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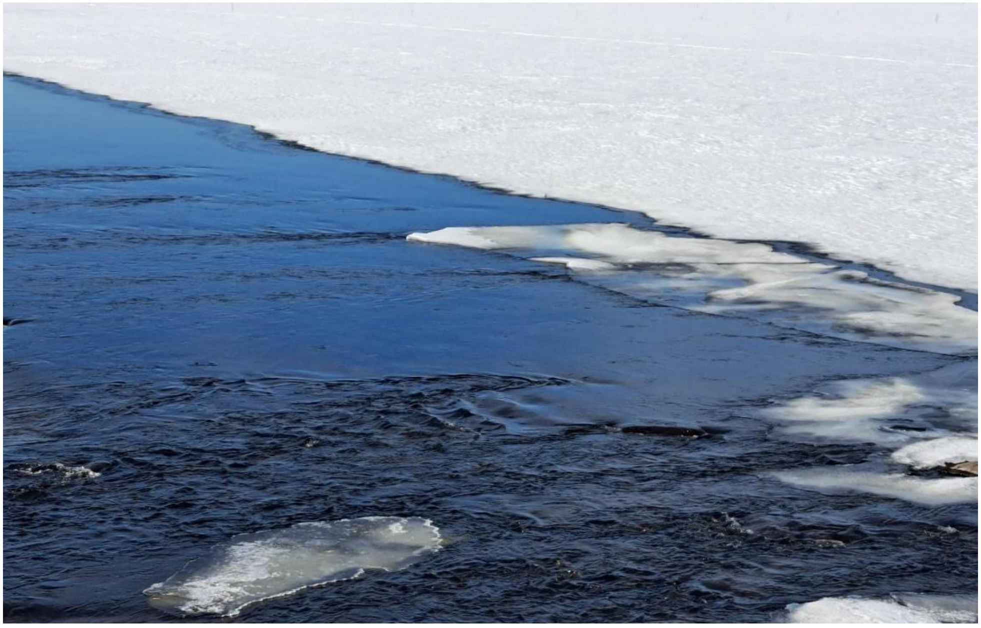

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Melting of ice cover in a lacustrine environment.

Raisa Alatarvas

Provenance analysis of Late Pleistocene Arctic glacial marine and lacustrine sediments – implications for deglaciation dynamics

Academic dissertation to be presented with the assent of the Doctoral Training Committee of Technology and Natural Sciences of the University of Oulu for public defense in auditorium L5, University of Oulu, on August 11th, 2023, at 12 o'clock noon.

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Provenance analysis of Late Pleistocene Arctic glacial marine and lacustrine sediments – implications for deglaciation dynamics

Raisa Alatarvas

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ABSTRACT

In this PhD thesis glacial sediment from the East Siberian Sea/Shelf, central Arctic Ocean, and Baltic Sea were investigated in order to present interactions between the Late Pleistocene deglaciations and sediment deposition in marine and lacustrine environments in the Northern Hemisphere. The main objective of the study was to determine provenance areas and transport mechanisms and pathways for sediments from the De Long Trough, southern and central Lomonosov Ridge, and Landsort Deep. Sedimentological, mineralogical, and geochemical proxies were determined from the SWERUS-C3, IODP Expedition 347 Site M0063, and AO96/12-1pc core materials to establish the rate of processes and products related to deglaciation dynamics, such as loss of ice and meltwater release. The heavy mineral signature of marine glacial sediments from a glacial trough and the related trough mouth fan setting from the East Siberian Shelf were used for far field reconstructions of ice sheet activity on the East Siberian continental margin. The changes in the mineralogy between the diamicts and the overlying clay-rich sediments from the last glacial cycle deposited in the De Long Trough reflect the changes related to deglaciation in the East Siberian continental margin. The clay mineral content and the isotope signatures of the sediments from the Lomonosov Ridge, central Arctic Ocean were used to evaluate the provenances and transportation of the detrital sediments related to the deglaciation event during the transition from Marine Isotope Stage (MIS) 4 to 3. Sedimentological, mineralogical, and geochemical analyses of the sediments from the Landsort Deep enabled to establish more detailed interpretation of the depositional events and environments of the sediments related to the Baltic Ice Lake between ~13.5 and 10.5 ka BP. The sediments reflect the fluctuations of the Fennoscandian Ice Sheet; retreat and melting of the ice sheet and/or lake drainage events associated to warm periods, such as the Bølling/Allerød interstadial; and the standstill and/or readvance of the ice sheet during the Younger Dryas stadial.

Keywords: Arctic, East Siberian Sea, De Long Trough, Arctic Ocean, Lomonosov Ridge, Baltic Sea, Baltic Ice Lake, Landsort Deep, ice sheet, deglaciation, heavy minerals, facies analysis, clay mineralogy, isotope

Arktisen alueen myöhäispleistoseeniajan glasiaalisten meri-ja järvisedimenttien lähdealueanalyysi – implikaatiot deglasiaation dynamiikkaan

Raisa Alatarvas

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TIIVISTELMÄ

Tässä väitöstutkimuksessa tutkittiin sedimenttikairanäytteitä Itä-Siperian mereltä, keskeiseltä Jäämereltä, ja Itämereltä tarkoituksena selvittää vuorovaikutuksia myöhäispleistoseeniajan deglasiaation ja sedimenttien kerrostumisen välillä pohjoisen pallonpuoliskon meri- ja järviympäristössä. Tämän työn päätavoitteena oli määrittää lähdealueet ja kuljetusmekanismit- ja reitit sedimenteille, jotka ovat kerrostuneet De Long kanavansuuviuhkassa, Lomonosovin harjanteen etelä- ja keskiosassa sekä Landsortin syvänteessä. SWERUS-C3:n, IODP Expedition 347 Site M0063:n, ja AO96/12-1pc:n sedimenttikairanäytteiden sedimentologisten, mineralogisten, ja geokemiallisten analyysien perusteella määritettiin kerrostumisprosessit ja kerrostuneet sedimentit, jotka liittyvät deglasiaation dynamiikkaan, kuten jään vähenemiseen ja sulamisveden vapautumiseen. Itä-Siperian mannerhyllyllä sijaitsevan jäätikön muokkaaman laakson ja sen edessä kerrostuneiden merellisten glasiaalisedimenttien raskasmineraalipitoisuuksia käytettiin Itä-Siperian mannerreunan jäätikön dynamiikan tutkimuksessa. Muutokset De Long kanavansuuviuhkaan kerrostuneiden subglasiaalisen diamiktonin ja viimeisimmän jääkauden savirikkaiden sedimenttien välillä heijastavat Itä-Siperian mannerreunan deglasiaatioon liittyviämuutoksia. Jäämeren keskiosan Lomonosovin harjanteelta peräisin olevien sedimenttien savimineraalien koostumusta ja isotooppipitoisuuksia käytettiin arvioidessa deglasiaatioon liittyvien detritaalisten sedimenttien alkuperää ja kulkeutumista merenpohjan isotooppivaihe (MIS) 4:stä 3:een siirtymisen aikana. Sedimentologiset, mineralogiset ja geokemialliset analyysit Landsortin syvänteen glasiaalisedimenteistä mahdollistivat yksityiskohtaisemman tulkinnan Itämeren jääjärven vaiheeseen liittyvistä sedimenttien kerrostumisesta ja kerrostumisympäristöistä aikavälillä ~13.5–10.5 ka. Sedimentit edustavat Fennoskandian mannerjäätikön levinneisyyden vaihtelua; lämpimiin aikoihin liittyviä vetäytymis- ja sulamisvaiheita ja/tai järven purkautumisia, kuten Bølling/Allerød interstadiaali, ja jäätikön pysähtymistä ja/tai etenemistä Younger Dryasin stadiaalin aikana.

Asiasanat: Arktis, Itä-Siperian meri, De Long kanavansuuviuhka, Jäämeri, Lomonosovin harjanne, Itämeri, Baltian jääjärvi, Landsortin syvänne, jäätikkö, deglasiaatio, raskasmineraalit, fasiesanalyysi, savimineralogia, isotooppi

ACKNOWLEDGEMENTS

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There are many people that really helped me during the research and writing process and I would like to thank all of them. I would like to express my gratitude to my principal supervisor Professor Kari Strand from the Oulu Mining School, University of Oulu, for giving me the opportunity to work on this thesis and supporting and encouraging me during the research process. I would like to thank my other supervisor Juha Pekka Lunkka and the members of my doctoral training follow-up group Professor Pertti Sarala and Senior Researcher Kari Moisio. I acknowledge the staff of the Centre for Material Analysis, University of Oulu where the analysis procedures were carried out, and also Riitta Kontio and Sari Forss from the Oulu Mining School Research Centre, University of Oulu for their help with sample preparation. I wish to express my appreciation to my pre-examiners Antti Ojala and Joonas Virtasalo for reviewing the thesis manuscript. I would also like to thank all the co-authors who contributed to the original papers which were included to this thesis. Likewise, I would like to thank all the colleagues, especially Tiina Eskola, at the Oulu Mining School, University of Oulu, for all the discussions related (and unrelated) to thesis work.

Finally, I would like to express my sincere gratitude to my family and friends who supported and encouraged me during the ups and downs of my doctoral studies, and the research and writing process.

Oulu, June 2023

Raisa Alatarvas

ORIGINAL PUBLICATIONS

This thesis is based on the following three peer-reviewed publications, which are referred to throughout the text by their Roman numerals:

Paper I — Alatarvas, R., O'Regan, M. & Strand, K. 2022. Heavy mineral assemblages of the De Long Trough and southern Lomonosov Ridge glacigenic deposits: implications for the East Siberian Ice Sheet extent. Climate of the Past 18, 1867–1881. https://doi.org/10.5194/cp-18-1867-2022

Paper II — Alatarvas, R., Strand, K., Hyttinen, O. & Kotilainen, A. 2022. Sedimentary facies and clay mineralogy of the late Pleistocene Landsort Deep sediments, Baltic Sea – implications for the Baltic Ice Lake development. Arctic, Antarctic, and Alpine Research 54:1, 624–639. https://doi.org/10.1080/15230430.2022.2155352

Paper III — Alatarvas, R., Immonen N. & Strand, K. 2023. Clay mineral and Nd, Pb, and Sr isotope provenance of a MIS 4-3 sediment record from the Lomonosov Ridge, central Arctic Ocean. Bulletin of the Geological Society of Finland. https://www.geologinenseura.fi/sites/geologinenseura.fi/files/alatarvas_et_al.pdf

Contribution of the author

In Paper I, R.A. performed the analysis and M.O. provided the samples. The manuscript was prepared and written by R.A. (70%), K.S. (20%), and M.O (10%). Paper II was planned by K.S. and O.H., R. A. made the analyses and compiled the data, and K.S. and R.A. interpreted the data and prepared the manuscript with comments by A.K. who provided the samples. The clay mineral data for Paper III was compiled and interpreted by R.A., and isotopic analysis was performed and interpreted by N. I. and K.S. The manuscript was prepared and written by R.A. (40%), N.I. (30%), and K.S. (30%).

