lena terraces (eastern shore) of probably Late Quaternary age opposite Yakutsk (Savelieva et al. 2012, 2013). Photo: J. Thiede 2013.

Abb. 6: Mächtige, geologisch junge Flussterrassen (wahrscheinlich spätquartären Alters) am Ostufer der Lena bei Yakutsk; Blick nach Norden (Savelieva et al. 2012, 2013). Foto: J. Thiede 2013.

Fig. 7: Lena terraces, western shore, upper reaches close to Kistjenova (to the North of Irkutsk) of probably Late Tertiary or Early Pleistocene age (Trophimov et al. 1955, Savelieva et al. 2012, 2013). Photo: J. Thiede 2012.

Abb. 7: Mächtige Flussterassenablagerungen am Westufer des Oberlaufes der Lena in der Nähe von Kistjenova, (nördlich von Irkutsk), vermutlich spättertiären oder frühpleistozänen Alters (Trophimov et al. 1955, Savelieva et al. 2012, 2013). Foto: J. Thiede 2012.

• The ACEX sediment cores from the central Lomonosov Ridge comprise horizons with *Azolla*-spores suggesting a warm, brackish or fresh water hydrography (at least during the summer time) for the central Arctic Ocean, which developed after the PETM (Paleocene-Eocene Thermal Maximum); also caught in these cores.
• The ACEX cores also revealed the major ice-rafting started approximately 46 ma and continued probably until the Holocene, even though the completeness of the sedimentary record is interrupted by two major hiatuses. This problem will hopefully be resolved through new ECORD deep-sea drilling on Lomonosov Ridge (ArcOP 2017).
• The nature of the upper Paleogene and early Neogene Arctic Ocean ice cover is a matter of debate. The almost continuous occurrence of coarse ice-rafted terrigenous debris suggests the occurrence and melting of icebergs in the Arctic Ocean, whereas we have no knowledge where on the adjacent land areas glaciers and/or ice sheets could have existed. However, proxies like the IP25 or the alkenone-based summer sea-surface temperatures of >4 °C suggest only a seasonal sea-ice cover for the central Arctic Ocean at that time.
• The Late Pleistocene glaciation history of the central Arctic Ocean is now fairly well known and can be related to the repeated establishment of large ice sheets in North America and northwestern Eurasia. During MIS 6 ice shelves with large extensions over the deep Arctic Ocean seem to have developed.
• The Holocene and modern sea ice cover (with some ice islands and very few icebergs) seem to have been highly variable, with the Transpolar Drift and the Beaufort Gyre shifting at times in strength and regional extent.
• At the present time, the Arctic Ocean sea-ice cover is shrinking fast, both in extent and thickness. It is predicted that it may disappear completely during summer time by the end of this century.

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