ECORD
EUROPEAN CONSORTIUM FOR OCEAN RESEARCH DRILLING

IODP
INTERNATIONAL OCEAN DISCOVERY PROGRAM

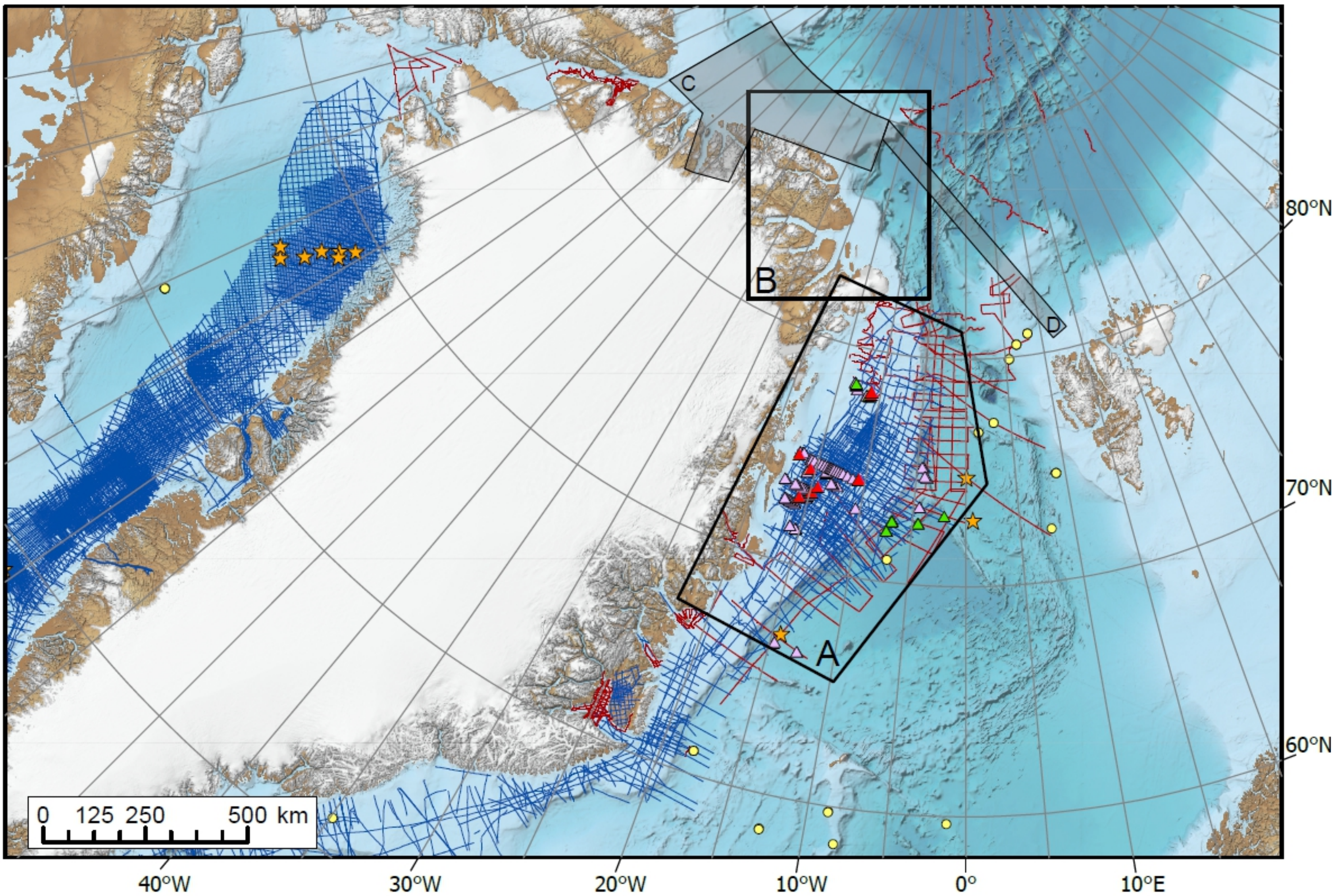
MagellanPlus Workshop

21-23 November 2022, Copenhagen, Denmark

NorthGreen

Northeast Greenland: Unlocking records from sea to land

Theodor Sorgenfrei auditorium
Geological Survey of Denmark and Greenland - GEUS
Øster Voldgade 10, Copenhagen (Denmark)



NorthGreen aims to develop MSP proposals with focus on Northeast Greenland margins (Areas A & B) and the surrounding Arctic Ocean.

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ECORD MagellanPlus Workshop Series Programme
CARLSBERGFONDET
GEUS
AARHUS UNIVERSITY
Stockholm University

Northeast Greenland: Unlocking records from sea to land

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Summary

NorthGreen aims to develop MSP proposals with focus on Northeast Greenland margins and the surrounding Arctic Ocean. The sensitivity of the northern Greenland Ice Sheet to polar amplification, and year-round sea ice conditions make this region one of the most critical locations on the planet for understanding the effects of global warming. Moreover, with its oceanward connection to the Fram Strait, the Northeast Greenland margin presents a natural laboratory for understanding ice-ocean-tectonic interactions in a gateway pivotal for Earth's climate.

Workshop description

Rationale: The projections of future scenarios under the current trend of global climate change demand a better understanding of long-term ice-ocean-tectonic interactions[1]. The largest uncertainties in future sea-level rise estimates concern the potential contributions from ice sheets in Greenland and Antarctica under a rapidly warming global climate[1,2]. The Greenland ice sheet has been a major contributor to global sea-level rise in recent decades[3], and future projections show a marked increase in the ice sheet runoff during this century as a consequence of the polar amplification[4,5]. In Northeast Greenland, coupling between the ice sheet, ocean and sea ice are readily observable today but geological records that can illuminate long-term trends are lacking.

The Northeast Greenland margin represents a major knowledge gap in the Cenozoic climate-tectonic evolution. Key scientific questions relate to: (1) Sea ice history: e.g., When did a perennial sea ice cover develop in the Arctic Ocean and how often did sea ice free conditions occur? (2) Greenland ice sheet evolution: When did glaciation incur and how did the ice sheet evolve over Cenozoic time scales? Did past warm climates (e.g., super-interglacials) cause whole or partial deglaciation in Northern Greenland[6]? Or is glaciation of Northeast Greenland a relatively pervasive feature in the climate system[7]? (3) Fram Strait Gateway: What is the timing and progression of the opening? What is the subsidence history of the conjugate Morris Jesup Rise and Yermak Plateau? How does the gateway opening influence the development of the Arctic Ocean, from isolated to fully ventilated[8,9]? While previous (ODP 151, IODP 302 - ACEX) and scheduled (979 and 985) IODP expeditions cover deep basins and the central Arctic Ocean, there is a need for paleo-data proximal to Greenland and across the land-ocean boundary, that can address these questions.