CONTENTS

1 INTRODUCTION

Rapid transformations occurring in the high latitude areas affect the entire Earth system, its climate and weather extremes through the continuing glacier retreat and loss of sea ice cover (IPCC 2018). The loss of the cryosphere in the Arctic will cause major physical environmental, ecological, social, and economic changes, in not only the Arctic, but will also influence environment and climate globally (IPCC 2018). The best high-resolution timing of rapid ice sheet melting events or releases of meltwaters from melting ice or outbursts of large lakes can be studied from deep marine records. The occurrence of clay (Stein *et al.* 1994; Wahsner *et al.* 1999; Kalinenko 2001; Viscosi-Shirley *et al.* 2003; Vogt & Knies 2008; Strand *et al.* 2008; Krylov *et al.* 2008, 2014) heavy minerals (Krylov *et al.* 2008; Zhang *et al.* 2015; Kaparulina *et al.* 2016) and radiogenic isotopes (Tütken *et al.* 2002; Fagel *et al.* 2014; Li *et al.* 2023) have been applied in sediment provenance tracing and transport mechanism reconstructions in the Arctic region, and the use of marine sediments containing ice rafted debris (IRD) enables the detection of ice sheet collapse events.

It is well known that continuous ice sheet melting events, thinning and melting of sea ice, and a rapid eustatic sea level rise are related to glacial/interglacial transitions i.e., deglaciations. All these changes have affected physical environments and their evolution in the terrestrial and marine realms, but the rate of changes and their nature during these transition periods is still largely unknown. This PhD thesis contributes to international efforts for solving research questions related to climate change and loss of ice, and it is in relation to history and mechanisms of events such as ice sheet decay and meltwater release in the Northern Hemisphere. This thesis also offers knowledge that is important in predicting and setting boundary conditions for future environmental and climate change in the Arctic region.

Various weathering and sedimentary processes are ultimately controlled by the climate. Sediment geochemical composition in the ocean basins close to continents is initially formed and derived from land through these processes. More than one analytical method is required to evaluate the natural complexity of sedimentary systems. In this research, the rate of processes and products related to loss of ice in the Northern Hemisphere is established through considerations of mineralogical, sedimentological, and geochemical factors. Geochemical proxy data including clay and heavy mineral, IRD, facies analysis, water and carbon content, and isotopes from the SWERUS-C3, IODP Expedition 347 Site M0063, and AO96/12-1pc core materials were applied in this thesis. The specific aim of this thesis was to characterize significant Late Pleistocene to Early Holocene climatic and environmental transitions, such as loss of ice and meltwater release during deglaciation. The research objectives of the included publications are listed below.

1) To define the heavy mineral signature of glacial marine sediments from the East Siberian continental margin, especially from a glacial trough and the related trough mouth fan setting (Paper I).

2) To evaluate the heavy mineral compositions of diamict samples from the De Long Trough to see if there is a unique mineralogical signature that can be used for far field reconstructions of ice sheet activity on the East Siberian continental margin (Paper I).

3) To estimate the provenance and source areas, and plausible transport mechanisms of the sediments from the heavy mineral assemblages from the East Siberian Sea/Shelf and southern Lomonosov Ridge, Arctic Ocean (Paper I).

4) To offer information on how the clay mineral content and the isotope signatures of the sediments from the Lomonosov Ridge, central Arctic Ocean correspond to the deglaciation event and deposition of an IRD rich layer during the transition from MIS 4 to 3 (Paper III).

5) To evaluate the provenances and transportation of the detrital sediments in the Lomonosov Ridge, central Arctic Ocean (Paper III).

6) To increase knowledge of the periodicity and effects of meltwater sediment supply and deposition in an ice-contact lake during the evolution of the Baltic Ice Lake from ~13.5 to 10.5 ka BP in the Landsort Deep area (Paper II).

7) To establish more detailed interpretation of varve deposition and environments of the glacial lacustrine sediments related to the Baltic Ice Lake from the sedimentological, mineralogical and geochemical determination of the sediments from the Landsort Deep (Paper II).

8) To outline the evidences of ice sheet melting and/or lake drainage events associated to warm periods, such as the Bølling/Allerød interstadial, and to find sedimentological evidence of the Younger Dryas stadial in the Landsort Deep sediment sequence (Paper II).

2 REGIONAL AND GEOLOGICAL SETTING

The study areas are located in the Northern Hemisphere, in particular, the De Long Trough in the East Siberian Sea/Shelf (Paper I), the Lomonosov Ridge in the central Arctic Ocean (Paper I and III), and the Landsort Deep in the Baltic Sea (Paper II) (Fig. 1). The Arctic Ocean is relatively confined as it has limited connections to the Atlantic via Fram Strait and to the Pacific Oceans via Bering Strait. During extensive Quaternary glaciations in the Eurasian Arctic ice sheets reached the northern continental margins and discharged icebergs into the Arctic Ocean (e.g., Spielhagen *et al.* 2004), and the existence of large ice shelves was possible, especially during the Late Glacial phases (Stein 2008). The East Siberian continental shelf extends over the East Siberian Platform and the North American Plate and it is covered by the East Siberian Sea and the Laptev Sea. Data from seafloor mapping provide substantial evidence of the existence of considerable ice masses on the East Siberian margin (Niessen *et al.* 2013; Jakobsson *et al.* 2014, 2016), but the extent and timing of these ice masses is still relatively undetermined. The Baltic Sea is one of the world's largest epicontinental and brackish water seas (Kaskela *et al.* 2012), and it is connected to the North Atlantic through narrow straits between Denmark and Sweden, which leads to a restricted water exchange. The great variance in bedrock lithology and the distribution of deformable Quaternary sediments enabled the forming of a thin and mobile ice sheet in the Baltic region (Lambeck *et al.* 1998).

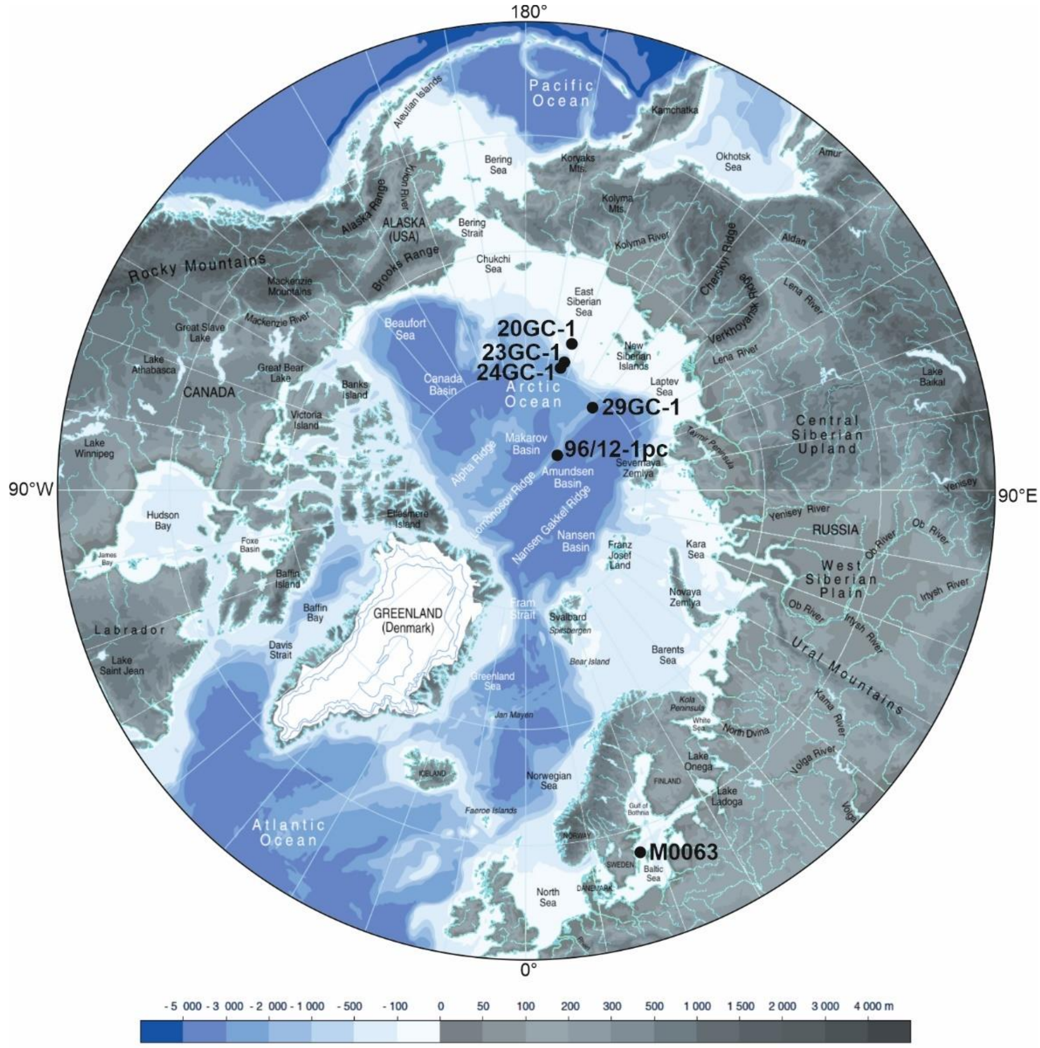

Figure 1. Map of the Northern Hemisphere. The locations of the studied cores are presented with black circles. Original map by AMAP (1998a).

2.1 De Long Trough, East Siberian Sea/Shelf

The De Long Trough, located north from the De Long and New Siberian Islands (Fig. 2), is the first glacial trough reported on the outer margin of the East Siberian shelf (O'Regan *et al.* 2017). According to Drachev et (2010), the shelf is composed of Late Mesozoic and Cenozoic siliciclastic sediments overlaying the crust of the Late Mesozoic fold belts. The East Siberian Sea is a relatively shallow sea and throughout the larger glaciations following the mid-Pleistocene transition, and during the sea level low stand of the Last Glacial Maximum (LGM), the region was most likely exposed due to most of the region having a depth of <120 m (Lambeck *et al.* 2014; Rohling *et al.* 2014), and due to the global mean sea level being more than 100 m lower than its present value (Klemann *et al.* 2015). The East Siberian Sea Basin is filled with siliciclastic sediments with inferred stratigraphic range of Late Cretaceous to Quaternary age (Drachev *et al.* 2010). The submarine glacial landforms on the shallow shelf, which indicate the presence of ice sheets, might have been eroded during transgressive and regressive cycles (Dowdeswell *et al.* 2016; O'Regan *et al.* 2017).

