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Ninna Immonen and Pertti Sarala
Editors

Abstracts of the 3rd PalaeoArc Conference
Rovaniemi, 23-26 August 2022

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Programme

Tuesday 23rd Aug

8.30-9.00	Registration and coffee
9.00-9.30	Opening Pertti Sarala (Organisers), Astrid Lyså (PalaeoArc Network), Markku Heikkilä (Arctic Centre)

Session: Marine geology

9.30-9.50	*Mid-Pleistocene to Holocene calcareous nannofossil taxonomy and biochronology in the central Arctic Ocean*, Razmjooei, M.J. et al.
9.50-10.10	*Comparing geochronological tools for dating Quaternary Arctic Ocean sediments*, O'Regan, M. et al.
10.10-10.30	*Cryosphere change and marine ecosystem dynamics in the low Arctic – a multi-proxy Holocene record from Nuup Kangerlua, SW Greenland*, Bang Kvorning, A. et al.
10.30-10.50	Break
10.50-11.10	*Effects of atmospheric circulation and water mass change on Holocene ice-drift patterns in the Nordic Seas*, Bauch, H.A.
11.10-11.30	*Terrestrial biomarkers in sediments from northern Svalbard reveal unprecedented subglacial meltwater drainage during the Last Termination*, Nogarotto, A. et al.
11.30-11.50	*Quantitative mineral analysis for revealing Arctic Ocean sediment provenances and transport history: review and outlook*, Strand, K.
11.50-12.00	Discussion
12.00-13.00	Lunch

Session: Applied geological and geochemical research

13.00-13.20	*Development of geochemical and indicator mineral on-site research techniques - in connection to professional competence for ore exploration, Sarala*, P. et al.
13.20-13.40	*Till geochemical data analysis and mineralogical research as a tool for the critical minerals' exploration*, Kalubowila, C. et al.
13.40-14.00	*Equating, analysis, and modelling of pre-glacially weathered bedrock composition with till unit geochemistry – application to mineral exploration*, Raatikainen, M.
14.00-14.30	Coffee break

14.30-16.00 **Poster session**

- *Sedimentary and clay mineralogy study from the Landsort Deep sediments related to the Baltic Ice Lake stage of the Baltic Sea*, Alatarvas, R. et al.
- *Geomorphological evidence of ice stream shutdown from the Iceland Ice Sheet, NE-Iceland*, Aradottir, N. et al.
- *Water masses oscillations west off Svalbard during the past 150 years: micropalaeontological evidences*, Bronzo, L. et al.
- *The influence of proglacial lakes on climate and surface mass balance of retreating ice sheets – An Investigation of the Laurentide and Fennoscandian ice sheets, 13 ka BP*, Sijbrandij, L. et al.
- *Trace element and isotope analyses of sulfide minerals as a fingerprinting tool for mineral exploration: Example from northern Finland*, Taivalkoski, A. et al.
- *Multiproxy paleoenvironmental reconstruction of the Ross ice shelf retreat and sea-ice dynamics in the Joides Basin, Ross Sea, Antarctica*, Pambianco, C. et al.

16.00-17.00 **PalaeoArc Steering Committee Meeting (hybrid meeting)**

16.00-18.00 Possibility to visit the Regional Museum of Lapland and exhibitions in the Arctic Centre

18.00-20.00 **Ice breaker on the riverside near the Arctic Centre**

Wednesday 24th Aug

9.00 **Excursion** (start from front of the Arctic Centre)

-Highest shoreline / supra-aquatic areas on top of Ounasvaara

-Glaciofluvial formations, Kolpene Esker

-Bouldery field, shoreline and glacial erratics in Sapilasselkä

-Ribbed moraines in Kivitaipale

~ 12.30-13.30 Lunch at Lähtevänoja, Kivitaipale

-Sukulanrakka potholes in Hirvas

-Erosional/depositional subglacial glaciofluvial channel in Hietavaara

-Streamlined subglacial (fluted) surface in Hirvas

-Santa Claus Village on the Arctic Circle

~ 17.30 Excursion ends to the centre of Rovaniemi

Thursday 25th Aug

Session: Glacial geology and morphology

9.00-9.40	**Keynote**: *Reconstructing the evolution of the Laurentide and Innuitian ice sheets prior to the Last Glacial Maximum (115 ka to 25 ka): recent progress and future challenges*, Stokes, C.
9.40-10.00	*Palaeo-ice stream in north Iceland revealed by streamlined subglacial bedforms in Bárðardalur*, Benediktsson, Í. et al.
10.00-10.20	*Holocene retreat of Greenland Ice Sheet from the mapping of ice marginal landforms*, Clark, C. et al.
10.20-10.50	Coffee break
10.50-11.10	*Reconstructing the flow evolution of the Fennoscandian Ice Sheet using high-resolution digital elevation models: a new, multi-scale sampling approach*, Butcher, F. et al.
11.10-11.30	*Controls on ice marginal dynamics of the soft-bedded Southern and Eastern sectors of the Scandinavian Ice Sheet during the last Glacial: An investigation using a land-from driven ice sheet reconstruction*, Diemont, C. et al.
11.30-11.50	*Occurrence of the subglacial ring-ridge-shaped moraines in the interlobate zones of the central part of Fennoscandian Ice Sheet*, Sarala, P. & Lunkka, J.P.
11.50-12.10	*DATED-2: Re-visiting the chronology and time-slice reconstruction of the last Eurasian ice sheets*, Hughes, A. et al.
12.10-12.20	Discussion
12.20-13.30	Lunch