Data required to illuminate these questions are potentially contained in the sedimentary successions offshore and onshore Northeast Greenland. However, the harsh environmental conditions have limited geophysical data acquisition needed to define drilling targets. Nevertheless, over the last two decades data collection has increased substantially. The Atlantic margin of Northeast Greenland (Area A) is now well covered by industry high-quality seismic data[10] (Fig. 1). In addition, collection of shallow seismic data, gravity cores, and shallow industry boreholes (Kanumas consortium) demonstrates the possibility of mission specific platform (MSP) operations. Hence, sufficient data is available to start developing an MSP proposal in Area A. In contrast, the Arctic margin of Northeast Greenland (Area B) remains largely unexplored. However, ice conditions have become more amenable in recent years, facilitating logistically feasible work as proved by 2018 Polarstern expedition that collected deep seismic and OBS data north of Peary Land, and the scheduled GoNorth and GEOEO projects to sail in 2024. Thus, we propose a long-term (10 years) research strategy of the Northeast Greenland margins to be discussed within this kickoff workshop. A nucleus for the research strategy will be the potential expansion and development of Pre-proposal 756 in *Morris Jesup Rise: Drilling the Arctic Ocean Exit Gateway*. This pre-proposal was submitted and favorably reviewed in 2009 by SEP, but, until now it has lacked site survey data to be fully developed. Thus, the workshop strategy aims for the materialization of one MSP proposal in Area A, but also to define the site survey needs for future proposals along Area B.

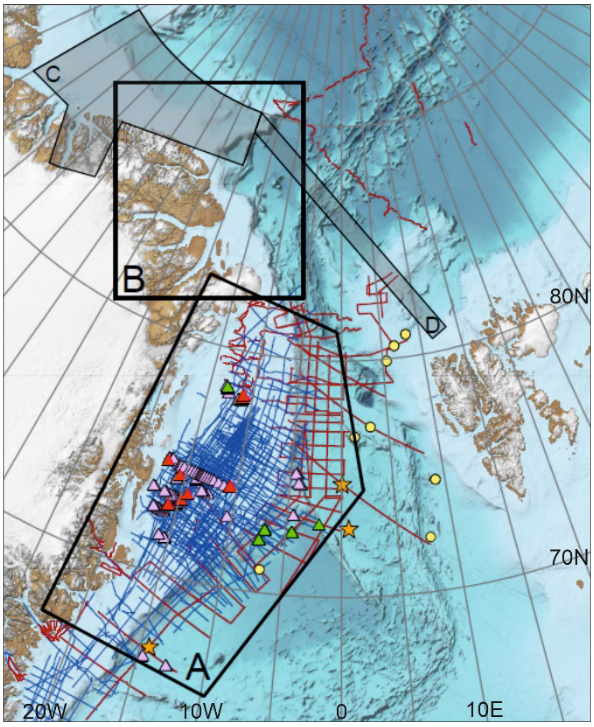

Figure 1: A and B - areas of interest of the NorthGreen MagellanPlus workshop; C and D - GEOEO and GoNorth 2024 plans; blue lines - seismic reflection data available at GEUS, red lines - other seismic reflection data available from data owners; yellow dots - existing DSDP and ODP drill sites; orange starts - proposed IODP drill sites with JRFB; red triangles - Kanumas 2008 cores; pink triangles - industry gravity cores; green triangles - industry dredges.

Goals: NorthGreen aims to develop coordinated International Ocean Discovery Program (IODP) MSP proposals in Northeast Greenland including both onshore and offshore operations, within short and longer timeframes. We aim to define specific Cenozoic drilling targets based on existing data but also to identify the data gaps in the key areas, e.g., along shelf to fjord transects. In addition, we aim to establish collaborations to integrate the results of past and forthcoming IODP expeditions around the Greenland margins. We envisage that resulting drilling projects may combine the MSP and International Continental Drilling Program (ICDP) proposals as outlined in the IODP 2050 Scientific Framework[11].

Outcomes: The workshop aims and expected outcomes are:

- To gather an international group of scientists of across different disciplines to discuss scientific objectives and hypotheses relevant for the Northeast Greenland margins and the adjoining ocean regions.
- To select relevant drilling areas with the potential to uncover the tectonic, oceanographic and cryospheric history of Northeast Greenland and the Arctic Ocean.
- To identify the major data gaps and develop a research strategy to obtain the site survey data needed for further IODP MSP proposals.
- To link outputs from past and forthcoming IODP expeditions towards the common aims described above.
- To address key topics for MSP proposals: e.g. (i) Greenland ice sheet extension during past interglacial periods; (ii) Cenozoic key intervals as paleo-constrains in future projections; (iii) Climate and biosphere interactions; and (iv) Oceanic gateways: the Arctic Ocean – North Atlantic tectonic connections and its implications on the global thermohaline circulation.
- To discuss further possibilities for scientific drilling onshore and offshore North Greenland, both in a short term and long-term perspective, identifying the needs for site survey data collection.
- To develop one or more compelling MSP proposals building on key research questions and hypotheses, within an overall framework of strategies for IODP-ICDP transects envisaging land to ocean connections.

Scientific drilling of the Northeast Greenland margins will allow research within the ***IODP 2050 Science Framework*** strategic objectives *Earth's Climate System*, *Feedbacks in Earth's Climate System*, *Tipping points in Earth's history* and *Natural hazards impacting society*[11]. By exploring suitable stratigraphic targets in the region, we hope to foster new insights on several themes such as the Cenozoic transition from hothouse to icehouse climate regimes, the development of the modern global thermohaline circulation, and the atmosphere-ice-ocean-tectonics interaction pertaining to the past dynamics of the Greenland ice sheet.

References:

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5. Hofer, et al. (2020) Greater Greenland Ice Sheet contribution to global sea level rise in CMIP6. Nat. Comm. 11, 6289
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Workshop programme

Monday 21 November 2022
9:00 Start of Day 1
○ Welcome and outline [*Organizers*] (15 mins)
Scientific Drilling: Active proposals
○ Summary of recent drilling and existing proposals relevant to Greenland margins and Arctic Ocean [*Organizers*] (15 mins)
○ The Opening of the Arctic-Atlantic Gateway: Tectonic, Oceanographic and Climatic Dynamics – IODP proposal 979/expedition 404 [*Keynote: W. Geissler*] (30 mins)
○ IODP 985Full, Eastern Fram Strait Palaeo-archive – FRAME [*Keynote: R. Lucchi*] (30 mins)
10:30-10:45 Coffee break
MSPs and challenges of drilling on polar margins (x 20 mins)
○ IODP Mission-Specific Platform Expeditions and Their Role in a Future Scientific Ocean Drilling Program [*Keynote: G. Uenzelmann-Neben & D. McInroy*]
○ Sensitivity of the West Antarctic Ice Sheet to +2°C (SWAIS 2C) [*Keynote: R. Levy*]
○ Drilling in the Amundsen Sea and results on West Antarctic paleoclimate and ice sheet history [*Keynote: K. Gohl*]
12:00-13:00 Lunch
Current projects and proposals along the Northeast Greenland margins (x 20 mins)
○ Project GreenDrill – Measuring cosmogenic-nuclides in sub-ice bedrock archives to constrain northern Greenland Ice Sheet size during interglacial periods [*Keynote: J. Briner*]
○ North Greenland Earth-Ocean-Ecosystem Observatory (GEOEO) [*Keynote: M. Jakobsson*]
○ GoNorth – Geosciences in the Northern Arctic [*Keynote: G. Sand (online)*]
○ Deglacial and Holocene changes in ocean conditions and interaction with the cryosphere: shallow seismic data and sediment records from NE Greenland [*Keynote: M. -S. Seidenkrantz*]
○ Morris Jesup Rise: Drilling the Arctic Ocean Exit Gateway [*Keynote: M. O'Regan*]
14:45-15:00 Coffee break
State of the art (x 20 mins)
○ Building deformable plate models for the Northeast Atlantic [*Keynote: G. Shephard*]
○ Cenozoic paleogeographic evolution of oceanic gateways to the Arctic Ocean: Implications for ocean circulation and climate [*Keynote: E. Straume*]
○ Geology of Northeast Greenland [*Keynote: M. Bjerager*]
○ Aspects of the Cenozoic depositional, tectonic, oceanographic and climatic development offshore NE Greenland [*Keynote: T. Nielsen & M. Fyhn*]
○ Informing future scientific drilling efforts in glaciated margins in support of Science Framework 2050 [*Keynote: S. Gulick (online)*]
General discussion: Open scientific questions and breakout session topics (50 mins)
17:30 End of Day 1
Reception/icebreaker - GEUS