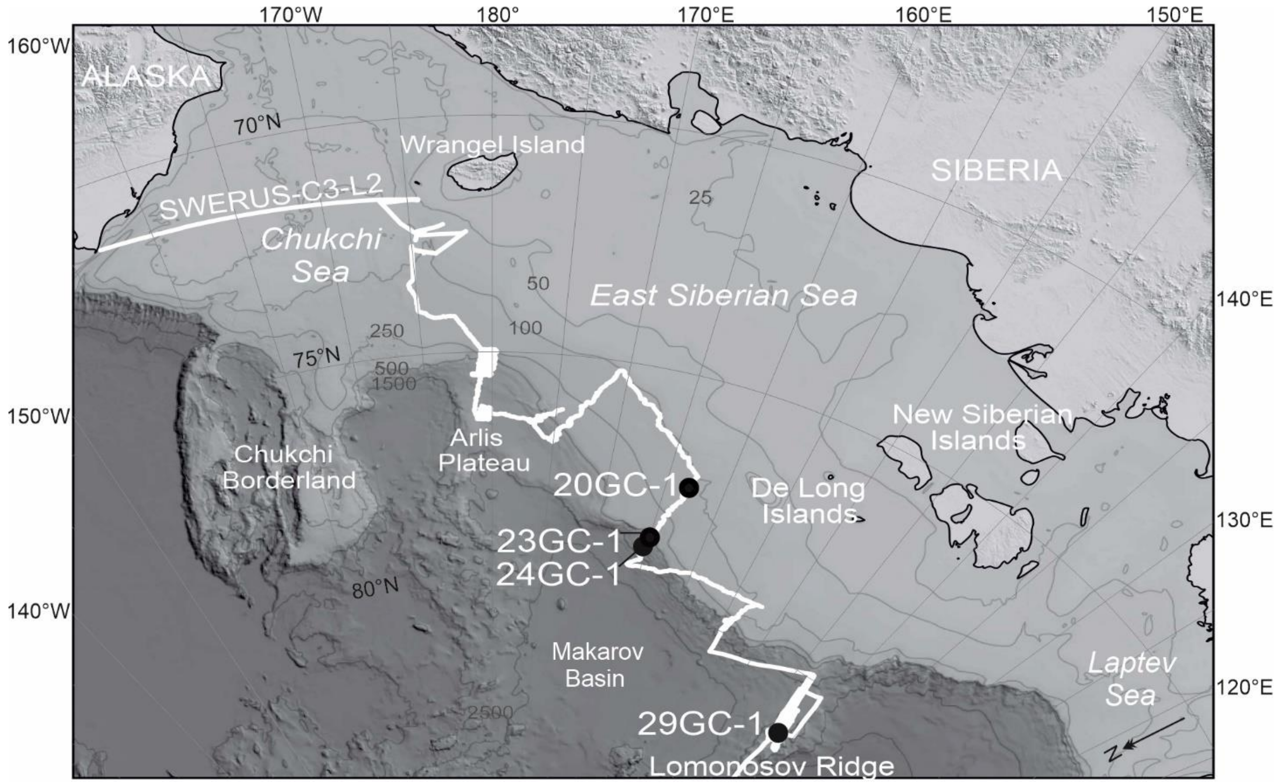

Figure 2. A map showing the locations of cores 20-GC1, 23-GC1, 24-GC-1, and 29-GC1, and the route of Leg 2 of the SWERUS-C3 2014 expedition (white line) (Paper I). Original map by O'Regan *et al.* (2017).

2.2 Lomonosov Ridge, central Arctic Ocean

The Lomonosov Ridge, interpreted as a continental fragment/crust, extends 1700 km from the central Siberian continental shelf, across the North Pole, to the north of Greenland dividing the Arctic Ocean into the Eurasian and the Amerasian Basins (Jokat & Ickrath 2015) (Fig. 3). The two major wind-driven surface-water circulation systems in the Arctic Ocean are the Transpolar Drift in the Eurasian Basin which flows towards the Fram Strait and the Beaufort Gyre which flows clockwise in the Amerasian Basin (Schoster *et al.* 2000; Adler *et al.* 2009) (Fig. 3). The entrained terrigenous sediments in sea-ice and/or icebergs are transported along the surface water masses by these currents.

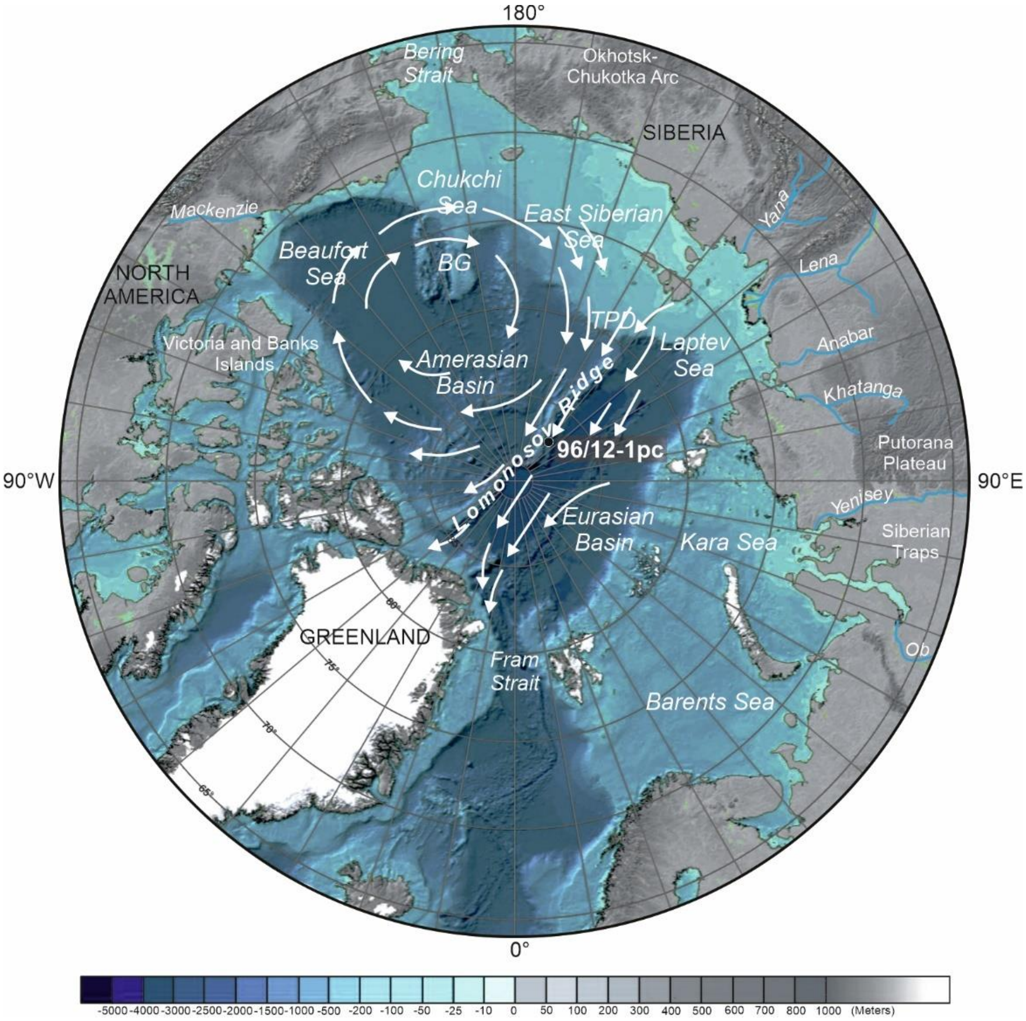

Figure 3. Map of the Arctic Ocean with the location of core 96/12-1pc on the Lomonosov Ridge (modified from Jakobsson *et al.* 2008) (Paper III). Two major surface-water circulations, the Transpolar Drift (TPD) and the Beaufort Gyre (BG) are indicated by white arrows (adapted from AMAP 1998b).

2.3 Landsort Deep, Baltic Sea

The Baltic Sea is a shallow inland sea comprised of several sub-basins and the deepest part of the sea is the Landsort Deep (up to 459 m), which is located in the north-western part of the Gotland basin between the southeast coast of Sweden and the island of Gotland (Fig. 4). The bedrock of the Baltic Sea basin comprises of Proterozoic crystalline basement rocks, and the bedrock is divided into blocks by several ancient tectonic lineaments and fracture zones (Winterhalter *et al.* 1981; Koistinen *et al.* 2001; Kaskela *et al.* 2012). The most notable features of the Baltic Sea basin are probably the depressions and troughs of pre-glacial origin. The Landsort Deep is a crescent-shaped depression with very steep walls (Myrberg *et al.* 2006) and it is situated along a major fault line that is deepened by glacial erosion (Lepland & Stevens 1998). Sediments of the deep present the changeover from low-organic glacial clay deposits to organic-rich Holocene clay deposits that corresponds with the transition from glacial to interglacial, and from freshwater to brackish marine environment (Andrén *et al.* 2015a).

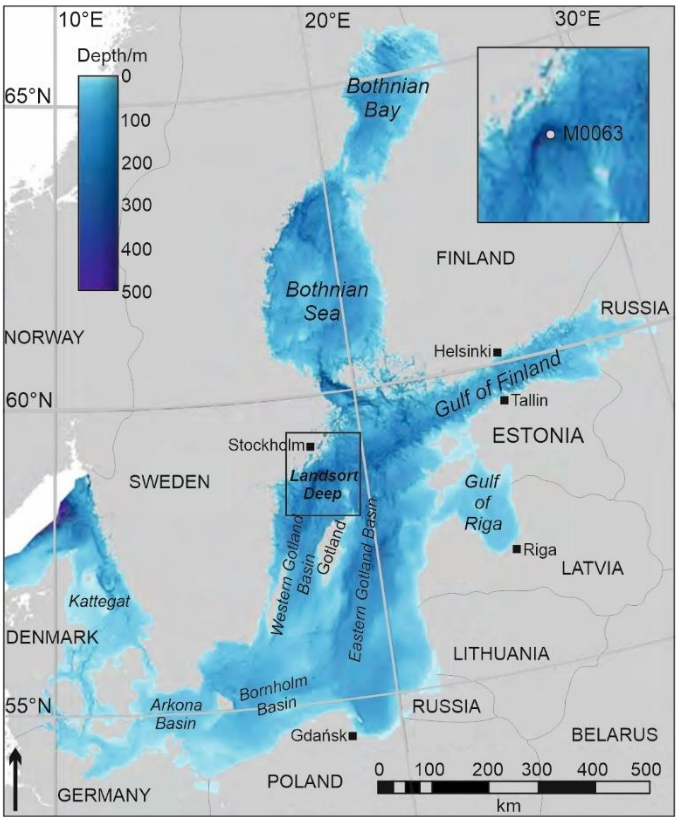

Figure 4. Map of the Baltic Sea (Bathymetry Database version 0.9.3 by Hell & Öiås 2014). Study area indicated by black rectangle and the insert showing location of Site M0063 in the Landsort Deep (Paper II).

The subdivision of the Baltic Sea's evolution into four different stages is related to the water exchange between the sea and the world ocean, as the different stages are characterised by intensive water-level fluctuations (Lepland & Stevens 1998). According to Houmark-Nielsen & Kjær (2003), the first phase of the Baltic Ice Lake formed at ca. 16.0 ka BP. During this phase the surface of the lake was most likely at sea level and the uplift of the Öresund threshold area possibly led to the damming of the lake and the rise of the lake level above sea level ca. 14.0 ka BP (Andrén *et al.* 2011). The main retreat of the ice sheet and the deglaciation of the Baltic region occurred between ~14.0 and 11.0 ka BP. The meltwater from the retreating ice sheet and the drainage from river systems from Europe and western Russia were captured in the lake (Patton *et al.* 2017). Andrén *et al.* (2011) have concluded that the altitudinal difference between the gradually rising sea and the level of the lake as well as the ice recession at Mt. Billingen and at the northern part of the south Swedish highlands possibly caused the first drainage of the Baltic Ice Lake which is estimated to have taken place ~13.0 ka BP. The ice sheet re-advanced during the Younger Dryas cooling (ca. 12.7 ka BP) and blocked the northern drainage of the lake, which led to transgression (Andrén *et al.* 2011). The water level of the lake dropped ca. 25 m down to sea level (Andrén *et al.* 2011) when a new draining point opened in south central Sweden (Bergsten & Nordberg 1992) and caused the final drainage of the Baltic Ice Lake at ~11.7 ka BP (Andrén *et al.* 2015b). The final drainage had a pronounced impact on the environment, including exposure of large coastal areas, changes in fluvial drainage, and reworking of sediments (Andrén *et al.* 2011).