Session: Applied geological and geochemical research

13.30-13.50	*Cosmic-ray muography: a new method for imaging and monitoring density variations in the Arctic*, Holma, M. & Sarala, P.
13.50-14.10	*Opportunities concerning mine tailings in the Arctic environments*, Juutinen, M.
14.10-14.30	*India in the Changing Geopolitics of Arctic region*, Dhankhar, S.
14.30-15.00	Coffee break
15.00-16.30	**Steering committee** PalaeoArc Workshop: Future PalaeoArc activities, cooperation and funding opportunities
19.00	**Conference dinner,** Restaurant Valdemari

Friday 26th Aug

Session: Marine, coastal and fluvial geology

9.00-9.20 *Oil slicks from natural seepage of oil and gas, a common occurrence on ice sheet influenced continental margins?* Winsborrow, M. et al.

9.20-9.40 *Coal particles in Arctic deep-sea sediments: Origin, composition and potential significance for paleo-ice drift reconstructions*, Spielhagen, R. et al.

9.40-10.00 *Deglacial records of terrigenous organic matter accumulation off the Yukon and Amur rivers based on lignin phenols and long-chain n-alkanes*, Cao, M. et al.

10.00-10.20 *Fluvial and permafrost history of the lower Lena River, NE Siberia, over the glacial-interglacial cycle*, Schwamborn, G. et al.

10.20-10.40 Coffee break

Session: Quaternary stratigraphy and chronology

10.40-11.00 *Chronostratigraphic marker horizons related to sudden ice-lake water level changes in eastern Fennoscandia*, Lunkka, J.P.

11.00-11.20 *Interglacial/glacial fire-vegetation-climate relations during MIS 104 - MIS 100 reconstructed from Lake El'gygytgyn sediments*, Andreev, A. et al.

11.20-11.40 *Update to the environmental and glaciation history of Northern Ostrobothnia and Finnish Lapland during the past 140 000 years*, Eskola, T.

11.40-12.10 Closing

Closing words; Best student presentations' awards; Introduction of the next meeting

12.10-13.10 Lunch

Abstracts

Sedimentary and clay mineralogy study from the Landsort Deep sediments related to the Baltic Ice Lake stage of the Baltic Sea
Raisa Alatarvas et al.

Interglacial/glacial fire-vegetation-climate relations during MIS 104 - MIS 100 reconstructed from Lake El'gygytgyn sediments
Andrei Andreev et al.

Geomorphological evidence of ice stream shutdown from the Iceland Ice Sheet, NE-Iceland
Nína Aradóttir et al.

Cryosphere change and marine ecosystem dynamics in the low Arctic – a multi-proxy Holocene record from Nuup Kangerlua, SW Greenland
Anna Bang Kvorning et al.

Effects of atmospheric circulation and water mass change on Holocene ice-drift patterns in the Nordic Seas
Henning A. Bauch

Palaeo-ice stream in north Iceland revealed by streamlined subglacial bedforms in Bárðardalur
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Water masses oscillations west off Svalbard during the past 150 years: micropalaeontological evidences
Laura Bronzo et al.

Reconstructing the flow evolution of the Fennoscandian Ice Sheet using high-resolution digital elevation models: a new, multi-scale sampling approach.
Frances Butcher et al.

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Controls on ice marginal dynamics of the soft-bedded Southern and Eastern sectors of the Scandinavian Ice Sheet during the last Glacial: An investigation using a land-from driven ice sheet reconstruction
Christiaan Diemont et al.

Update to the environmental and glaciation history of Northern Ostrobothnia and Finnish Lapland during the past 140 000 years
Tiina Eskola

Cosmic-ray muography: a new method for imaging and monitoring density variations in the Arctic
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Markus Raatikainen

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Occurrence of the subglacial ring-ridge-shaped moraines in the interlobate zones of the central part of Fennoscandian Ice Sheet
Pertti Sarala and Juha Pekka Lunkka

Fluvial and permafrost history of the lower Lena River, NE Siberia, over the glacial-interglacial cycle
Georg Schwamborn et al.

India in the Changing Geopolitics of Arctic region
Shivani Dhankar

The influence of proglacial lakes on climate and surface mass balance of retreating ice sheets – An Investigation of the Laurentide and Fennoscandian ice sheets, 13 ka BP
Lianne Sijbrandij et al.

Coal particles in Arctic deep-sea sediments: Origin, composition and potential significance for paleo-ice drift reconstructions
Robert F. Spielhagen et al.

Reconstructing the evolution of the Laurentide and Innuitian ice sheets prior to the Last Glacial Maximum (115 ka to 25 ka): recent progress and future challenges
Chris R. Stokes et al.

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Kari Strand

Trace element and isotope analyses of sulfide minerals as a fingerprinting tool for mineral exploration: Example from northern Finland
Atte Taivalkoski et al.