Tuesday 22 November 2022
9:00 Start of Day 2
○ Welcome to Day 2 and Summary of Day 1 [*Organizers*] (15 mins)
Breakout session 1: Potential for MSP coordinated proposals in Northeast Greenland
10:30-10:45 Coffee break
Breakout session 1
12:00-13:00 Lunch
Data availability and considerations (x 10 mins)
• GreenFlux - Effect of climate change on greenhouse gas fluxes from marine Artic regions [*C. Böttner*]
• Crustal and sedimentary thicknesses from Receiver Function analysis – North Greenland [*T. Dahl-Jensen*]
• SEGMENT-2017 & GREENMATE 2018 seismic surveys from NE Greenland and links to field work of CASE 20 [*P. Klitzke*]
• AWI data: seismic and hydroacoustics [*C. Gebhardt & W.H. Geissler*]
• LAMEX campaign [*C. Gebhardt*]
• IODP proposal 962 [*J. Stoner*]
14:00-15:00 Coffee break and **Posters**
Breakout session 2: Potential for site survey studies and data acquisition
17:00 Summary of Day 2 and overview of proposed site surveys
17:30 End of Day 2
NorthGreen Dinner – Almanak at Opera House

Wednesday 23 November 2022
9:00 Start of Day 3
○ Welcome to Day 3 and Summary of Day 2 [*Organizers*] 15 mins
Core database and proxies (x 10 mins)
• Pre-Holocene proxies for the northern high latitudes [*K. Sliwinska*]
• Lipid and nucleic acid biomarkers as temperature, water cycle, and ecosystem proxies [*E. Thomas*]
• Using paleomagnetism for high resolution stratigraphy [*J. Stoner*]
• Petermann Project (OD15): the geomagnetic field in NorthGreen [*J. Stoner*]
• The sedimentary imprint of the Greenland ice sheet on the NE Greenland continental shelf [*D. Roberts*]
10:15-10:30 Coffee break
Breakout session 3: Proposal work in groups and discussion
12:00-13:00 Lunch
13:00-14:00 Workshop synthesis and outcome [*Organizers*]
Breakout rooms available for continued discussion
16:00 End of Day 3

Posters:

Katrine J. Andresen	Cyclic sedimentation patterns and mass transport deposition in Young Sound, NE Greenland
Trine Dahl-Jensen	Receiver functions in Greenland
Joseph Stoner	The last interglacial in Eirik Ridge (South Greenland): insights on deglacial processes
Joseph Stoner	BaD-Ex NSF in Baffin Bay
Dieter Franke	SEGMENT seismic survey (2017) - Northern East Greenland Volcanic Province
Lutz Reinhardt	NE-Greenland – fieldwork of expedition CASE 20 in relation to RV POLARSTERN seismic survey GREENMATE (2018)
Kwangchul Jang	Future KOPRI research plan on paleoceanographic studies at the Atlantic gateway to the Arctic Ocean
Wolfram. H. Geissler	The opening of the Fram Strait and its influence on sediment transport, climate and ocean circulation between the Arctic Ocean and the North Atlantic
Thomas Funk	Seismic refraction data from the northern continental margin of Greenland towards the Morris Jesup Rise
Christian Schiffer	Recent research activities and future proposals in the Arctic, Geophysics Section, Uppsala University
Monica Winsborrow	iC3- Centre for ice, Cryosphere, Carbon and Climate
Paul Knutz	KANUMAS records
John Hopper	Northeast Greenland data

Breakout rooms

Theodor Sorgenfrei (0-242)

Tove Birkelund (0-238)

Arne Noe-Nygaard (0-306)

Inge Lehmann (2-240)

Ellen Louise (0-327)

Geological survey of Denmark and Greenland (GEUS)
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The Opening of the Arctic-Atlantic Gateway: Tectonic, Oceanographic and Climatic Dynamics

(International Ocean Discovery Program proposal 979/expedition 404)

***Wolfram H. Geissler*[1], *Jochen Knies*[2,3]**

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Today's polar cryosphere reflects a climate state that developed during a stepwise global cooling during the Cenozoic greenhouse-to-icehouse climate transition. Polar ocean gateways such as the Drake Passage in the Southern Hemisphere and the Arctic-Atlantic Gateway (AAG) in the Northern Hemisphere played pivotal roles in changing the global climate through their influence on oceanic circulation, heat transport and ice sheet development. The Arctic Ocean was isolated from the global oceanic thermohaline circulation system during most of its geological history. This gradually changed when Greenland and Svalbard began to move apart from each other, initiating the opening of the AAG through the Fram Strait. Although this gateway is known to be important in Earth's past and modern climate, little is known about its Cenozoic development. Indeed, the opening history and AAG's consecutive widening and deepening must have had a strong impact on circulation and water mass exchange between the Arctic Ocean and the North Atlantic.

As a first order approximation, the timing of Fram Strait opening can be inferred from geophysical and stratigraphic records as well as modelling studies which form the basis of the hypotheses to be tested with this proposal. Climate and tectonic modelling studies suggest that a certain width and depth of the Fram Strait are required to allow the bi-directional exchange of water masses of Atlantic and Arctic origin through the AAG. To test these models, direct geological evidence from ocean drilling sediment records from three primary sites between 73°N and 78°N are needed to constrain the age of the opening, widening, and deepening of this deep-water Arctic-North Atlantic Oceans connection.

These sites will provide unprecedented sedimentary records from the Eocene/Oligocene through the Miocene that will unveil (1) the history of shallow-water exchange between the Arctic Ocean and the North Atlantic and its impact on the global cryosphere evolution, and (2) the development of the AAG to a deep-water connection and its influence on global climate changes. By filling the current time gap of ~20 million years in the AAG region with new, well-dated borehole material, we will address these large uncertainties and gaps in the paleoclimate record.