3 DEGLACIATION DYNAMICS AND GLACIAL DEPOSITS

A close relationship between climate changes and orbital cycles has been acknowledged widely (e.g., Imbrie *et al.* 1984) and changes in the Earth's climate caused by orbital forcing were first recorded in marine sediments. The transition from colder glacial conditions to warmer interglacial conditions, referred to as deglaciation, comprises global warming and sea level rise resulting from the change in the ice volume. The most abrupt and notable periods of sea level rise occurred in the course of the major deglaciations due to an enhanced amount of meltwater (Fig. 5). Deglaciation is the retreat of an ice sheet, a glacier or a frozen surface layer, and it can occur on a global or local scale or relate to a specific ice sheet. The imbalance between glacial extent and climatic conditions is reflected in the process of deglaciation, and the retreat of ice sheets and glaciers results from net negative mass balance over time. The physical mechanisms that impact the occurrence of deglaciation are melting, calving, sublimation, evaporation, and aeolian processes. The onset and pace of deglaciations is driven by the variations in the latitudinal and seasonal distribution of incoming solar radiation (insolation) which is connected to the cyclical changes in the Earth's orbit around the Sun (e.g., Berger 1978; Berger & Loutre 1991). The variations in the Earth's eccentricity, obliquity, and precession are the cause for three dominant cycles called the Milankovitch Cycles which are related to the changes in the insolation. The time frame for the eccentricity cycle is ~100 ka, obliquity changes in a ~ 41 ka cycle, and the course of the precession cycle is ~26 ka. Although the major deglaciations correlate with an increase in insolation (Fig. 5), Menviel *et al*. (2019) stated that changes solely in insolation are not adequate to explain the magnitude of major warmings during deglaciations. Menviel *et al.* (2019) have concluded that additional magnification mechanisms are associated with the disintegration of the Northern Hemisphere ice sheets and their related change in albedo, changes in sea ice and vegetation cover, as well as with the voluminous increase in atmospheric greenhouse gas concentrations e.g., CO_2. The orbital cycles may have further effect on ocean circulation and atmospheric CO_2 concentration, which intensify the influences of the changes in insolation (Imbrie *et al.* 1993). Deglaciation occurs as a feedback to the increased insolation, as the Earth's climate system tends to enforce glacial conditions to continue until a threshold is passed, e.g., ice sheet extending too far south (Imbrie *et al.* 1993; Clark *et al.* 1999).

Generally, glacials last for ~100 ka and interglacials for >10 ka, and they are related to the 100 ka cycles associated with the Milankovitch Cycles. The recurrence of deglaciations is approximately every 100 ka for the last 500 ka and the last deglaciation commenced after the Last Glacial Maximum (LGM) ~21 ka BP and continued until the early Holocene. Winsborrow *et al.* (2010) have concluded that, during the ice sheet melting and subsequent deglaciation, the marine-based parts of the Late Weichselian ice sheets were characterised by extensive ice streams along with substantial variations in their flow. In active deglaciation ice sheets disintegrate in a continual way through the retreat and decay of the ice margin. Rapid but gradual retreat of the ice margin across the continental shelf, as well as abrupt and wide fluctuations in ice streams, is a typical pattern for the deglaciation of marine-based ice sheets which continues until the retreating ice margin reaches the land, and from thereon any additional retreat take place at a diminishing rate (Winsborrow *et al.* 2010).

The relatively rapid events of deglaciations represent large-scale changes of the climate. The cooling and warming of the global climate as well as the deglaciation phases can be presented by the isotope ratio $^{18}O/^{16}O$ or $\delta^{18}O$ (‰) record derived from planktonic foraminifera. During colder/glacial periods, large quantities of ^{16}O are trapped in the ice, which leads to relative enrichment of ^{18}O in the oceanic waters. During warmer/interglacial periods, large amounts of ^{16}O is released back into the ocean from the melting ice sheets. Oxygen stratigraphic scales are created based on the oxygen isotope data from deep-sea calcareous sediment cores. Fluctuations in the oxygen isotope composition are illustrated as specific stages – Marine Isotope Stages (MIS) – which were first described by Emiliani (1955). The transitions between these stages correlate with the occurrence of deglaciations (Fig. 5). The MIS timescale can be further subdivided into stadials and interstadials (e.g., MIS 5a-e) based on minor climate fluctuations within the glacial or interglacial periods. MIS 5e, however, is also referred to as the last interglacial period. Stadials endure for a maximum of 1 ka, and interstadials <10 ka. Rapid climate changes and the subsequent warming are recorded in Heinrich events, indicated by the deposition of IRD layers detected in sediment cores from the North Atlantic that are due to a massive collapse of the Northern Hemisphere ice sheets along with the subsequent release of a substantial amount of freshwater via melting icebergs (e.g., Heinrich 1988; Bond *et al.* 1992; Hodell *et al.* 2008, 2017). Andrews & Voelker (2018) have concluded that the durations of the Heinrich events are probably <1 ka.

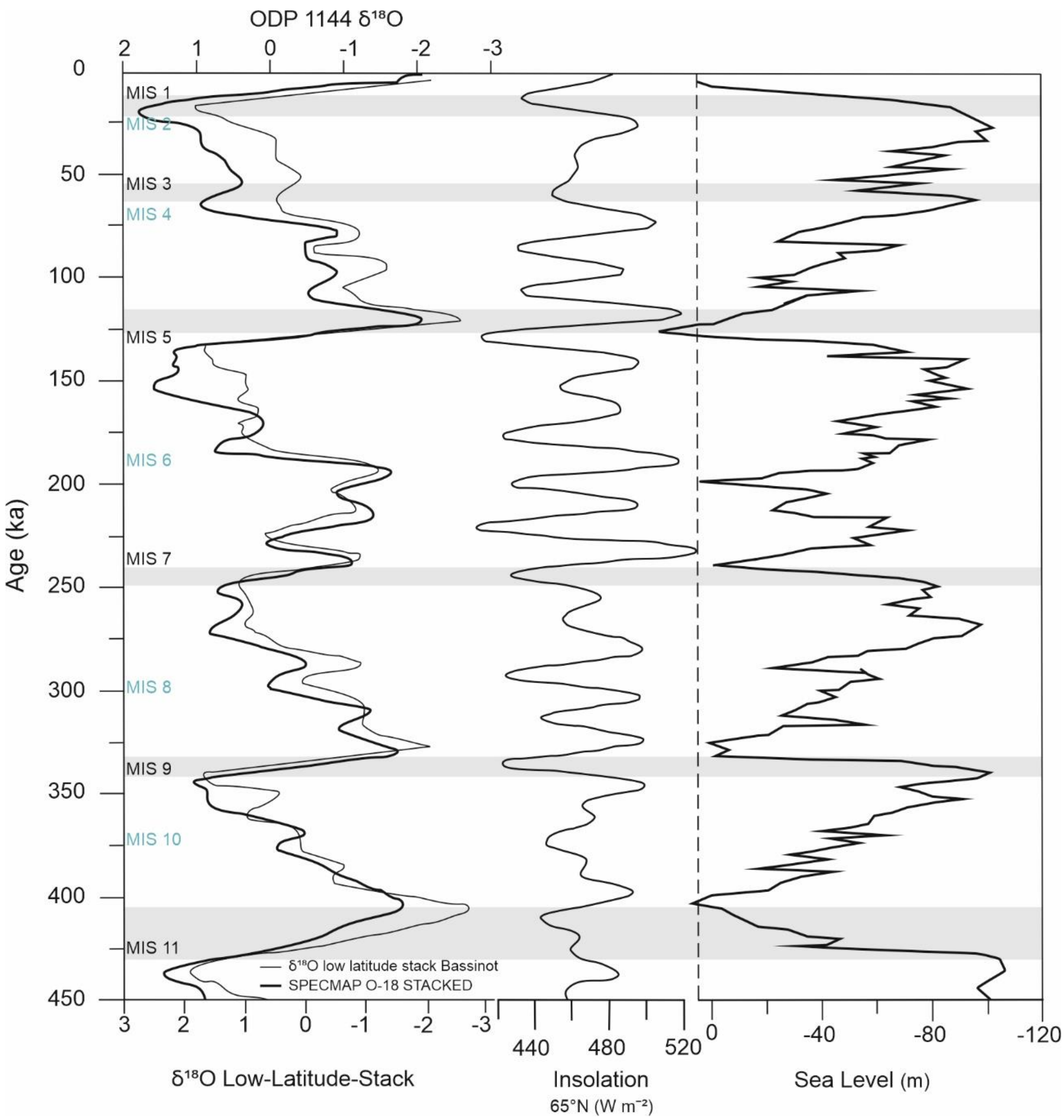

Figure 5. Global deep-sea oxygen ($\delta^{18}O$) curves modified from Kaparulina *et al*. (2016) according to Imbrie *et al*. (1984). The glacial periods of Marine Isotope Stages (MIS) in blue and interglacial periods in black. Insolation at 65°N (Berger & Loutre 1991), sea level variations (dashed line indicating present-day sea level) (Clark *et al*. 2009), and five deglaciations (light grey bars) during the last 450 ka are redrawn from Carlson 2011, respectively. The deglaciation during the transition between MIS 4 and 3 is also indicated.

3.1 Glacial marine and lacustrine deposition environments

In glaciomarine environment (Paper I and III), glacier ice is adjacent to or floats over the sea and the water balance is influenced by glacial meltwater. The glacial conditions on the continental shelf and onshore largely control the deposition of the deep-sea sediments in high latitude areas. The presence of mega-scale glacial lineations, large grounding zone deposits, iceberg ploughmarks, and subglacial hydrological systems, such as tunnel valleys and channels, indicate rapid, but gradual retreat of the ice margin during deglaciation (Esteves *et al*. 2023) (Fig. 6). According to Batchelor & Dowdeswell (2014), areas of fast-streaming glacial ice are represented by the occurrence of glacially excavated cross-shelf troughs on previously glaciated continental shelves (Paper I) (Fig. 6). Stacked glacigenic debris flow deposits of trough mouth fans are formed by the voluminous discharge of subglacial sediments in front of the troughs when the ice was at or near the shelf break (Paper I).

Glaciolacustrine environment receives glacial meltwater, and a proglacial lake (Paper II) can be formed by the confinement of the meltwater adjacent to an ice sheet due to isostatic depression of the crust, by damming of the ice, or damming by a moraine deposition during the retreat of the ice sheet. The stratification of the lake and temporal fluctuations in meltwater inflow affect the dispersal of sediments and control the varying sedimentation common to glaciolacustrine deposits (Paper II). During deglaciation, proglacial lakes experience a transition from proximal, ice-contact sediment accumulation to ice-distal (Paper II).