Oil slicks from natural seepage of oil and gas, a common occurrence on ice sheet influenced continental margins?
Monica Winsborrow et al.

Sedimentary and clay mineralogy study from the Landsort Deep sediments related to the Baltic Ice Lake stage of the Baltic Sea

Raisa Alatarvas[1], Kari Strand[1], Outi Hyttinen[2], and Aarno Kotilainen[3]

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3) *Geological Survey of Finland, Finland*

The retreat history of the southern margin of the Fennoscandian Ice Sheet and related ice-marginal Baltic Ice Lake development from ~13.5 to 10.5 ka is studied using data from sediment cores obtained from the Landsort Deep, Baltic Sea. The Landsort Deep is the deepest part of the Baltic Sea, and it is located between the southeast coast of Sweden and the island of Gotland. The location of the deep is just south on the postulated margins of the Weichselian glaciations, and it displays a high-resolution sediment sequence from Late Weichselian and Holocene. The uniquely long varved glacial clay and diamict sequences provide sufficient detrital clay mineralogical indications of how the sedimentation of the Baltic Ice Lake stage and the Fennoscandian Ice Sheet responded to climate fluctuations. The cores recovered from Site M0063 during the Expedition 347 of the Integrated Ocean Drilling Program (IODP) were used for multiproxy sediment analysis. The studied samples are from Hole M0063C from lithostratigraphic Unit V (48–54 mbsf) and VI (54–93 mbsf). The multiproxy study includes lithostratigraphy, sedimentary facies, grain size and clay mineral distribution, loss on ignition (LOI) determination, and the utilisation of the physical properties dataset and carbon content acquired during the expedition. This study increases knowledge on detrital sources and sediment transport mechanisms during the Baltic Ice Lake evolution. The objectives of the study are to distinguish Baltic Ice streams proximal and distal sediment facies during the glacial lake phase, and to outline the evidence of the melting and drainage events associated to warm periods such as the Bølling/Allerød interstadials, and evidence related to cold stadials like the Younger Dryas.

Interglacial/glacial fire-vegetation-climate relations during MIS 104 - MIS 100 reconstructed from Lake El'gygytgyn sediments

Andrei Andreev[1,2], Ulrike Herzschuh[2,3,4], Elisabeth Dietze[1,2,5]

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5) *Organic Geochemistry, German Research Centre for Geoscience, Potsdam, Germany*

The increased fire intensity in the Siberian Arctic raises concerns on how far rising temperatures and fire occurrence lead to shifts from tundra to summergreen or evergreen boreal forest. Changes in biomes and fire regimes would strongly affect global biogeochemical and biophysical cycles. However, it is unknown if fires can initiate or support these shifts under the ongoing amplified warming or if climate drives fire regime and biome changes independently.

Here, we investigate shifts in vegetation and fire regimes during multiple glacial-interglacial cycles at Lake El'gygytgyn (Russian Far East) at the beginning of the Pleistocene, where ice caps were limited at the poles and higher CO2 in the atmosphere. The vegetation and climate changes were previously reconstructed basing on the palynological studies of the ICDP sediment core 5011-1A (e.g. Brigham-Grette et al. 2013; Andreev et al. 2014, 2016). In this study, we provide a more high-resolution pollen record and additionally analyze various fire proxies preserved to enable a quantitative reconstruction of changes in fire intensities and the type of biomass burnt. Sedimentary charcoal reflects mid-to-high intensity fires and was analyzed in two size classes using classical microscopy from pollen slides. Charcoal morphotypes were distinguished and used to reconstruct the type of biomass burnt. Together with pollen- and non-pollen palynomorph-based vegetation reconstruction, we find different types of centennial-to-orbital-scale biome shifts, mostly related to climatic changes. Yet, only some of them were accompanied by changes in fire regimes suggesting various long-term fire-vegetation-climate feedbacks. To assess the role of fire in driving and/or responding to biome changes, interglacial periods can provide natural system analogues for the future - unbiased from human impact on current landscapes.

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Geomorphological evidence of ice stream shutdown from the Iceland Ice Sheet, NE-Iceland

Nína Aradóttir[1], Ívar Örn Benediktsson[1], Ólafur Ingólfsson[1], Skafti Brynjólfsson[2], Wesley R. Farnsworth[1,3], Margrét Mjöll Benjamínsdóttir[1], Lena Björg Ríkharðsdóttir[1]

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3) *GLOBE Institute, University of Copenhagen*