The proposed drilling addresses a number of key questions raised in the IODP Science Plan 2013-2023. It is specifically linked to the Research Theme "Climate and Ocean Change: Reading the Past, Informing the Future".

IODP 985Full, Eastern Fram Strait Palaeo-archive (FRAME)

Lucchi Renata Giulia[1-2], Stefan Buenz[2], Michele Rebesco[1], Florence Colleoni[1], Riccardo Geletti[1], Thomas M. Cronin[3], Katrine Husum[4], Andreia Plaza-Faverola[2], Sunil Vadakkepuliyambatta[2], Jan Sverre Laberg[5], Anne de Vernal[6], Chiara Caricchi[7], Juliane Müller[8], Jennifer Pike[9], Haflidi Haflidason[10], Steffen Leth Jørgensen[11], Patrick Grunert[12], Caterina Morigi[13], Jochen Knies[2-14], Rüdiger Stein[8-15], Claude Hillaire-Marce[6]l, Jens Gruetzner[8]

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The North Atlantic-Arctic Oceans are unquestionably major players in the climatic evolution of the Northern Hemisphere and in the history of the meridional overturning circulation of the Atlantic Ocean. The establishment of the modern North Atlantic Water has been indicated as one of the main forcing mechanisms for the onset of the North Hemisphere Glaciation. North Atlantic Water control the extent and dynamics of circum-Arctic and circum-North Atlantic ice sheets and sea ice in addition to deep water and brine production. How the ocean system and cryosphere worked during past warmer intervals of either/both high insulation and/or high atmospheric CO2 content, is still unknown and debated.

The required information can only be attained by offshore scientific drilling in high-resolution, continuous and undisturbed sedimentary sequences at the eastern Fram Strait along the main pathway and northern penetration of the North Atlantic Water flowing into the Arctic Ocean. As matter of fact, this area around Svalbard can be considered as a “sentinel of climate change”. The reconstruction of the dynamic history of the paleo Svalbard-Barents Sea Ice Sheet, is important as it is considered the best available analogue to the West Antarctic Ice Sheet (WAIS), whose loss of stability is presently the major uncertainty in projecting future global sea level in response to the present global climate warming induced by the anthropogenic rising of atmospheric CO2 content.

IODP 985-Full2 drill proposal is motivated by the necessity of retrieving long and inter-connected sedimentary records along the eastern side of the Fram Strait in order to establish a robust chronostratigraphy, and to improve our understanding of the boundary conditions and forcing mechanisms determining the evolution of the Northern North Atlantic and Arctic regions and their past and present connections with global climate.

The proposal is presently scheduled on the JOIDES Resolution in FY24 as Exp. 403 (June 4th – August 2nd).

IODP Mission-Specific Platform Expeditions and Their Role in a Future Scientific Ocean Drilling Program

Gabriele Uenzelmann-Neben[1], David McInroy[2]
[1]ECORD Facility Board Chair, Alfred Wegener Institute, [2]Science Manager, ECORD Science Operator, British Geological Survey

IODP[1] is currently supported by 22 Funding Agencies from around the world, and delivered by 3 Platform Providers. The United States NSF[2] provides the riserless drillship *JOIDES Resolution*, Japan's MEXT[3] provides the riser drillship *D/V Chikyu*, and the ECORD[4] provides mission-specific platforms (MSPs) which are contracted on a case-by-case basis.

Each IODP platform provides specialist capability. The *JOIDES Resolution* has provided high-quality riserless coring since 1985, and has played a pivotal role in global scientific ocean drilling throughout various generations of IODP. The *D/V Chikyu* delivers deep riser-mode drilling capability, giving earth scientists access to deeper targets and potentially providing a method to reach the Mohorovičić discontinuity. As capable as the two dedicated IODP platforms are, they are unable to reach all geological targets, such as those located under ice-covered seas, in shallow water, in environmentally sensitive areas or in certain hard-to-drill lithologies such as carbonate reefs and loose sediments.

ECORD has provided MSPs to tackle the targets unreachable by either the *JOIDES Resolution* or *D/V Chikyu*. To date, ECORD has implemented 9 MSP expeditions including to the Central Arctic Ocean, to the coral reefs offshore Tahiti and the Great Barrier Reef, to the shallow shelf areas offshore eastern United States, Mexico and in the Baltic Sea, and to the ultra-deep waters of the Japan Trench. These projects had multiple scientific objectives, including the recovery of records of climate and sea level change, and the recovery of previously unknown buried microbiological communities.

MSPs typically do not have the same level of onboard laboratory infrastructure compared to the *JOIDES Resolution*, *D/V Chikyu* and other scientific research vessels. The offshore phase of an MSP expedition carries a smaller scientific team, who focus on measuring ephemeral properties and other measurements that are required to guide the coring strategy at sea. All other analyses are deferred to the Onshore Science Party, held after the offshore phase at the IODP Bremen Core Repository and MARUM[5], where the cores are split and the invited Science Party conduct a full IODP analysis of the cored material.

As IODP evolved, so did the methods used to collect cores from below the seabed. ECORD actively promotes the use of alternative coring technologies on MSPs, in addition to heave-compensated wireline coring that is traditionally used for scientific drilling. Examples include the use of land-based mining-style coring offshore (Expeditions 310: Tahiti, 313: New Jersey, 364: Chicxulub), robotic sea floor drills to collect high quality core at multiple locations for Expedition 357: Atlantis Massif on an oceanic core complex in the Central Atlantic, and giant piston coring used for Expedition 386 in the Japan Trench. Alternative systems like these have several advantages, including better core recovery in target lithologies and lower operating costs than heave-compensated wireline systems deployed by a drill ship.

Following the end of the present IODP program in 2024 ECORD and Japan have liaised to combine their efforts in scientific ocean drilling. Under this new program MSPs will leave their niche as drilling platforms in ice-covered, shallow water, etc areas and embrace scientific drilling in all ocean environments.

This presentation will summarise past MSP achievements, outline the latest ideas for future ocean drilling program(s), and provide future scientific ocean drilling proponents and scientists with information on the key capabilities, benefits, and flexibilities of MSPs.

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Title: Sensitivity of the West Antarctic Ice Sheet to +2°C (SWAIS 2C)

Richard H. Levy, Molly O. Patterson, Tina van de Flierdt, Huw Horgan, Denise K. Kulhanek, G. B. Dunbar, and the SWAIS 2C Science Team

The West Antarctic Ice Sheet (WAIS) presently holds enough ice to raise global sea level by 4.3m if completely melted. Despite efforts through previous land and ship-based drilling on and along the Antarctic margin, unequivocal evidence of major WAIS retreat or collapse in times of past warmth has remained elusive. Yet such data are vital to inform numerical models aimed at quantifying predictions of future sea level rise.

The International Continental Scientific Drilling Program (ICDP) project 'Sensitivity of the West Antarctic Ice Sheet to a Warming of 2°C (SWAIS 2C)' will constrain past and current drivers and thresholds of WAIS dynamics to improve projections of the rate and size of ice sheet changes under a range of elevated greenhouse gas levels in the atmosphere as well as the associated average global temperature scenarios to and beyond the +2°C target of the Paris Climate Agreement.