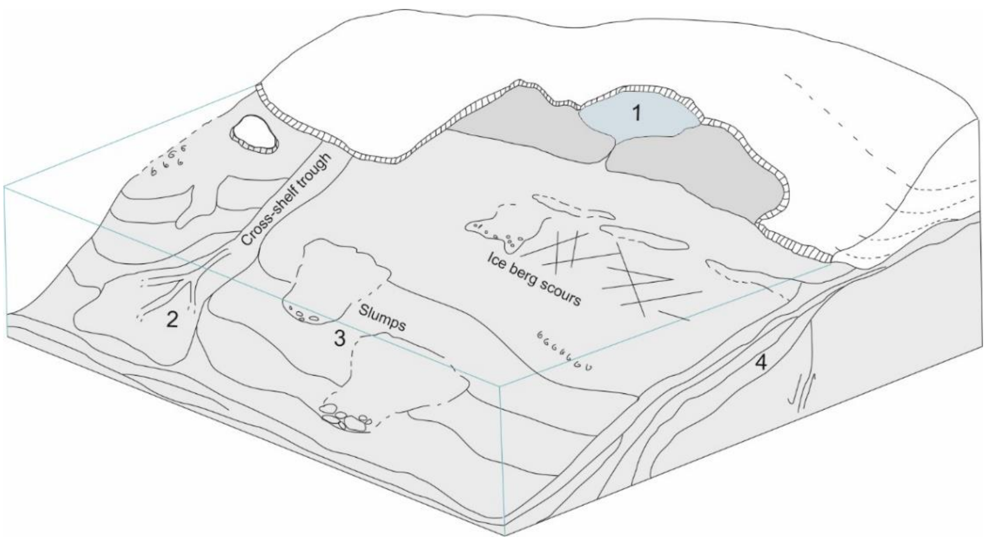

Figure 6. Examples of glacial deposit environments: glaciolacustrine (1), submarine channel (2), slope (3), and shelf (4). Modified from Eyles & Eyles 1992.

3.2 Glacial sedimentary facies

Four genetic facies groups of glacial sediments are determined from their principal constituent facies (Edwards 1986).

1) The subaqueous facies comprise glacial marine and lacustrine laminaes and diamicts (Fig. 7). The laminaes comprise varve deposits formed in the sea with or without rhythmic structure,

or deposits formed in fresh and brackish water. The composition varies between clay, silt and sand fraction. Supplementary features include the presence of dropstones, intercalated sandstones or diamict beds, for example. Ice-rafted diamicts can be massive, laminated or reworked. The massive glaciomarine ice-rafted diamicts can show gradational contact with other, stratified sediments and the intercalation of turbidites, for example.

2) The proglacial outwash deposits include sandstones and conglomerates, with stratification ranging from poor to excellent due to the activity of glacial meltwater in front of the ice sheet.
3) The supraglacial facies comprise diamict interbedded with stratified deposits. These deposits occur in extensive areas of ice-disintegration topography or in discrete linear end moraines formed at the former ice sheet margin.
4) The subglacial facies include massive diamicton deposited as lodgement, melt-out, sublimation, or undermelt tills.

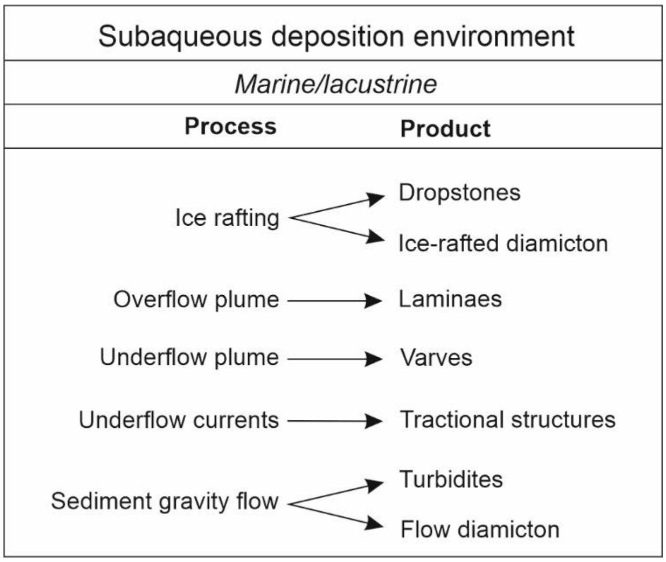

Figure 7. Examples of sedimentary processes and products in subaqueous marine and lacustrine proglacial environments (adapted from Edwards 1986).

3.2.1 Glacial marine and lacustrine deposits

The grain-size distribution and sedimentation rate of glacial sediments vary in a cyclic pattern and seemingly correspond to glacial/interglacial changes (Henrich 1989). Glacial sediments can vary from coarser grained diamict, related to maximum extension of the ice sheets and periods of deglaciation to fine grained muds characteristic of interglacial periods. The presence and amount of coarser IRD is a significant parameter in the study of glacial sediments. Variations in the concentration of the IRD are usually associated with changes in the glacial regime. Peaks of higher IRD content detected at the early stage of deglaciation relate to large-scale iceberg influx (Elverhoi & Henrich 2002). As the icebergs melt, glacial debris is released as coarse deposits or singular dropstones within finer grained deposits. The source areas of the sediments transported to the deposition site by the run-off from the melting ice sheet can be traced by analysing the abundance of terrestrially derived elements from the sediments.

4 CORING SITES, LITHOLOGY, AND AGE MODEL

This PhD thesis combines multi-proxy data obtained from two coring sites from the De Long Trough and one coring site from each of the following: the East Siberian Shelf; Lomonosov Ridge, central Arctic Ocean; southern Lomonosov Ridge; and Landsort Deep, Baltic Sea (Table 1; Fig. 1).

Table 1. Locations, lengths, and water depths of the studied cores. Data from O'Regan *et al.* (2017) and the SWERUS cruise report (2014) (Paper I); Andrén *et al.* (2015c) (Paper II); and Jakobsson *et al.* (2000, 2001) (Paper III).

Paper	Core	Water depth (m)	Length (m)	Coordinates	Location
I	20–GC1	115	0.83	77°21.5'N; 163°2.0'E	East Siberian Shelf
I	23–GC1	508	4.06	78°39.7'N; 165°0.9'E	De Long Trough
I	24–GC1	964	4.05	78°47.8'N; 165°22.0'E	De Long Trough
I	29–GC1	824	4.66	81°17.9'N; 141°46.9'E	Southern Lomonosov Ridge
III	96/12-1pc	1003	7.22	87°05.51'N;144°46.22'E	Lomonosov Ridge
II	M0063C	437	96.4	58°37.34′N; 18°15.25′E	Landsort Deep

4.1 De Long Trough, East Siberian Sea/Shelf

The studied sediments are from cores 20-GC1, 23-GC1, 24-GC1 and 29-GC1 (Paper I), which were collected from various locations and water depths during Leg 2 of the SWERUS-C3 2014 (SWERUS-C3: Swedish – Russian – US Arctic Ocean Investigation of Climate-Cryosphere-Carbon Interactions) expedition in the Arctic Ocean (Table 1; Fig. 2). The cores were collected using a gravity corer (GC), and the geophysical mapping methods used during the expedition included multibeam bathymetry and sub-bottom profiles (Jakobsson *et al.* 2016; O'Regan *et al.* 2017). The sub-bottom stratigraphy from the East Siberian shelf to the shelf break is divided into six acoustic units (AU), and two of the studied cores (23-GC1 and 24-GC1) are divided into sedimentary units A and B. The summarised description and interpretation of these acoustic and sedimentary units is from O'Regan *et al.* (2017). Core 20-GC1 sampled sediments from AU 1 which is interpreted as iceberg-scoured postglacial sediments with a sharp basal contact on the shallow shelf. The unit thickens in deeper water depths and incorporates preglacial and glacial sediments reworked during the last glacial cycle sea level lowering. Cores 23-GC1 and 24-GC1 penetrated to the base of AU 3, which is represented by the undisturbed sediments of sedimentary Unit A. AU 3 is a coherent and laterally continuous acoustically layered sequence extending seaward of the shelf break and downslope to water depths of > 2000 meters below sea level (m b.s.l.). The coarser-grained glacial sediments of sedimentary Unit B correspond to AU 4 which is interpreted as sub-glacially deposited sediments.

A total of 17 samples were analysed from the studied cores. Two samples from core 20-GC1, recovered from the East Siberian Shelf (Table 1; Figs. 2, 8), are from dark grey, coarser-grained facies at the base of the core. Two diamict samples are from core 23-GC1, and nine samples from core 24-GC1 recovered from the De Long Trough, East Siberian Sea/Shelf (Table 1; Figs. 2, 8). The samples studied from core 24-GC1 also include surface sediments and other lithologies between the diamict and the seafloor. Four samples of core 29-GC1 are from acoustically stratified sediments deposited on top of the ice-scoured surface of the southern Lomonosov Ridge, Arctic Ocean (Jakobsson *et al.* 2016) (Table 1; Figs. 2, 8).

Radiocarbon ages of ~13–11 ka BP from the lower part of core 20-GC1 indicate that the deglacial dark grey sediments do not correlate to a resembling lithology predating the LGM at the base of cores 23-GC1 and 24-GC1; however, they do correlate with the thin grey sediment sequence in the upper 0.5 m of these cores (Cronin *et al.* 2017). The radiocarbon age of core 23-GC1 (1.69–1.86 m b.s.f.) is 33 200 ± 560 ^{14}C years BP and its calibrated medium age is 37 000 $\pm\frac{2600}{1300}$, while the radiocarbon age of core 24-GC1 (1.92 m b.s.f.) is 43 000 ± 1800 ^{14}C years BP and its calibrated medium age is 46 300 $\frac{3500}{2600}$ cal years BP (O'Regan *et al.* 2017). The radiocarbon ages show that the base of Unit A is older than ~50 cal ka BP (Fig. 8). The calcareous nannofossil *E. huxleyi* occurring in core 23-GC1 at 2.28 m b.s.f. indicates, that the sediments are younger than MIS 8/7 in that point (Backman *et al.* 2009; O'Regan *et al.* 2017; O'Regan *et al.* 2020). O'Regan *et al.* (2017) postulated an MIS 6 age for the basal diamict of cores 23-GC1 and 24-GC1; however, they also recognised possible deposition during a younger stadial in MIS 5 or 4. The results of luminescence dating by West *et al.* (2021) support a pre-Eemian age for the sediments at the base of core 29-GC1. The core correlates to a neighbouring core, the base of which has been proposed to be MIS 6 age (Stein *et al.* 2001), while the inferred MIS 6/5 transition in the core 29-GC1 is at ~ 4 m b.s.f. (Jakobsson *et al.* 2016) (Fig. 8). A Holocene age is indicated by the calcareous nannofossils in the uppermost 5 cm of the core (Jakobsson *et al.* 2016).

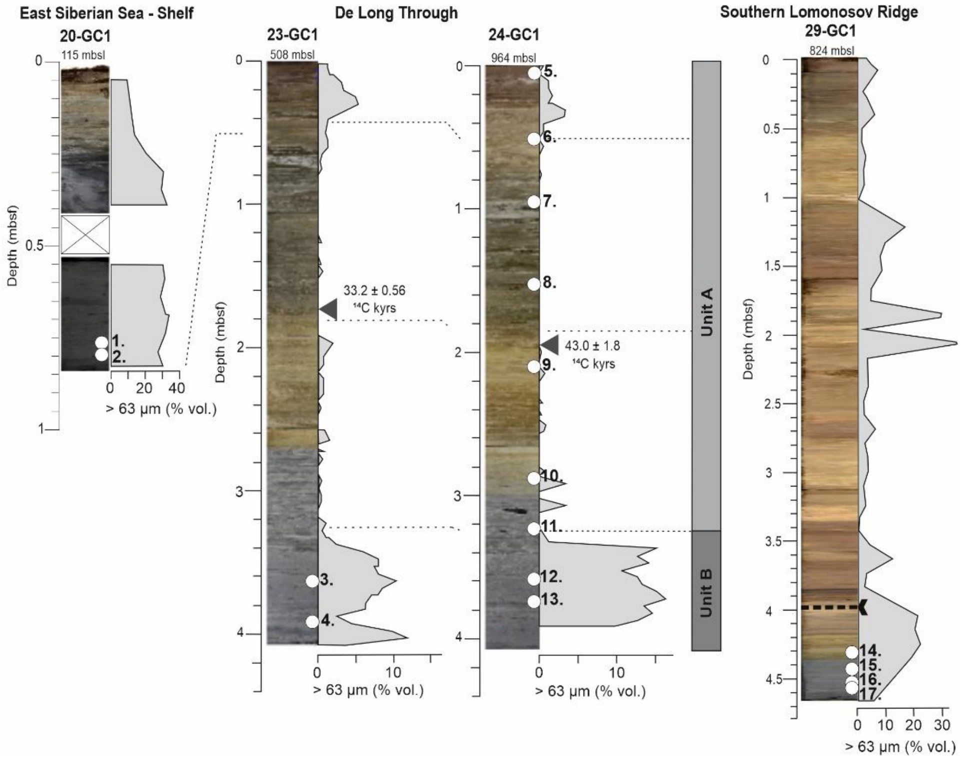

Figure 8. Digital images of the studied cores (Paper I), including sample points (white circles), stratigraphic correlation of the cores (dotted line), and the division of sedimentary Units A and B (adapted from O'Regan *et al.* 2017). The inferred MIS 6/5 transition (black dotted line) in core 29-GC1 is from Jakobsson *et al.* (2016) and the grain size from West *et al.* (2021).