Mapping of streamlined subglacial bedforms (SSBs; drumlins and MSGLs) in NE-Iceland reveals cross-cutting flow-sets of palaeo-ice streams within the Iceland Ice Sheet (IIS) during and following the Last Glacial Maximum (LGM). Here we map ridges (transverse and reticular), hummocky topography, glaciofluvial bedforms and raised shorelines in the Bakkaflói and Þistilfjörður regions. We combine this morphological data with sedimentological analyses of key glacial bedforms to increase our understanding of the dynamics of the IIS in NE-Iceland. While the transverse ridges in Bakkaflói have been previously interpreted as ribbed moraines, we suggest the ridges (transverse and reticular) are crevasse-squeeze ridges based on morphology, spatial setting and internal composition. In both areas, the CSRs are superimposed on the SSBs, indicating that they post-date the formation of the SSBs and probably signify the final stages of the ice stream shutdown. The variance in the morphology of the CSRs between the flow-sets could indicate different spatial-setting within the ice stream and the relative timing of the shutdown of the ice streams. At the eastern margin of Þistilfjörður, close to the cross-cutting of the Þistilfjörður and Bakkaflói flow-sets, is a chaotic hummocky area with prominent transverse ridges overlying vague but discernible streamlining. Based on their appearance and dense network, these transverse ridges are interpreted as ribbed moraines. The cross-cutting relationship between the ribbed moraines and the SSBs is complex, although in general the ribbed moraines are superimposed on the SSBs and therefore associated with the ice stream shutdown. The overall landform assemblage in Bakkaflói and Þistilfjörður is interpreted to represent active flowing ice streams during both the LGM and the following deglaciation of the IIS. Furthermore, the preservation of the CSRs suggests ice stagnation following the ice stream shutdown.

Cryosphere change and marine ecosystem dynamics in the low Arctic – a multi-proxy Holocene record from Nuup Kangerlua, SW Greenland

Anna Bang Kvorning[1*], Sofia Ribeiro[1], Maija P. Heikkilä[2], William Colgan[1], Kristian Kjellerup Kjeldsen[1], Christof Pearce[3], Marit-Solveig Seidenkrantz[3], Nicolaj Krog Larsen[4]

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The Arctic amplification of global warming is rapidly decreasing sea-ice cover and leading to increased discharge from the Greenland Ice Sheet. Consequently, the physical and chemical properties of the water column change affecting the Arctic marine ecosystem. At the base of the marine food web, primary producers sustain higher trophic levels and are part of the biological carbon pump exporting organic matter to the deep ocean and seafloor. Thus, it is crucial to investigate how marine primary productivity will respond to a changing Arctic. To fully assess how ongoing cryosphere changes will impact Arctic marine ecosystems, there is a need to place them in a larger context to separate human-driven versus natural changes. Marine sedimentary records work as archives holding long-term information about past environmental changes and have the potential to constrain future ecosystem responses to climate warming. Here, we present the first multi-proxy record of Holocene environmental changes from Nuup Kangerlua, the largest fjord system in west Greenland. We analysed the dinoflagellate cyst assemblages alongside grain-size distribution, and biogeochemical indicators (total organic carbon (TOC), nitrogen (TN), calcium carbonate (CaCO3), stable isotopes (13C and 15N), and biogenic silica (BSi)). Our study reveals significant environmental changes throughout the Holocene especially during a period of relatively warmer sea-surface waters when compared to present and a higher productivity, attributed to the Holocene Thermal Maximum (HTM). In the uppermost part of the record a freshening signal is observed which is attributed to the increasing freshwater discharge deriving from the Greenlandic ice sheet to the fjord system.

Effects of atmospheric circulation and water mass change on Holocene ice-drift patterns in the Nordic Seas

Henning A. Bauch[1]

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After the last glaciation numerous temperature sensitive climate proxies from around the Arctic – ice cores, terrestrial and marine archives alike – show a tight connection to northern insolation with highest temperatures noted in the early Holocene. For further in-depth understanding of the post-glacial environmental development the Nordic seas are of special interest, because this region is a through road for the oceanic heat of the Norwegian Atlantic Current (NAC) northward and the southward-flowing polar waters. The situation leaves the formation of three oceanographic watermass components separated by the Arctic Front (AF) and the Polar Front (PF).

Using deep-sea sediment records different foraminiferal species were analyzed for O-isotopes and combined with data from planktic foraminiferal assemblages and ice-rafted detritus (IRD). It is shown that after adjacent ice shelves and glaciers had retreated inland and away from the coastlines, highest surface temperatures occurred between 11 and 9 ka. An intermittent cold phase around 8 ka is associated with both IRD and increased abundance of polar species N. pachyderma. Afterwards, higher surface temperatures were regained but started to decrease at the AF after 6 ka, concomitant with a persistent occurrence of IRD and a cooling trend which continued until today. Within the warm NAC watermass, by contrast, relatively stable and warm conditions persisted until 2.5 and 1 ka, in both planktic and benthic O-isotopes. Although variability among certain foraminiferal species would indicate some surface changes, the abundance of N. pachyderma increased to 70 % during the last 1ka (i.e., during the Little Ice Age). That drastic increase was associated with highly variable O-isotope values throughout the entire water column.

While records until the mid-Holocene (5-6 ka) occurred under circumstances still related to the overall post-glacial environmental reorganization (i.e., deglaciation, global sea-level rise and associated Arctic Ocean sea-ice expansion onto the vast shelf areas), the situation observed since then is interpreted to be mainly driven by atmospheric circulation changes. The atmosphere forced more Atlantic water into the Nordic seas thereby intensifying the gyre system in the Greenland and Iceland seas. For the Little Ice Age in particular the situation caused a rerouting of both polar water masses and sea ice far into the eastern Nordic seas.