A primary goal of SWAIS-2C is to acquire records of WAIS extent during late Quaternary "super-interglacials", which were characterised by warmer than present conditions, both in Antarctica and globally. Proxy environmental data from the Last Interglacial (LIG) (MIS 5e; ca. 129–116 ka) suggest global mean temperature peaked at 1°C higher than the pre-industrial period. Maximum global mean sea level was 2–9 m above present-day. Global average temperatures during MIS 11 (ca. 425–395 ka) may have been 2°C higher than pre-industrial levels and maximum global mean sea level was 6–13 m higher than today. Although orbital parameters during these interglacial periods were different from today, their warmer temperatures allow insights into past sensitivity of WAIS to climates that were like those projected under the Paris agreement target. Sea level reconstructions imply that WAIS and Greenland Ice Sheet (GIS) were significantly smaller during these interglacials and imply a high sensitivity to small temperature increases. However, the ice volume loss and meltwater contribution from each ice sheet is still debated. Ever since the influential paper by John Mercer, WAIS collapse is assumed to occur during super-interglacials, but causes of WAIS retreat are equivocal and evidence of full collapse is indirect.

Researchers, engineers, and logistics providers representing Australia, Germany, Italy, Japan, New Zealand, Republic of Korea, United Kingdom, and United States have established an international partnership comprised of geologists, glaciologists, oceanographers, geophysicists, microbiologists, climate and ice sheet modelers, and engineers to tackle the specific research objectives and logistical challenges associated with the recovery of Neogene and Quaternary geological records from the West Antarctic interior adjacent to the Kamb Ice Stream and at Crary Ice Rise. New geophysical surveys at these locations have identified drilling targets in which new drilling technologies will allow for the recovery of up to 200m of sediments beneath the ice sheet.

The scientific and technological advances developed through SWAIS 2C will enable us to test whether WAIS collapsed during past intervals of warmth. Connection to similar research efforts in Greenland offers an opportunity to examine bi-polar response to past climate change and determine the sensitivity of WAIS and GIS to a +2°C global warming threshold. Together our communities can identify when, where, and by how much Earth's most vulnerable ice sheets melted in the past and drove sea level change across the planet.

Drilling in the Amundsen Sea and results on West Antarctic paleoclimate and ice sheet history

Karsten Gohl

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The West Antarctic Ice Sheet (WAIS) has been subject to a very dynamic history as most of its base is grounded below present sea level and, thus, sensitive to climatic changes. Its collapse would result in a global sea-level rise of 3.4-5 m. The reconstruction and quantification of WAIS collapses in warm periods in the geological past will provide constraints required for ice sheet models predicting its future behaviour and resulting sea-level rise. The Amundsen Sea ice sheet drainage sector in particular has shown unusual rapid retreat and dramatic changes over the last decades, which has been suggested to be a precursor to the behaviour of the entire WAIS.

The main objective during the RV *Polarstern* expedition PS104 in early 2017 was the application of the MARUM-MeBo70 seabed drilling system to recover a series of sediment cores at sites from the oldest to the youngest sedimentary sequences of the Amundsen Sea Embayment shelf. The expectation was that these cores provide sample material for proxy analyses required to reconstruct the development and past dynamics of the WAIS in the Amundsen Sea sector. A multi-barrel seabed drill rig was used for the first time to drill unconsolidated sediments and consolidated sedimentary rocks from an Antarctic shelf with core recoveries between 7 and 76%. We deployed the MARUM-MeBo70 drill device at nine drill sites in the Amundsen Sea Embayment. Three sites were located on the inner shelf of Pine Island Bay from which soft sediments, presumably deposited at high sedimentation rates in isolated small basins, were recovered from drill depths of up to 36 m below seafloor. Six sites were located on the middle shelf of the eastern and western embayment. Drilling at five of these sites recovered consolidated sediments and sedimentary rocks from dipping strata spanning ages from Late Cretaceous to Miocene.

With IODP Expedition 379 in early 2019, we aimed to drill long cores on the shelf and rise of the Amundsen Sea to target in particular past warm periods of the Pliocene, Miocene and older. Severe sea-ice prevented any shelf drilling. However, continuous late Miocene to Holocene sediments were recovered from a sediment drift on the continental rise, allowing assessment of sedimentation processes in response to climate cycles and trends since the late Miocene. Via seismic correlation to the shelf, we interpret massive prograding sequences that extended the outer shelf by 80 km during the Pliocene through frequent advances of grounded ice. Buried grounding zone wedges indicate prolonged periods of ice-sheet retreat, or even collapse, during an extended mid-Pliocene warm period from 4.2 to 3.2 Ma inferred from IODP Expedition 379 drill records. These results indicate that the WAIS was highly dynamic during the Pliocene and major retreat events may have occurred along the Amundsen Sea margin. More detailed core analysis are still being undertaken.

This presentation describes some results of both drilling expeditions, the challenges posed by drifting icebergs and sea ice, and technical issues related to deployment of the MeBo70. It includes also recommendations for similar future drilling campaigns on polar continental margins.

Project GreenDrill – Measuring cosmogenic-nuclides in sub-ice bedrock archives to constrain northern Greenland Ice Sheet size during interglacial periods

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Direct observations of the size of the Greenland Ice Sheet during Quaternary interglaciations are sparse yet valuable for testing numerical models of ice sheet history and sea level contribution. Recent measurements of cosmogenic nuclides in bedrock from beneath the Greenland Ice Sheet collected during past deep drilling campaigns reveal that the ice sheet was significantly smaller, and perhaps largely absent, sometime during the past 1.1 million years. These discoveries from decades-old basal samples motivate new, targeted sampling for cosmogenic nuclide analysis beneath the ice sheet. Current drills available for retrieving bed material from the US Ice Drilling Program require <700 m ice thickness and a frozen bed, while quartz-bearing bedrock lithologies are required for measuring a large suite of cosmogenic nuclides. We identify locations beneath the Greenland Ice Sheet that are best suited for potential future drilling and analysis; following the above requirements yields only ~3.4 % of the Greenland Ice Sheet bed as a suitable drilling target using presently available US drills. These sites include regions bordering Inglefield Land in northwestern Greenland, near Victoria Fjord and Mylius-Erichsen Land in northern Greenland, and inland from the alpine topography along the ice margin in eastern and northeastern Greenland. Information about the ice sheet response to interglacials from these locations should be paired with offshore sediment sequences for a more complete picture of ice sheet history.

North Greenland Earth-Ocean-Ecosystem Observatory (GEOEO)

Martin Jakobsson[a], Nina Kirchner[b] and GEOEO-members

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The *North Greenland Earth-Ocean-Ecosystem Observatory* (GEOEO) is a Research Theme developed by an international consortium of scientists for the Swedish Polar Research Secretariat's (SPRS) call for proposals within their Polar Process 2021. GEOEO is one of two Research Themes adopted by SPRS. The Theme addresses scientific questions focused on understanding the marine cryosphere's dynamic history and response to future climate change, including implications for marine and terrestrial ecosystems in North Greenland and adjacent Arctic Ocean. GEOEO is centred around the *North of Greenland 2024* expedition with icebreaker (IB) *Oden*.