4.2 Lomonosov Ridge, central Arctic Ocean

Core 96/12-1pc (Paper III) was recovered from the crest of the Lomonosov Ridge, central Arctic Ocean (Table 1; Fig. 3) during the Arctic Ocean-96 expedition (AO96) (Jakobsson *et al.* 2000, 2001). The core sediments are mostly composed of horizontally bedded silty clay and clay (Jakobsson *et al.* 2000). From 722 to 193 cm below seafloor (bsf), the core consists of medium to dark brown clays characterised by an overall high content of manganese, common bioturbation, and fine particle size. A coarser-grained, light grey-brown, sandy clay between 193 and 186 cmbsf gradually changes to an olive to light brown clay at 186 to 163 cmbsf. The latter unit is overlain with a sharp contact by a homogenous, dark grey, 48 cm thick, silty clay layer between 163 and 115 cmbsf. The uppermost 115 cmbsf of the core consist of light brown to light yellowish-brown, mottled clayey silt with faint horizontal banding.

According to an approximative age model based on nannofossil biostratigraphy and Mn cyclicity the upper 220 cmbsf of the core extends back to ca. 860 ka BP (Jakobsson *et al.* 2000).

4.3 Landsort Deep, Baltic Sea

The studied cores were recovered from Hole M0063C of Site M0063 in the Landsort Deep (Table 1; Fig. 4) during the IODP Expedition 347 'Baltic Sea Paleoenvironment' in 2013 (Andrén *et al.* 2015c). The coring site is divided into seven (I–VII) lithostratigraphic units and the studied samples derive from Unit V (47.80–51.15 mbsf) and Unit VI (51.15–92.16 mbsf). The main lithologies of Unit V and VI are described based on Andrén *et al.* (2015a). The diamict of Unit VII is overlain by the thick (~41 m) Unit VI, the lowermost part of which is composed of frequent well-sorted sand laminae with a gradational lower boundary and an increased grain size, along with cm-scale pebble grains and dispersed clasts of subangular sand. There are individual mm-scale sand laminaes, as well as several distinct upward-fining sandy silt-clay couplets present in the lower part of Unit VI. Massive structures, reddish brown clay-silt-sand interlaminaes in thicker units, and clay laminaes with occasional internal slumping are common up to ~85 mbsf, and cm-scale carbonate concretions occur within laminated silty clay upward from ~75 mbsf. The uppermost part of the unit comprises of homogeneous, dark grey-brown clay interbeds along with mm-scale silt interlaminaes. The overlying Unit V contains dark grey to greyish brown, very well sorted clay, which displays internal structures of massive appearance along with contorted silt laminated intervals with convolute bedding. In the lower parts of the unit, the laminated clay is displaced by microscale faults.

A new nonoverlapping depth scale was calculated for each hole, expressed as adjusted meters below seafloor (ambsf), which took account of the expansion that the cores experienced due to degassing during decompression (Obrochta *et al.* 2017). This adjusted meter scale was applied for the depths of the studied samples.

In this study, Unit VI was divided into three Subunits: VIc (84–92.16 ambsf); VIb (68–84 ambsf); VIa (51.15–68 ambsf). The division was established on the basis of visual core descriptions, consideration of the sedimentary facies, variations in the sediment grain size and clay mineral assemblages, and changes in the physical property and water and carbon content trends.

Existing age constraints of the Baltic Ice Lake were applied to the sediments studied. According to e.g., Björck (1995) and Andrén *et al.* (2011), the first drainage and ice recession of the Baltic Ice Lake took place at ~13.5–13.0 ka BP. The onset of deglaciation of the Landsort Deep is inferred to take place ~13.5 ka BP (Hughes *et al.* 2016; Stroeven *et al.* 2016; Obrochta *et al.* 2017), and the reconstruction of the Baltic Ice Lake by Vassiljev & Saarse (2013) indicates that the deep was fully deglaciated at ~12.2 ka BP. According to Andrén *et al.* (2015a), specific pollen types at ~66 mbsf could indicate a pre-Holocene age for that range, and a pollen spectrum typical for 11.0–10.5 ka BP age at ~56.8 mbsf suggests a correlative age for the sediments in that point.

5 METHODS

5.1 Sampling procedure

The studied sediment samples from the SWERUS cores (Paper I) were collected on 2 cm interval from 22–29 cmbsf (20-GC1), 108–130 cmbsf (23-GC1), 3–124 cmbsf (24-GC1), and 114–147 cmbsf (29-GC1). Sediment samples of 2 cm interval from core M0063C (Paper II) were obtained between 47.8–92.16 mbsf, which corresponds to the Baltic Ice Lake stage. Sediments from core 96/12-1pc (Paper III) were sampled at a spacing ca. 2–3 cm from the interval between 42 and 230 cmbsf.

5.2 Physical properties

The physical parameters of core M0063C (Paper II), including gamma wet bulk density and low-field volumetric magnetic susceptibility (MS), were measured with an automated GEOTEK® Multi-Sensor Core Logger (MSCL) from the core sections shortly after their recovery (Andrén *et al.* 2015a).

5.3 Facies analysis

Facies analysis was applied to trace the vertical character of the recovered sequence from core M0063C (Paper II) and interpret the depositional processes, events, and environments of the sediments (cf. Miall 2022). The sedimentary lithofacies within the lithostratigraphic Unit V and VI were identified by incorporating the trends in changes of lithology, sedimentary structures, and grain size. The different depositional events related to the Baltic Ice Lake evolution are presented by these lithofacies and interpreted in terms of their hydrodynamic origin.

5.4 Grain size analysis

The laser diffractometer analysis for 76 samples from core M0063C (Paper II) was done by using the Malvern Mastersizer 2000G device at the Department of Geosciences and Geography, University of Helsinki, Finland. Each sample was measured three times (750 rpm stirrer speed, 2000 rpm pump speed), and the analysis of grain size statistics was calculated using GRADISTAT software (Blott & Pye 2001).

5.5 Water and carbon determination

The loss on ignition (LOI) is an analytical method used to estimate the relative organic matter and water content of sediments. The 29 samples from core M0063C (Paper II) were studied with the LOI_{550} method at the Department of Geosciences and Geography, University of Helsinki. The values reported as LOI_{550}% were calculated using the equation from Heiri *et al.* (2001).

The total carbon (TC), total organic carbon (TOC), and total inorganic carbon (TIC) values of core M0063C (Paper II) were determined during the Expedition 347 using a LECO CS-300 Carbon Sulphur Analyser, following the IODP procedures (Andrén *et al.* 2015d). The measured values were obtained from the Pangaea data portal (Expedition 347 Scientists 2014a).

5.6 Mineralogical analysis

5.6.1 Heavy mineral analysis

Examination of heavy minerals in the coarse fraction (<63 µm) can be used in the estimation of provenance and source areas, and possible transport mechanisms and pathways. The preparation of the 17 samples from the SWERUS cores (Paper I) were done at the Oulu Mining School Research Centre, University of Oulu, Finland. Nine samples had enough coarser material to pour into a separating funnel consisting of heavy liquid – sodium heteropolytungstate (LST Fastfloat) – with a density of 2.82 g/cm^3. For six samples, the heavy mineral separation was done with liquid nitrogen, following the method of Mange & Maurer (1992). Due to the low amount of material, separation was not done for two samples.

The heavy mineral samples for the electron microscope were prepared in the thin section laboratory at Oulu Mining School, University of Oulu, and they were analysed with Zeiss Ultra Plus Scanning

Electron Microscope (SEM) at the Centre for Material Analysis, University of Oulu. A total of 18 oxides and elements expressed in wt.% – Na_2O, MgO, Al_2O_3, SiO_2, P_2O_5, S, K_2O, CaO, TiO_2, V_2O_3, Cr_2O_3, FeO, CuO, ZnO, Zr_2O, La_2O_3, Ce_2O_3, and Nd_2O_3 – were used for mineral determination. Heavy minerals were identified using MinIdent-Win 3.0 computer software.

5.6.2 Clay mineral analysis

The oriented clay slides of 24 clay samples from core M0063C (Paper II) and 47 samples from core 96/12-1pc (Paper III) were prepared at the Oulu Mining School Research Centre, University of Oulu. X-ray diffraction (XRD) was carried out at the Centre for Material Analysis, University of Oulu, using the method described by Hardy & Tucker (1988) and Moore & Reynolds (1997). Oriented clay mineral mounts for core M0063C samples (Paper II) were measured on a Rigaku SmartLab 9 kW XRD system with cobalt radiation and Bragg-Brentano para-focusing geometry. The diffractometer system was controlled by SmartLab Guidance software. For the semiquantitative estimation of clay mineral abundances, a PDXL2 software suite with integrated access to ICDD PDF-4+ 2020 database of powder diffraction patterns was used. The diffractograms for the core 96/12-1pc samples (Paper III) were recorded by a Siemens D 5000 with fixed divergence slit (FDS), with copper radiation. MacDiff freeware software version 4.2.5 was used to quantify the clay minerals, which were subsequently used to calculate percentages using weighting factors (Biscaye 1965).

5.7 Isotopic analysis

Sample preparation and measurements of Nd, Pb, and Sr isotope compositions for 17 clay fraction samples from core 96/12-1pc (Paper III) were carried out at the Geological Survey of Finland, Espoo. For isotope ratio measurements, Pb was isolated using an AG1-X8 anion exchange resin in HBr environment and all the washing acids were collected for Sr and Nd purification purposes. Then, Sr and REEs were eluted by using an AG50-X8 cation exchange resin in HCl environment. From the REE fraction, Nd was eluted using HDEHP-coated (hexyl di-ethyl hydrogen phosphate) Teflon powder as the ion exchange medium in dilute HCl environment (Richard *et al.* 1976). The Nd isotope analysis was performed using VG Sector 54 thermal ionisation mass spectrometer (TIMS). Sr and Pb isotope analyses were carried out with a standard liquid sample introduction system involving a 50μl meinhart nebuliser, a DSN and a Multi-Collector Inductively Coupled Plasma Mass Spectrometer (Nu InstrumentsTM).