Palaeo-ice stream in north Iceland revealed by streamlined subglacial bedforms in Bárðardalur

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3) *Department of Environmental Science, University of Virgina, USA*

Ice streams are important constituents of ice sheets as they drain massive amounts of ice and sediments to the margins and leave distinct geomorphological signatures on the ice sheet bed. Streamlined subglacial bedforms (SSBs), including drumlins and mega scale glacial lineations (MSGLs), have been firmly linked to fast ice flow and are considered an important geomorphological signature of ice streaming. In this study, SSBs in Bárðardalur, north Iceland, have been studied with the aim of reconstructing a palaeo-ice stream within the Icelandic Ice Sheet (IIS). Detailed morphological mapping and spatial analysis of the SSBs reveals high parallel conformity and elongation ratio, supporting the conclusion of a palaeo-ice stream bed. The distribution of the SSBs suggests a minimum length and width of the palaeo-ice stream of 16 and 62 km, respectively. Three sedimentological cross-sections show that the SSBs are primarily composed of fissile diamict, with rafts and lenses of sorted sediments that show ductile deformation, which potentially indicates that high subglacial water pressure enhanced the fast flow. This research elucidates the existence and scope of ice-streams in the IIS and contributes towards further understanding of drumlin and MSGL formation under actively streaming ice.

Water masses oscillations west off Svalbard during the past 150 years: micropalaeontological evidences

L. Bronzo[1,2,3], F. Torricella[1], K. Gariboldi[1], V.M. Gamboa Sojo[4], R.G. Lucchi[5], L. Langone[6], S. Apsemidou[7], A. Cascella[2], C. Morigi[1]

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Micropalaeontological proxies are highly sensitive to environmental changes and are useful tools to investigate the paleo-features (i.e., temperature, sea ice coverage, nutrient supply, etc.) of Arctic environments. The box core GS191-02BC was collected at 1650 m of water depth on the Bellsund Drift crest, on the western slope of Svalbard (Lucchi et al., 2014). It consists of 25 cm of bioturbated sediments, which were analysed for calcareous nannofossils, benthic and planktic foraminifera and diatoms associations. The record covers the last 150 years, from 1866 CE to 2014 CE (210Pb ages).
The H/P ratio (Emiliania huxleyi/Coccolithus pelagicus) of calcareous nannofossil was used to investigate the fluctuations between the warm, salty Atlantic Waters (AWs) and the cool, fresher Arctic Waters (ArWs; Carbonara et al., 2016). A ratio >1 was related to predominant AWs influence, while the <1 ratio was referred to the ArWs influence (Andruleit and Baumann, 1998). This proxy was coupled with distributional variations of total nannofossil and diatom abundances using "Sea Ice Margin" (Actinocyclus curvatulus and Fragilariopsis oceanica) and "Cold Water Group" (Thalassiosira antarctica, Rhizosolenia hebetata and Bacterosira bathyomphala) diatom species and variations in planktic and benthic foraminifera associations. The ratio of the benthic foraminifera Epistomenella exigua/Oridorsalis tener was used as a food availability index.
Three principal water masses fluctuations were identified: i) from 1905 CE to 1980 CE there is a shift from Arctic to Atlantic waters affinity, ii) from1980 CE to 2005 CE, the AWs dominated conditions shift to a cooler environment (ArWs dominated), in which diatoms bloom while calcareous nannofossil abundance decreases, iii) from 2005 to 2014, there is a return to warmer waters conditions.
These micropalaeontological evidences highlight that over the last 150 years, the investigated area went through intense and fast changes. In this framework, sedimentological and geochemical considerations will be furtherly made to have a complete overview of the reported events.

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Reconstructing the flow evolution of the Fennoscandian Ice Sheet using high-resolution digital elevation models: a new, multi-scale sampling approach.

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Data-driven reconstructions of palaeo-ice sheets based on their landform records are required for validation and improvement of numerical ice sheet models. We are exploiting the recent expansion in availability and coverage of very-high-resolution (1–2 m/pixel) digital elevation models (DEMs) within the domain of the former Fennoscandian Ice Sheet to reconstruct its flow pattern evolution from the glacial landform record.

The Fennoscandian Ice Sheet reached its maximum extent at 21–20 ka. Previous data-driven ice flow reconstructions over the whole ice sheet domain (e.g. Kleman et al. 1997; Boulton et al. 2001) have necessarily relied upon landform mapping from relatively coarse-resolution (decametre-scale) data, predominantly from satellite images and aerial photographs. However, 1–2 m/pixel LiDAR DEMs have recently become available over a large portion of the ice sheet domain above contemporary sea level. This reveals previously unobserved landform assemblages recording past ice sheet flow, including fine-scale cross-cutting and superposition relationships between landforms. These observations reveal additional complexity in the flow evolution of the ice sheet. However, the data richness and the large ice sheet domain amplify labour-intensity challenges of data-driven whole-ice-sheet reconstructions. We present a new multi-scale sampling approach for systematic ice-sheet-scale mapping, which aims to overcome the data-richness challenge while providing informative data products for model-data comparisons.