The Arctic climate has warmed three times more over the last two decades than the rest of the Earth, with huge implications for the marine cryosphere, the marine and terrestrial ecosystems of the region, and global climate. The "marine cryosphere" is here defined as glaciers and ice sheets in contact with the ocean, sea ice, gas hydrates and subsea permafrost. The GEOEO Research Theme will take a multidisciplinary approach to address research questions on the marine and terrestrial ecosystems, specifically how these ecosystems interact with the cryosphere, and how they will be affected by a continued climate warming. Several Northern Greenland fjords, hosting outlet glaciers that drain the Greenland Ice Sheet, are still unvisited by vessels and therefore uncharted and unsampled. This lack of basic information has hampered assessments of the future mass loss from calving and submarine melt of Greenland's marine outlet glaciers, which constitutes one of the largest uncertainties in predictions of future global sea-level rise. The 2019 *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC)* emphasizes this large uncertainty. This was one of the main motivations for the GEOEO Research Theme, which specifically will assess the future contribution to global sea-level rise from the North Greenland Ice Sheet.

The *North of Greenland 2024* expedition builds on two successful expeditions with IB *Oden*; *Petermann 2015* and *Ryder 2019* expeditions. We aim to continue surveying areas north of Sherard Osborn Fjord, where the C.H Ostenfeldt Glacier drains into the unsurveyed Victoria Fjord. During year 2024 our collaborating partners within the Norwegian led *GoNorth*-project plan an expedition with FF *Kronprins Haakon*. This permits the two ships to complete the first synoptic transect, extending west of Svalbard (FF *Kronprins Haakon*), across the Fram Strait to Morris Jesup Rise, to north-western Greenland (IB *Oden*). Heat transport by warmer Atlantic water will be one of the key targets for this transect.

Under our the GEOEO Research Theme, we have brought together Swedish research groups from Stockholm University, University of Gothenburg, Uppsala University, Linnaeus University and Swedish Museum of Natural History to work with groups from the Geological Survey of Denmark and Greenland, Aarhus University, University of Oslo, University of Tromsø, University of Bergen, University of New Hampshire and US Geological Survey. We envision the IB *Oden* expedition to be a Swedish-US-Danish-Norwegian collaborative enterprise.

GoNorth – Geosciences in the Northern Arctic

Gunnar Sand

SINTEF

The GoNorth consortium has proposed a wide-ranging and cross-disciplinary program to explore the Arctic Ocean north of Svalbard. The mission is to acquire new and essential knowledge about the oceanic areas, from the sea floor and subsea geology, through the water column, to the surface sea ice. Education will be an important part of the program.

It is the goal of the program to be scientifically excellent, economically feasible and useful for the future management of the Arctic Ocean. The program shall bring Norway to the forefront as a responsible manager of the environment and the natural resources.

The first GoNorth expedition left Longyearbyen on 15. October 2022 onboard RV Kronprins Haakon. Ten research groups representing Norwegian universities and research institutes are onboard, together with researchers from GEUS. The expedition will last until November 19 and cover the Nansen Basin and the northern part of the Knipovich Ridge.

Two more GoNorth expeditions are planned for 2023 and 2024. In 2023 we plan to investigate the Gakkel Ridge, halfway between Svalbard and the North Pole. This will be a collaboration with the Alfred Wegener Institute. In 2024 we will head westward towards Morris Jessup Rise, in collaboration with Stockholm University, GEUS and others.

The Norwegian Government has defined the High North as its most important strategic foreign policy area. Presence and knowledge are key elements. The government's Ocean Strategy, Blue Opportunities, addressing knowledge building and sustainable development, adds a new dimension to the policy. Collaborative cruises with international partners are vital, for scientific, logistical and financial reasons.

Deglacial and Holocene changes in ocean conditions and interaction with the cryosphere based on shallow seismic data and marine sediment records from NE Greenland

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The NE Greenland shelf region is highly sensitive to changes in the Greenland Ice Sheet and to variability in the ocean circulation – in particular at surface and subsurface levels. In 2017, the NorthGreen2017 expedition, funded by the Danish Centre for Marine Research and the Natural Science and Engineering Research Council of Canada, took place from September 11 to October 1 collecting 2200 km shallow seismic data and 84 sediment cores from 15 different stations to investigate the geological, oceanographic, climatic and biological habitat development of the NE Greenland shelf since the last glaciation.

Investigations are still ongoing, but based on a combination of these shallow seismic and sediment core data, we have now a much better estimate of the maximum extent of the glacial North East Greenland ice sheet , which in fact did not reach all the way out to the shelf break everywhere during the Last Glacial Maximum (Rasmussen et al. in press) as well as of the timing and speed of the post-LGM ice retreat (Lopez Quirós et al., in prep.; Davies et al., 2022; Hansen et al., 2022). Moreover, the combination of CTD data and multiproxy analyses of sediment cores shows significant shifts in hydrography occurring after the deglaciation, with a larger influx of Atlantic Water through deep troughs occurring during the Early Holocene, followed by stepwise increases in Polar Water influx (Syring et al., 2020a,b; Zehnich et al., 2020; Pados-Dibbatista et al., 2022; Davies et al., 2022; Jackson et al., 2022; Hansen et al., 2022).

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Morris Jesup Rise: Drilling the Arctic Ocean Exit Gateway

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In 2010 we submitted a pre-proposal to IODP to drill 3 sites on Morris Jesup Rise. The proposal was designed to build on the successes of past drilling in Arctic and sub-Arctic seas and address outstanding key tectonic and paleoceanographic questions central to our understanding of the Cenozoic evolution of the Arctic Ocean. The *Science Evaluation Panel* favorably reviewed the pre-proposal and we were encouraged to develop it into a full proposal, however this has not been done. We now have an opportunity to revisit this theme and develop a mission specific drilling proposal that addresses 1 or more of the original scientific questions, as well as new questions that have emerged over the past 10+ years. The original pre-proposal was designed to investigate 1) the opening of the Fram Strait, the Arctic Ocean's deep Gateway to the North Atlantic, linked to the timing and geologic formation of the Morris Jesup Rise and its subsequent rifting from the Yermak Plateau and 2) the Neogene evolution of circulation and sea ice characteristics within both the Eurasian and Amerasian basins as recorded at the 'Exit Gateway' of the Arctic Ocean. As a conjugate feature of the Yermak Plateau, and lying directly in the passage of surface, intermediate and deep waters exiting the Arctic Ocean, the Morris Jesup Rise is ideally situated to record variations in both water mass properties and the provenance of sea ice and iceberg rafted detritus leaving the Arctic Ocean. Furthermore, as one of the last regions predicted to become ice-free, it may hold the key to understanding when, through the Neogene, the Arctic Ocean was free from perennial sea ice. Additional questions related to the inception, growth and dynamics of the Greenland, Innuitian and Laurentide ice sheets can also be addressed through provenance studies of ice rafted sediments. In 2010, a limited amount of seismic reflection data was available from the Morris Jesup Rise. It was collected during the ARCTIC'91 and LOMROG 2007 expeditions [Jakobsson et al., 2009; Jokat et al., 1995]. Based on this data, 3 sites were selected, 2 with penetration depths of 400 m targeting Neogene and tectonic questions, and 1 site chosen to recover Paleogene sediments but with a penetration depth of 750 m. Here I review the scientific aims and rationale behind the site selections of this pre-proposal. One of the key aspects to consider in developing a full drilling proposal to the Morris Jesup Rise is the balance between scientific ambitions and the feasibility of drilling in this region of the Arctic.