6 REVIEW OF THE ORIGINAL PUBLICATIONS

6.1 Paper I

Alatarvas, R., O'Regan, M. & Strand, K. 2022. Heavy mineral assemblages of the De Long Trough and southern Lomonosov Ridge glacigenic deposits: implications for the East Siberian Ice Sheet extent. Climate of the Past 18, 1867–1881. https://doi.org/10.5194/cp-18-1867-2022

The first paper defines the mineralogical signature of glacial marine sediments from a recently discovered glacially scoured cross-shelf trough, the De Long Trough, which extends to the edge of the East Siberian continental shelf. Heavy mineral assemblages in coarse fraction of the sediment cores from the East Siberian shelf (20-GC1), the De Long Trough (23-GC1 and 24-GC1), and the southern Lomonosov Ridge (29-GC1) which were collected during the SWERUS-C3 2014 expedition were used in the estimation of sediment provenance and source areas and possible transport mechanisms. The major eastern Siberian geological provinces such as the Omolon massif, the Chukotka and Verkhoyansk Fold Belts, and possibly the Okhotsk–Chukotka Volcanic Belt are interpreted as the parent rock areas for the studied sediments.

The heavy mineral assemblages of the diamicts from the De Long Trough principally comprise amphiboles and pyroxenes with a minor content of garnet and epidote which shows a clear delivery from the eastern part of the East Siberian Sea. The Indigirka and Kolyma rivers are the primary sources of the sediments delivered to the East Siberian shelf that were eroded and re-deposited by glacial ice in the De Long Trough. Although the physical properties of the sub-glacial diamict from the De Long Trough resemble the ice-rafted debris (IRD) containing diamict recovered from the southern Lomonosov Ridge, the heavy mineral assemblage indicate a dissimilar source material. The elevated amphibole and garnet content, along with a slightly higher titanite and ilmenite content of the IRD-rich diamict from the southern Lomonosov Ridge, emphasise the Verkhoyansk Fold Belt as a possible source area. The presence of glacial-tectonic features and glacial sediments on the East Siberian continental shelf and slope, along with the heavy mineral analysis of this study, led us to conclude that glacial ice existed on parts of the East Siberian Sea during the previous glaciations of MIS 6 and 4, that glacial ice grew not only from the East Siberian shelf but also from the De Long Islands, and that ice rafted sediments were transported also from westerly sources, such as the Laptev Sea, to the southern Lomonosov Ridge.

6.2 Paper II

Alatarvas, R., Strand, K., Hyttinen, O. & Kotilainen, A. 2022. Sedimentary facies and clay mineralogy of the late Pleistocene Landsort Deep sediments, Baltic Sea – implications for the Baltic Ice Lake development. Arctic, Antarctic, and Alpine Research 54:1, 624–639. https://doi.org/10.1080/15230430.2022.2155352

The second paper describes late Pleistocene sediments from the Landsort Deep deposited during the Baltic Ice Lake phase of the Baltic Sea between ~13.5 and 10.5 ka BP. The Landsort Deep is the deepest part of the Baltic Sea located just south of the postulated Weichselian ice sheet margin. The deep contains an excellent high-resolution sediment sequence from Late Pleistocene to Early Holocene that is suitable for studying the retreat history of the southern margin of the Fennoscandian Ice Sheet, as well as the periodicity and effects of the meltwater sediment supply and deposition in an ice-contact lake. The interpretation of the studied Baltic Ice Lake record is based on the identification of sedimentary facies, grain size characteristics, detrital clay minerals, water and carbon content, and physical properties of sediments from the lithostratigraphic Unit V and VI of Hole M0063C which were obtained during the Integrated Ocean Drilling Program (IODP) Expedition 347.

The occurrence of IRD in the lowermost part of Unit VI represents a proximal glaciolacustrine environment and the transition from ice-proximal varved sediments to ice-distal fine-grained varved clayey and silty sediments within the middle part of the unit indicate the onset of the Fennoscandian Ice Sheet deglaciation and the related rise of the proglacial lake water level during the warm Bølling/Allerød interstadial. The following clay-rich interval represents the erosion and redeposition of the emerged lake bottom sediments during the first drainage event of the Baltic Ice Lake. The onset of cooler climate conditions and a possible ice sheet re-advance during the Younger Dryas caused a decrease in the meltwater release and sediment availability that could be indicated by the reduced grain size and increased chlorite content of the overlying sediments. The occurrence of elevated sand content and a kaolinite peak are associated with a rapid ice retreat and a substantial release of sediment laden meltwater at the end of the Younger Dryas. The final drainage of the Baltic Ice Lake made possible the recurrent erosion of coastal clay sediments, and the termination of the ice lake led to an enhanced deposition of clayey sediments in the Landsort Deep.

6.3 Paper III

Alatarvas, R., Immonen N. & Strand, K. 2023. Clay mineral and Nd, Pb, and Sr isotope provenance of a MIS 4-3 sediment record from the Lomonosov Ridge, central Arctic Ocean. Bulletin of the Geological Society of Finland. https://www.geologinenseura.fi/sites/geologinenseura.fi/files/alatarvas_et_al.pdf

The third paper presents clay mineralogy and radiogenic neodymium (Nd), lead (Pb), and strontium (Sr) isotope values from the Late Pleistocene sediment record of core 96/12-1pc from the Lomonosov Ridge. The clay mineral and isotopic analyses were applied in sediment provenance tracing and transport mechanism reconstructions in the central Arctic Ocean. The sediments of the core alternate from clay to silty clay with intervals of silt to fine sand size material. The clay mineral assemblage and the isotope signatures of the sediments illustrate distinct changes within a grey, IRD-rich sedimentary layer deposited during the transition from MIS 4 to MIS 3, which correlates with the Middle Weichselian deglaciation. The elevated smectite and kaolinite content in the grey layer indicates that they originate from the shelves of the Kara Sea and the western Laptev Sea, and the Nd and Sr isotope values also fall mostly within ranges that are typical for these shelf areas. The abrupt changes in the Nd, Pb and Sr isotopic values of the grey layer are likely to be an indication of a pronounced deglaciation event. A change in the sedimentation regime, which also includes a strong iceberg rafting component, is indicated by the increased coarse debris content of the grey layer that may also be related to a relatively sudden release of meltwater from an ice-dammed lake in northern Siberia. The sediments deposited on the Lomonosov Ridge could have been transported by icebergs or sea ice or in suspension during the disintegration of the Middle Weichselian ice sheet and the discharge of the proglacial lake during deglaciation in the MIS 4 to MIS 3 transition.

7 DISCUSSION

The deglaciation dynamics and glacial deposits of the Late Pleistocene Eurasian ice sheets in the investigated areas – the East Siberian Sea/Shelf, central Arctic Ocean, and Baltic Sea – are reviewed in this chapter to achieve the main aim of this research, which is to produce boundary values in sedimentological and geochemical information on past climate change/warming events and loss of ice in the Northern Hemisphere. Mineralogical proxies, sediment geochemistry and isotope information were used to investigate deglacial dynamics, loss of ice and the related meltwater releases in marine and lacustrine environments. The interpretations and discussion are based on the results obtained from the provenance tracing of marine glacial sediments from the De Long Trough and the Lomonosov Ridge, and on the description of the glacial lake deposits and the depositional environment of the Landsort Deep during the Late Pleistocene deglaciation.

7.1 Late Pleistocene deglaciations

Increased insolation in the high northern latitudes is inferred as the initial driving force of the transition between the Late Saalian glacial stage (MIS 6) and the Eemian warm period (MIS 5e), the glacial of MIS 4 and the interglacial of MIS 3, the Late Weichselian glacial stage (MIS 2) and the early Holocene interglacial climate (MIS 1). According to Svendsen *et al*. (2004), seasonally open waters are inferred to exist in the eastern and central Arctic Ocean during MIS 5e and 5c (130–95 ka BP). A pronounced freshwater and IRD peak occurring during MIS 5b (95–85 ka BP) possibly corresponds to the drainage of some of the ice-dammed lakes that existed south of the Early Weichselian ice sheet. The sediments deposited during MIS 5a (85–72 ka BP) also imply an interval with seasonally open waters (Jakobsson *et al*. 2001; Spielhagen *et al.* 2004) along with the inferred deglaciation signal (~78 ka BP) with high IRD input (Svendsen *et al.* 2004). The uppermost pronounced IRD layer, which is also detected in our study as a rapid increase in IRD content (Paper III), found in the Arctic Ocean deposits has an age of ~64–50 ka BP (Svendsen *et al.* 2004) which correlates with the MIS 4/3 transition. The onset of the deposition of this layer was abrupt, and the layer most likely corresponds to the Middle Weichselian Ice Sheet readvance at ~60–50 ka BP (Svendsen *et al.* 2004). A significant meltwater spike in the $\delta^{18}O$ record is associated with the end of the IRD input ~50 ka BP (Svendsen *et al*. 2004), possibly indicating the drainage of the postulated ice dammed lakes that occurred during the Middle Weichselian. During MIS 3 (~60–25 ka BP), the climatic conditions fluctuated over a broad range on millennial time scales from rapid warmings to cold periods and it is also suggested to have been merely an interstadial period between MIS 4 and 2. During the Last Glacial Termination at the end of MIS 2, the last deglaciation and the related meltwater release were small-scale events in the eastern and central Arctic Ocean in comparison to those at ~130 and 50 ka BP (cf. Stein *et al.* 1994), and it is suggested that only a brief glacial surge across the northern Kara Sea occurred during the LGM, with no large ice dammed lakes (Svendsen *et al*. 2004). An abrupt global eustatic sea level rise of 10–15 m is associated with the widespread retreat of the ice sheets commencing ~20 ka BP (Clark *et al*. 2004), which was likely due to a rapid increase in insolation in the Northern Hemisphere. The subsequent drainages during deglaciation, in a glacial lake environment, were followed by a distinctive deposition of massive clay sequence (Paper II).

7.2 Sediment deposition during deglaciations

Sea ice and icebergs from ice sheet decay are the main pathways for sediment supply and the material transported from continental margins is carried by ocean currents. The two main surface circulation systems in the Arctic Ocean are the clockwise flowing Beaufort Gyre in the western Arctic and the Transpolar Drift that flows from the Siberian margin towards the Fram Strait (Schoster *et al*. 2000; Adler *et al*. 2009). These two ocean circulation systems transport sea ice and icebergs with entrained sediment material from the Eurasian marginal seas, such as the Kara and Laptev Sea, and from the Amerasian side. Sediments deposited during the deglacial conditions, usually comprise suspended finer-grained material consolidated in sea ice and iceberg rafted sediments with a high content of coarse-grained material. The changes in clay and heavy mineral, and isotope compositions are good indicators for the changes in the source areas. The high IRD content indicates that icebergs supplied material throughout the deglaciation and were in a proximal location to the deposition site.

7.2.1 Marine deposits

The variation between sub-ice and subglacial shelf and open-marine sedimentary processes influence the distribution of heavy minerals in sediments. The changes related to the dynamics of the deglaciation in the East Siberian Sea/Shelf is reflected in the changes of the mineralogy between the sub-glacial diamicts and the overlying clay-rich sediments from the last glacial cycle deposited in the De Long Trough. The sediments covering the glacial deposits are older than ~ 50 cal ka BP, which indicates that the diamicts were deposited during the MIS 6, stadial in MIS 5, or MIS 4 (cf. O'Regan *et al.* 2017). The sediments delivered by the Indigirka and Kolyma Rivers are inferred as a major contributor to the materials eroded and re-deposited by glacial ice in the De Long Trough. A distinct feature in these deposited diamicts is the elevated content of minerals characteristic of ancient volcanogenic and volcanogenic-sedimentary rocks enriched in amphibole, pyroxenes, and epidote, and it illustrates a clear delivery from the eastern part of the East Siberian Sea/Shelf. A decreasing amphibole content and an increasing diversity in the contents of all the heavy minerals indicate that the finer-grained, grey sediments above the diamicts relate to glacial maxima and the following deglacial deposition. A lack of coarser grain size and an absence of heavy minerals in the subsequent sediments imply that they were derived from the inner shelf characterised by low concentrations of heavy minerals (cf. Naugler *et al.* 1974), and also indicate that the shelf or at least the shoreline and river discharge region were presumably free from ice, or the ice sheet was relatively thin and not grounding on the shelf.