We present mapping products produced using our new approach. This includes mapping of >250 000 subglacial bedforms and bedform fields over Finland, Norway, and Sweden, and an in-progress map of ‘landform linkages’. Landform linkages summarise the detailed landform mapping but do not extrapolate over large distances between observed landforms. They provide a reduced data product that is useful for regional-scale flow reconstruction and model-data comparisons, and remains closely tied to landform observations. We also present in-progress ‘flowsets’, which describe discrete ice flow patterns within the ice sheet. We use landform cross-cutting relationships, where relevant, to ascribe a relative chronology to overlapping flowsets. Our flow-pattern reconstruction over Finland, Norway, and Sweden is an ingredient for a reconstruction of the entire Fennoscandian Ice Sheet within the ERC-funded ‘PALGLAC’ project (PI Prof Chris Clark; see e.g. Dewald et al., 2022; Diemont et al. 2022).

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Deglacial records of terrigenous organic matter accumulation off the Yukon and Amur rivers based on lignin phenols and long-chain n-alkanes

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Arctic warming will lead to widespread permafrost thaw. Sedimentary records of past warming events during last deglaciation can serve as analogues to study the conditions under which permafrost mobilization occurs. Long-chain n-alkanes and lignin phenols are two types of biomarkers excellently suited for the reconstruction of terrestrial higher plant vegetation. For the Bering and Okhotsk Seas off the mouths of the Yukon and Amur rivers, respectively, published records reported only the temporal variations of lipid accumulation recording mostly erosive processes. Vegetation type, wetland extent and organic matter degradation as reflected by lignin have so far not been investigated.

Here we present new lignin phenol records from two marine sediment cores. We find that in the Yukon Basin, vegetation change and wetland expansion began in the early deglaciation (ED). This timing is different from that of observed changes recorded in sediments from the Okhotsk Sea reflecting the Amur Basin, where wetland expansion and vegetation change occurred in the Preboreal (PB). In the two basins, angiosperms contribution and wetland extent all reached maxima during the PB, both decreasing and stabilizing after the PB. We also find that the permafrost of the Amur Basin began to be remobilized in the PB. Retreat of sea-ice coupled with increased sea-surface temperatures in the Bering Sea during the ED might have promoted early permafrost mobilization. In both records, accumulation rates of lignin phenols and lipids are similar suggesting that under conditions of rapid sea-level rise and shelf flooding, both types of terrestrial biomarkers are delivered by the same transport pathway.

Holocene retreat of Greenland Ice Sheet from the mapping of ice marginal landforms

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During the Late Weichselian the Greenland Ice Sheet extended offshore and out across the continental shelf. By 14 to 9 ka it had reduced in size such that its margins had back-stepped onshore, and over the Holocene the margin retreated across the terrestrial periphery and toward the present day margin of the ice sheet. During this Holocene terrestrial retreat a wealth of ice marginal landforms were left behind, such as such as moraines and ice marginal meltwater channels. Using the 2-metre resolution ArcticDEM of topography we mapped over 270,000 terrestrial landforms recording former ice margin positons across the whole ice-free land around Greenland's periphery. Here we present the first landform-based empirical reconstruction of deglaciation for the whole of the Greenland Ice Sheet during the Holocene. The timing of ice marginal retreat was constrained using published geochronometric dates (n=1085) from 145 studies, to produce an ice sheet-wide margin reconstruction from 13 ka to 6 ka. We present our preliminary reconstruction of deglaciation and explore the main controls on retreat. Next on our PalGlac project, we will use PISM ice sheet model simulations that reasonably match the new empirical record to make inferences about ice sheet extent and volume during the mid-Holocene thermal maximum, the state of (im)balance of the contemporary ice sheet, and use our optimised modelled simulation as a starting point for exploring the ice sheet's future evolution.

Controls on ice marginal dynamics of the soft-bedded Southern and Eastern sectors of the Scandinavian Ice Sheet during the last Glacial: An investigation using a land-from driven ice sheet reconstruction

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The Numerical ice sheet modelling community require scenarios to test predictive models on. The last Scandinavian Ice Sheet (SIS) provides a data rich scenario to test numerical and conceptual ice sheet models. The spatial dynamics of the SIS beyond the hard bed rock shield are yet to be conclusively constrained. This is in part due to the regional nature of morphological and stratigraphic studies used to reconstruct ice sheet behaviour. Integrating and evaluating varying evidence and reconstructions from local studies into an ice sheet scale model is difficult with locals studies often being irreconcilable. Here we apply consistent land-form driven reconstruction method across the entire soft bedded Southern and Eastern sector of the SIS. We believe this first order reconstruction may assist in integrating knowledge from more detailed regional studies. We briefly outline the challenges of data variability in this ~1.2 million km2 study region and outline the methods developed to overcome these challenges. Our initial reconstruction efforts point towards a range of non-climatic controls on margin positions and flow configurations. The possible influences of GIA effect, Ice divide shifts and Ice sheet confluence are discussed in relations to our emerging reconstruction.

Update to the environmental and glaciation history of Northern Ostrobothnia and Finnish Lapland during the past 140 000 years

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The Scandinavian Ice Sheet (SIS) repeatedly covered Fennoscandia during the Pleistocene causing both erosion and glaciotectonic deformation and leaving behind glaciogenic sediments and fragile information. Despite all the studies accomplished within years, the extent and precise time and duration of glacial and non-glacial phases have not been fully compiled for the eastern part of the SIS.