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Building deformable plate models for the Northeast Atlantic

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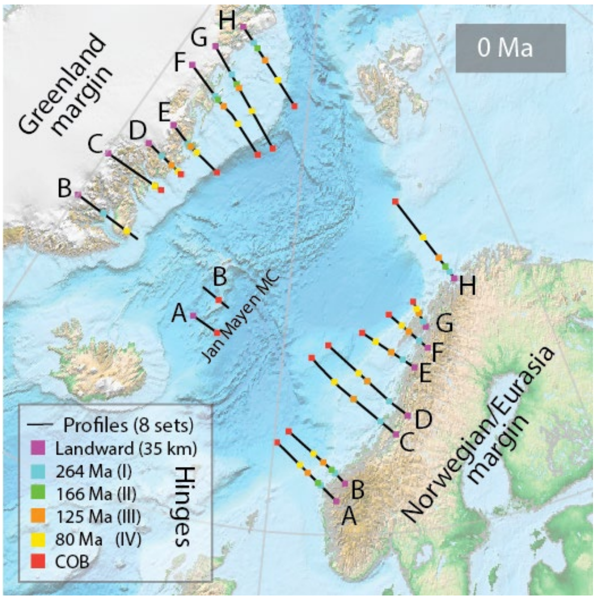
Plate tectonic reconstructions are traditionally built using a rigid plate theory; which assumes that most of the deformation occurs at or near plate boundaries. This approach captures much of the first-order changes in past plate motions, and especially for oceanic lithosphere. However, the assumption of full-plate rigidity leads to issues in regions of diffuse deformation such as rift zones (areas of extension). The GPlates software now enables zones of diffuse deformation to be implemented into plate reconstructions, and resultant characteristics to be analysed (e.g. crustal thickness, accumulated strain, stretching factors, rift velocity). Crucially, a deforming regional domain must still be constructed within the confines of a broader rigid plate setting; the two settings must be carefully considered for consistency, at all times and all locations.

The long-lived and multi-phase episodes of rifting that formed the North Atlantic are clear candidates for a deforming model. However, there are a number of regional kinematic challenges and methodological considerations which much be made, which largely stem from significant along-margin variability and uncertainty in geological interpretations. These include, but are not limited to, variations in margin width and geometry, rift obliquity to final break-up line, the timings, direction and amount of rifting, multi-phase overlaps, crustal thickness, magmatism and underplating, hinge identification, potential depth-dependent stretching, paleomagnetic data, and microcontinents. The conjugate northeastern Greenland and Barents margin are a particular challenge due to their more sheared-extensional nature – nearly all models to-date predict erroneous or unverified overlaps (e.g. superimposing thick crust) during pre-breakup times, however, on the converse, the region provides a key testing ground for any new rotations.



We use a series of eight conjugate profiles which extend from the NE-Greenland and Barents margins in the north to Jameson Land and Møre margins in the south (Abdelmalak et al., in review). The profiles are the result of a wealth of tectonic-stratigraphic-seismic datasets. We use these data to quantify the timings (Ma), amounts (km), and directions (i.e. stage rotations) of rifting for each of these episodes. These temporal and spatial constraints are used to developed a deforming plate model incorporating four phases of rifting;

- 264-247 Ma (Permian), average of 86 km extension across all profiles, E-W directed,
- 166-140 Ma (Late Jurassic), average 60 km, NW-SE,
- 125-110 Ma (Early Cretaceous), average 60 km, NW-SE, and
- 80-56 Ma (Late Cretaceous-Paleocene) average 67 km, NNW-SSE.

We compare our model to the global deforming model of Müller et al. (2019), which for the Northeast Atlantic is based on Barnett-Moore et al., (2016). In their deforming model they include only two phases of rifting, 200-120 Ma and 80 Ma to breakup. Finally, because we are investigating relative motion between Greenland and Eurasia, the results will affect the regional plate circuit around Greenland's margins, including northern Greenland (including the Eurekan Orogeny, Eurasia Basin and Amerasia Basin) and northwest Atlantic (including the Labrador Sea and Baffin Bay). The results and implications for future drilling programs, which will offer crucial constraints for refined plate models, will be emphasized.

Cenozoic paleogeographic evolution of oceanic gateways to the Arctic Ocean: Implications for ocean circulation and climate

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The paleogeographic evolution of Northern Hemisphere and Arctic oceanic gateways played an important role for regional and global ocean circulation and climate during the Cenozoic time (66 – 0 Ma). Models show that even small bathymetric variations in such ocean pathways, especially in the Atlantic – Arctic sector, can influence the global ocean circulation pattern. Accurate paleogeographic reconstructions of the oceanic gateways to the arctic are therefore very important to better understand the Cenozoic climate variations and the gradual greenhouse – icehouse climatic transition. Here, we present new detailed paleogeographic reconstructions of the Atlantic – Arctic oceanic gateways and the West Siberian Seaway including updated paleogeography of Eurasia and new models for dynamic topography. In addition, we run numerical ocean circulation experiments (using the NorESM and MITgcm) to test the impact of circum-Arctic oceanic gateway changes on global ocean circulation. One general result of these simulations is that a warm Eocene climate is highly sensitive to depth variations of the Greenland–Scotland Ridge, the Barents Sea, and/or the proto–Fram Strait as they control the freshwater leakage from the Arctic to the North Atlantic. We suggest that changes in these gateways controlled the ocean circulation and played a critical role in the growth of land-based ice sheets, alongside CO_2-driven global cooling. A shallow connection between the Arctic and North Atlantic may have restricted the southward flow of Arctic fresh surface waters during the Late Eocene allowing for a North Atlantic overturning circulation. Later, the connection to the Arctic deepened due to weakening dynamic support from the Iceland Mantle Plume. This weakened the North Atlantic overturning and cooled the Northern Hemisphere, thereby promoting glaciations there.

Geology of Northeast Greenland

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Onshore Northeast Greenland exposed a Precambrian to Holocene geological evolution with sedimentary basins formed from Proterozoic and throughout the Phanerozoic. The northern margin is structurally related to the Ellesmerian orogeny, and the eastern margin is related to the Caledonian orogeny. Subsequent basin formations can be grouped in Devonian continental basins, Carboniferous to Mesozoic rift associated basins, succeeded by the Tertiary rift to drift successions, and finally the Pleistocene and Holocene cover. Major unconformities are recorded in the stratigraphy marking important restructuration's in the sedimentary systems. A tour de geology of Northeast Greenland is presented with highlights from the recent geological expeditions in the area.