The diamicts from the southern Lomonosov Ridge in the Arctic Ocean are inferred to have been deposited dominantly during the scouring of the ridge related to MIS 6 (cf. Stein *et al.* 2017; O'Regan *et al.* 2020; West *et al.* 2021). According to our study, the elevated amphibole and garnet content of the diamicts indicates the Verkhoyansk Fold Belt as a possible source area, as well delivery by ice rafting and large-scale iceberg inputs from westerly sources such as the Laptev Sea, thus implying deposition during deglaciation. This might refer to sediment transportation dominantly by sea ice and icebergs related to the break-up of the ice sheet during MIS 6.

The distinct grey sediment layer found from the Lomonosov Ridge, central Arctic Ocean refers to enhanced sedimentation during the transition from MIS 4 to 3. The deposition of this layer during the deglacial transition phase and the sharp contact with the underlying sediments indicate an abrupt change in the environmental and sedimentation conditions that is reflected in the mineralogical composition of the layer. The weathered smectite-rich material from the Siberian trap basalts is transported into the Kara and Laptev Seas by the Yenisey, Anabar and Khatanga rivers (e.g., Rossak *et al.* 1999; Schoster *et al.* 2000) and the notable increasing trend of the smectite content in the grey layer is inferred to have been delivered from the retreating Eurasian ice sheet during more open water conditions related to abrupt deglaciation as indicated by the results of our study. The fluctuating kaolinite content may be derived from the reworked, older, kaolinite-bearing sediments (cf. Darby 1975; Chamley 1989; Hambrey *et al.* 1991) and it may relate to the intensity of erosion in the continental source areas. The abrupt transition to the higher kaolinite content occurring in the lower part of the grey layer in relation to the underlying sediments and an excursion at the MIS 4 top are suggested to originate from the Kara and western Laptev Seas. Increased illite content is characteristic for sediments of the eastern Laptev Sea and the East Siberian Sea (Wahsner *et al.* 1999). Although the higher illite content indicates that the illite-rich IRD is derived from glacial sources, the decrease of illite content in the grey layer implies the availability of other clay minerals during deglaciation. This is indicated by a slight increase in the chlorite content, for example. Elevated chlorite content is characteristic for deglacial and interglacial environments (Dong *et al.* 2017) and is delivered by the Lena and Yana rivers to the Laptev Sea (Rossak *et al.* 1999).

The εNd values and $^{87}Sr/^{86}Sr$ ratios mainly relate to the isotopic composition of the sediments from the Kara Sea and western Laptev Sea which contain weathering products from the Siberian flood basalts, and thus, have generally higher εNd values and lower $^{87}Sr/^{86}Sr$ ratios in comparison to the eastern Laptev Sea and the East Siberian Sea that mainly are fed by crustal sources (e.g., Li *et al*. 2023). The average εNd values are clearly lower within the sediments below and above the grey layer which indicates evident delivery from the Kara and western Laptev Seas for the grey layer sediments. The high $^{87}Sr/^{86}Sr$ ratios may be explained by the components derived from primitive intrusive rocks and granitoids of the Archean basement in the Siberian hinterland (cf. Czamanske *et al*. 2000). Igneous rocks are normally enriched in Pb (Tütken *et al*. 2002) and the high radiogenic $^{207}Pb/^{206}Pb$ values in the grey layer sediments support the inferenced sedimentary contributions from the Eurasian margin during the deglacial transition.

Significant amounts of sediment were derived from the Eurasian continent during the deglacial conditions in the MIS 4/3 transition. The obtained results support the Eurasian margin's contribution to most of the sediments deposited at the Lomonosov Ridge, thus being consistent with the results by Spielhagen *et al.* (2004), Krylov *et al.* (2008), Martinez *et al*. (2009), and Kaparulina *et al*. (2016). The sediments could have been transported during deglaciation by sea ice, by icebergs, and in suspension. The source areas of the sediments, such as the shelf of the southern Kara Sea and Putorana Plateau, were situated within the boundaries of the postulated ice dammed lake (Mangerud *et al*. 2004). Large amounts of sediments from could havew been discharged from these provenances during an abrupt flooding event of the lake. The sediments in the grey layer most likely are related to the disintegration of the Middle Weichselian ice sheet and the discharge of the large proglacial lake during deglaciation.

7.2.2 Lacustrine deposits

The stratification and rhythmical banding of the Late Pleistocene sediments from the Landsort Deep, Baltic Sea are inferred to refer to the sedimentation of a glacial lake environment in which sandy lamination intervals relate to direct deposition in front of the ice sheet, rain-out from icebergs, or deposition from meltwater plumes (cf. Bennett & Glasser 2009; Teller 2013). The inferential onset of the deglaciation of the Fennoscandian Ice Sheet led to a rise of the glacial lake level. A depositional environment with a decreasing intensity of meltwater release is suggested by the diamictic sediments with an upward-fining succession of silt interlaminaes. Seasonal fluctuations of meltwater discharge in an ice-contact lake are represented by the rhythmically laminated silt and clay couplet (varves) that overlay the ice-contact facies. During Bølling/Allerød interstadial, substantial amounts of meltwater were stored in the Baltic Ice Lake due to the rapid ice retreat and glacio-isostatic processes (Kelly & Passchier 2018) which led to the deposition of finely laminated silty clays with a relatively uniform grain size distribution. A constant sediment supply and rapid sediment accumulation characterise the deposition prior to the first drainage, the impact of which can be seen in the increased clay content. The increased kaolinite/chlorite and quartz/feldspar ratios correspond to a contribution from the longer sediment transport pathways of major rivers and wider drainages (cf. Leipe &

Gingele 2003). The clay-rich distal varves are inferred to be deposited from distal meltwater suspension plumes. The cooler conditions and the possible ice sheet re-advance related to the Younger Dryas cold reversal led to a decrease of meltwater and sediment availability, as indicated by the reduced grain size variation and increased clay fraction and chlorite content. The following rapid ice retreat and reprised meltwater release that caused the lake level to rise could be indicated by the sharp increase of sand content. The subsequent final drainage enabled the erosion of the clay sediments on the emerged coastal region and the increased illite and feldspar content are characteristic for these reworked clays.

7.3 Deglaciation dynamics: importance of the study and future aspects

Fast and important climatic and environmental transitions from glacial to interglacial conditions have caused profound environmental changes in the Arctic. These transitional phases comprise loss of ice and meltwater release, which are related to deglaciations in the past. It is well known that the continuous ice sheet melting events, thinning and melting of sea ice, and a rapid eustatic sea level rise are related to deglaciation. All these changes have affected the physical environments and their evolution in the terrestrial and marine realms; however, the rate of the changes and their nature during these transition periods is still largely unknown. Previously, the ice sheets in the Eurasian north were viewed as responding slowly to climate warming, and deglaciation was assumed to be a linear process. However, the results on the ice melting in the Eurasian Arctic indicate that the ice sheets were active and melted during a relatively short time span (cf. Svendsen *et al.* 2004; Larsen *et al.* 2006; Lunkka *et al.* 2004; Wohlfarth & Näslund 2010; Johansson *et al.* 2011). A detailed deglaciation chronology or the possible non-linear behavior of the ice sheets is not well known. The information of this study on past climate change/warming events and related loss of ice in the Northern Hemisphere is of relevance to predicting the future development of global environmental and climate change. Understanding the meltwater forming processes, glacial lakes and palaeohydrological perspectives as well as the sediment source characteristics, transport, and processes is important. The results of this research contribute to the identification of glacial sediment source areas and transport pathways, and the reconstruction of palaeoenvironments related to deglaciation dynamics in the Northern Hemisphere.

As the present climate warming scenarios predict, the Arctic regions will experience possibly rapid and extreme climate change in the course of the next 100 years (IPCC 2018). There is no knowledge of how this will change the Arctic environments and habitats. Therefore, studying the past climatic transitions in the Arctic region can enlighten on the role of the Arctic in the Earth system, while extreme climate events are highly relevant in predicting our future climate evolution. In conclusion, deglaciation periods provide a framework to investigate the effects of changes in insolation and ice sheet behaviour. The oceanic circulation and thus the global climate and biogeochemistry are also affected by the meltwater input related to the disintegration of ice sheets. In order to improve our knowledge of ice sheet dynamics and the related depositional environments, processes, and products in the Arctic region, further samples obtained from local areas will be needed to investigate a complex of various proxies and for novel sedimentological and mineral geochemical techniques. The time scales involved in these studies range from thousands of years to tens of thousands, and they involve non-linear processes; this needs to be taken into consideration in climate modelling. To improve our understanding of the fully coupled physical climate system (atmosphere-ocean-land) on diverse space and time scales can be a challenge for these studies.

8 CONCLUSIONS

The initial motivation for this research process was to gain more knowledge of deglaciation dynamics by studying glacial deposits of the Late Pleistocene Eurasian ice sheets from the East Siberian Sea/Shelf, central Arctic Ocean, and Baltic Sea. The results of this research comprise sedimentological and geochemical information related to past climate change/warming events and loss of ice in the Northern Hemisphere. The following conclusions can be drawn based on this research:

- The examination of heavy minerals in coarse fraction (Paper I), and the clay mineral content and isotope signatures in clay fraction (Paper III) from glacial sediments from the East Siberian Sea/Shelf and central Arctic Ocean are suitable for the determination of provenance and source areas and the possible transport mechanisms and pathways of the sediments.

- The changes in the heavy mineral assemblages between the sub-glacial and ice-rafted diamicts and the overlying clay-rich sediments from the last glacial cycle deposited in the De Long Trough reflect the changes in the deglaciation dynamics in the East Siberian Sea/Shelf (Paper I).

- The deglaciation phase during the transition from MIS 4 to 3 is reflected in the clay mineral content and the isotope signatures of the detrital sediments from the Lomonosov Ridge, central Arctic Ocean (Paper III).

- During the MIS 4/3 transition, sediments were delivered from the Eurasian margin along with a rapid IRD rich sedimentation event to the Lomonosov Ridge. This event is associated with the disintegration of the Middle Weichselian ice sheets and a possible drainage of an ice-dammed lake on the Siberian hinterland enhancing material input into the central Arctic Ocean (Paper III).

- The last deglaciation and the waxing and waning of the Fennoscandian Ice Sheet, including the retreat and melting and/or lake drainage events during warm periods, e.g., Bølling/Allerød interstadial, and the possible readvance and/or standstill during the Younger Dryas cold period are reflected in the glaciolacustrine sediment sequence obtained from the Landsort Deep, Baltic Sea (Paper II).

- A variety of varve-types and a depositional model related to the Baltic Ice Lake were established based on the sedimentological and mineralogical analyses of the glacial lacustrine sediments from the Landsort Deep, Baltic Sea (Paper II).

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