More detailed scene of the paleoenvironmental and glacial history of the Weichselian (MIS 5 - 2) and the late Saalian (MIS 6) stages is drawn based on the three sites from central and northern Finnish Lapland and western central Finland studied in my PhD work. The data presented here includes litho- and biostratigraphical data together with optically stimulated luminescence (OSL) and radiocarbon (C-14) dating results.

The results of the three sites were compiled and correlated with the previously published data to shed light to more complete stratigraphy for the study area. The overall results indicate more extended ice advances, and warm ice-free environment during the Middle Weichselian stage (MIS 3).

Cosmic-ray muography: a new method for imaging and monitoring density variations in the Arctic

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Atmospheric muons are short-living elementary particles generated in the upper atmosphere by primary cosmic radiation. The deep penetrative power of muons in geological materials is exploited in muography to reconstruct density maps of the object of interest. We propose this novel passive astroparticle geophysical method called muography offers new opportunities for researchers of the Arctic environment. Muography is reminiscent of medical X-raying in that the attenuation of radiation forms the basis of imaging. However, muography operates in scales of hundreds of metres instead of just a few metres, like with X-rays. Another significant difference is that muons are natural, and one does not need to generate radiation like in X-ray-based methods. In fact, generating muons is possible only in large particle accelerators.

Mineral grain sizes and shapes are important factors influencing soil porosities and their density profiles. Hence, muography may be useful in determining soil packing, porosity and structure. We propose that muography is not only suitable for imaging Arctic soils and landforms for these parameters but also for long-term monitoring of processes that are capable of changing soil bulk densities (Holma et al., 2022). Optimal environments include, for example, steep geomorphological landforms experiencing thawing permafrost. Such objects of interest can be found, for instance, in some Arctic coastal regions. The benefits of applying muography in these and other suitable Arctic environments include at least: improved and confirmed estimates on permafrost thawing rates, an improved understanding of the melting process and internal structure of the target volume, detection of high-porosity soil layers, and monitoring of water table levels. Our assumptions are based on the idea that thawed Arctic soil has, on average, a lower density than that under permafrost and the general notion that saturated soils are adequately denser than their dry counterparts. However, some moisture loss is required for the former to be true.

The actual possibilities of muography for research of processes and palaeo-environmental changes in the Arctic require a more profound analysis of the scale of local density contrasts and the nature of the given scientific object. We look forward to collaborating with any research projects interested in piloting muography in their respective case studies.

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DATED-2: Re-visiting the chronology and time-slice reconstruction of the last Eurasian ice sheets

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DATED-1 comprised a fully-documented empirical reconstruction of the changing extent of the last Eurasian ice sheets 40-10 ka (at 1000-year resolution after 25 ka) based on an assessment of all relevant chronological data (Hughes et al. 2016). All uncertainties within the underlying data are synthesised and expressed in terms of distance; deviation between maximum and minimum limits, and their relative proximity to the extent considered 'most-credible', indicates the degree of uncertainty along the ice margin for each 100-year time-slice. Explicitly representing all uncertainties in this way provides a straightforward means to compare geological data with results from numerical modelling of past ice extent. Our process also created an archive of published dates (and associated data necessary for their interpretation, quality, and recalculation) relating to the build-up and retreat of the Eurasian ice sheets. Both the time-slice reconstructions and underlying chronological dataset are available via the online data repository PANGAEA (Hughes et al. 2015).

Here, we present progress towards the second-generation Eurasian ice sheets' synthesis, DATED-2, which brings the chronological dataset and reconstructions up-to-date; including all new chronological information published since the DATED-1 census nearly a decade ago. We highlight the main changes required to satisfy this new chronology, and discuss implications for, and obstacles to, constraining the timing of build-up and deglaciation of the last Eurasian ice sheets using empirical geological data.

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Opportunities concerning mine tailings in the Arctic environments

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Tailings are almost solely gangue-minerals-containing, fine grained and homogenous mining waste. This major side stream is formed during the ore enrichment process after valuables of ore are separated from unwanted minerals. Tailings are then pumped as a slurry in tailings storage facilities. Formerly there has not been much use or utilization of tailing sands due to their challenging features such as particle size and presence of sulfide minerals. Under the conditions of the earth surface, sulfides tend to oxidize, and it may lead to release of acidic and metalliferous waters which can cause serious threat to vulnerable arctic environment. Consequently, tailing sands need to be identify and quantify for safe storing and consideration of their future utilization. Along with gangue-minerals there might be, depending on processed ore, relatively large amount of valuable minerals and metals in tailings. This is because mineral processing techniques were poorly developed decades ago. In addition, negligible applications for some raw materials restricted their recovery and further utilization. Subsequently, tailings storage facilities are considered as a secondary raw material resources. Mineralogical and geochemical characterization methods which have conventionally used rather in mining environmental investigations, can be applied also in resource potential evaluations. In this case, characterization procedures aim to identify and quantify valuable mineral compositions of tailings sands in terms of reprocess them for metal recovery. Moreover, there has been plenty of studies concerning utilization of tailing material in applications of cement and ceramic industry. All the same, reprocessing and recycling of tailings can reduce primary raw material exploitation locally, which is particularly important in the Arctic region with sensitive natural conditions. Also, recovery of sulfide minerals can decrease the environmental impacts caused by sulfide oxidation.