Aspects of the Cenozoic depositional, tectonic, oceanographic and climatic development offshore NE Greenland

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GEUS

The climatic, oceanographic, depositional and tectonic developments of the East Greenland margin are intimately related. The increasing amount of East Greenland offshore seismic and stratigraphic data provide a means for investigating this interrelationship. Paleogene basalt covers and conceals the deeper geology of the East Greenland margin apart from in the northern third. Here, super deep rift basins and structural highs formed during a long Late Paleozoic to Cretaceous history of rifting interspersed by periods of tectonic relaxation. During the latest Cretaceous, rifting centered around a narrow belt in the proto-northernmost Atlantic eventually leading to continental rupture in the Paleogene accompanied by massive volcanism. During the same period, regression took place culminating around the time of break up. Two landbridges connecting SE Greenland with Scotland and NE Greenland with Lofoten virtually closed off the north Atlantic seaway for a period of time. At the same time, East Greenland uplift redirected fluvial drainage and funneled sediment input into the Thetis Basin in the north where marine conditions remained. NE Greenland subaerial plateau basalts were transgressed already during the Early and Middle Eocene and contourite drift and moats witness the establishment of a north Atlantic current system already during the Eocene. Offshore Central East Greenland, a new phase of rifting commenced during the same period, which over time gradually separated the Jan Mayen micro continent from Greenland and led to the establishment of a major syn-rift fan-delta system offshore Central East Greenland. Meanwhile, the Icelandic hotspot trail remained subaerially exposed offshore SE Greenland forming a North Atlantic barrier.

Uplift and seaward tilting of NE Greenland and its margin led to an increase in offshore sediment input during the late Paleogene. Consequently, a shelf slope gradually built up and prograded eastwards from Greenland and into the Thetis Basin. In the Fram Strait, the Boreas Basin presumably started to open sometime during middle or even Early Eocene time, but it was not before the Middle Miocene that Greenland became entirely separated from Eurasia. Before then, a continental sliver, in the order of ~10,000 km2 large and located north of the Hovgaard Ridge, had acted as an inundated continental connection between Greenland and Europe. The Middle Miocene continental rupture of this connection led to a reorganization of ocean currents and an Arctic cooling of NE Greenland and its shelf. It was only a few million years later that the transgression of the Denmark Strait High separated Iceland from Greenland and, thus, allowed the passage of cold-water currents along SE Greenland's margin establishing high-Arctic conditions in this region too.

In early Late Miocene, a marked paleo-shelf embayment developed on the central NE Greenland margin, evident by a ~120 km long paleo-shelf break lying 80-90 km landward of the present-day shelf break. A thin plastered contourite cover the floor of the embayment, evidencing the presences of bottom current action for a short period prior to the onset of shelf glaciation. During the subsequent glacial periods, the NE Greenland shelf became covered by thick ice and ice streams multitude times. This caused erosion and sub-glacial depositions on the shelf area surrounding the paleo-embayment and deposition of more than 2 km thick, amalgamated and interfingered trough mouth fans off the paleo-shelf break. Eventually, this resulted in filling of the paleo-embayment and development of the arc-shaped present-day shelf, that also displays all the classic morphological elements of a glaciated continental margin.

Informing future scientific drilling efforts in glaciated margins in support of Science Framework 2050

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High latitude glaciated continental margins are high-risk high-reward settings for scientific ocean drilling. Three of the Science Framework 2050 strategic objectives- *Earth's Climate System, Feedbacks in the Earth System, and Tipping Points in Earth's History*- and one of the Flagship Initiatives- *Ground Truthing Future Climate Change*- require drilling glaciated and ice-prone margins. The Science Mission Requirements (SMR) presented to the National Science Foundation for a successor scientific drilling vessel to the *JOIDES Resolution* (JR) emphasize the need for operational capability in high latitudes. Beyond the ship infrastructure, recovery of glaciogenic sequences can be technically challenging, but recent successful expeditions provide some lessons learned on site selection, drilling methodologies, and trade-offs. As highlighted in the Science Framework 2050, high latitudes are the most sensitive to changing climate states and comprise critical scientific drilling targets.

Integrated Ocean Drilling Program Expedition 341 to the Gulf of Alaska represents both a success and a cautionary tale regarding best strategies for continuous sampling of the sedimentary archives containing records of glacial sedimentary flux to shelf, slope, and deep-sea fans. Extremely high sedimentation rates allow for very high-resolution records of the transition from proximal to distal depositional processes. However, in subglacial shelf-crossing trough environments and/or trough mouth fans, clast-rich glacial diamict results in low recovery. Nonetheless, the high sedimentation rates allow for well dated, if incomplete, sequences. For instance, despite incomplete recovery, analysis of Sites U1420 and U1421 sedimentology, ice-rafted debris, foraminifera, and ^{14}C dating correlated to downhole logging and high-resolution seismic data supports the hypothesis that tidewater glacial sediment flux can stabilize glacial termini close to a shelf edge. Site U1419, located on a continental slope basin near, but not within, a trough mouth fan, demonstrates the possibility of high core recovery with careful site selection, and yielded detailed paleoceanographic reconstructions during Cordilleran ice sheet deglaciation. A second Gulf of Alaska expedition is proposed to the International Ocean Discovery Program targeting westward from Site U1419 westward into the shelf-crossing Junken Trough, Prince William Sound, and Port Valdez. Key goals include studies of the Alaska earthquake and tsunami paleo record and examining the timing and abruptness of Cordilleran ice sheet deglaciations.

In addition to the recovery challenges of glacimarine sediments, sea ice provides a significant hurdle for many high-priority paleoclimate targets. Two successful high recovery expeditions (Expeditions 374 and 382) drilled shelf, slope and rise sites in relatively ice-free regions of the Ross and Weddell Seas, and are yielding important millennial to orbital scale records of Antarctic climate evolution. High sedimentation rates, coupled with excellent recovery and detailed chronological controls are enabling sub-orbital scale understanding of ice proximal oceanographic conditions through the Neogene. However, Expedition 379 was unable to access any of the proposed shelf sites due to inability for the ship to maneuver near seasonal sea ice. This experience helped to drive the SMR for a JR successor to be ice strengthened and highlights the importance of ice capable mission-specific platforms; such assets will be key to allow scientific drilling to unlock more of the Arctic and Antarctic climate history. For example, two proposed transects of drill sites offshore the Totten Glacier system in East Antarctica may contain the record of initial East Antarctic ice advance onto the continental shelf, a history of Oligocene and Miocene glacial-interglacial fluctuations of a meltwater-rich outlet glacier system, and the timing of the transition to today's "polar state" of the East Antarctic ice sheet. Offshore records, coupled with terrestrial drilling in the landward Aurora subglacial basin may yield the most complete understanding of early East Antarctic ice sheet development possible.

As with Antarctica, potential scientific ocean drilling targets in north Greenland may contain critical records of key climate transitions and Earth system feedbacks, accessible by drilling, that will require the ability to operate in icy waters. Past drilling successes demonstrate the possibility of identifying feedbacks and tipping points in Earth climate system on glaciated margins with existing drilling platforms and technology, optimized geophysical site characterization, and careful site selection. Further scientific advances may be advanced by integrating land-to-sea drilling strategies that span a range of glacial processes and records.