Till geochemical data analysis and mineralogical research as a tool for the critical minerals' exploration

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Critical raw materials (CRMs) are important to the EU industry and the green energy transition. EU published a list of 30 CRMs in 2020 which are hosted in different types of ore deposits. Among them, the orthomagmatic sulfide and oxide deposits host the most significant mineralizations with several (critical) raw materials which are important for renewable energy technology (e.g., Co, Cu, Ni, PGM and V). Currently there are only two mines in the EU for those metals and they are located in Finland. Northern Finland, , especially the Central Lapland, are the most potential areas for new ore deposit although there are potential of the same types of deposits in central and southern Europe as well.

One of the projects which focus on the development of new exploration techniques for the critical metals and minerals is the EU funded Sustainable exploration for orthomagmatic (critical) raw materials in the EU: Charting the road to the green energy transition (SEMACRET). The main aims of this project are to provide a clearer understanding of the EU's mineral potential, and to develop sustainable (i.e., environmentally, and socially friendly) exploration techniques for green transition (critical) raw materials hosted in orthomagmatic ore deposits. One part of this approach is fulfilled by using existing regional surface geochemical data sets. For example, in Finland all available high-resolution till (and soil) geochemical datasets had not been fully deployed for exploration due data analytical challenges. To resolve these issues and detecting geochemical indicators in till and possible new resources in the bedrock advanced data analysis techniques such as the compositional data analysis (CoDa) approach, outlier detection, data-driven clustering algorithms, e.g., self-organizing mapping (SOM) together with till stratigraphical and glacial morphological guidance will be used. Re-analysed and classified till geochemical datasets with other geological and geophysical multiple data layers can then be integrated on a GIS platform to generate prospectivity maps distinguishing areas of low and high exploration potential. This approach provides environmentally friendly and cost-effective exploration methods for sensitive nature areas such as the Arctic area.

In addition to the development of regional geochemical method, exploration needs also new techniques for mineralogical research to identify potential source rocks and their indicators. Advance identification techniques for indicator minerals are benefitted to analyse samples from glacial till and weathered or fresh bedrock. For example, geochemical and mineralogical analyses of sulfide minerals using fingerprinting techniques can be used in tracing potential source rocks for gold and many other commodities (Kalubowila 2022). This has been the focus also in the EIT Raw Materials funded project Enhanced use of Heavy Mineral Chemistry in Exploration Targeting (MinExTarget).

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Chronostratigraphic marker horizons related to sudden ice-lake water level changes in eastern Fennoscandia

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During the last deglaciation extensive ice lakes were formed next to the ice margins in North America and in Fennoscandia. The most extensive ice lakes (e.g. Lake Agassiz - Lake Ojibway ice lake complex) existed in North America during deglaciation while in Fennoscandia the Baltic Ice Lake and the White Sea Ice Lake were the most extensive ice lakes in the Baltic and the White Sea basins. Perhaps the most significant event in the history of the Baltic basin area took place during the last deglaciation when the water level of the Baltic Ice Lake suddenly dropped 25-28 m as a new outflow route opened in the Billingen area, south central Sweden (e.g. Donner 1995). It has been estimated that 7800 km3 of freshwater catastrophically drained into the North Atlantic within a couple of years (Jakobsson et al. 2007). Two age estimates of the drainage event, 11590±100 cal. yr BP (Saarnisto & Saarinen 2001) and 11690±10 cal. yr BP (Andrén et al. 2002), suggest that the catastrophic outburst event took place at or very close to the Pleistocene/Holocene boundary.

Like the Baltic Basin, also the White Sea Basin was occupied by a glacial lake during the last deglaciation (Lunkka et al. 2012). This glacial lake had no direct connection to the Baltic Ice Lake. Shore displacement studies show that water a level drop of 60 m in the White Sea Ice Lake took place when the outflow route via present Gorlo Strait to the Barents Sea opened at around 12 000±200 cal. 14C yr BP (Lunkka et al. 2012). Lunkka et al. (2012) estimated that during this event at least 3000 km3 of freshwater drained into the Barents Sea.

In the present study, Laser scanning (LiDAR-DEM) imageries and Ground Penetrating Radar (GPR) were used to study glaciofluvial Gilbert-type deltas in the Younger Dryas Salpausselkä, Kaleva and Keiva end-moraine zones in southern Finland and northwest Russia. The data analysed was used to reconstruct the water level history of the Baltic and the White Sea Ice ice-contact lakes. The results indicate that the drop of the Baltic Ice Lake left its imprint on glaciofluvial deltas north of the Second Salpausselkä throughout southern Finland. Although glaciofluvial delta levels have been mapped in this area already in the last century, the development of LiDAR-DEM imageries and GPR-techniques enabled to define more accurately the Pleistocene-Holocene chronostratigraphic boundary in southern Finland. This boundary can be placed at the sites where the Gilbert-type deltas occur at two different levels, the higher-level delta formed during the Baltic Ice Lake BI-water level stage and the lower-level delta during Yoldia Sea YI- water level stage. In NW Russia, Gilbert-type deltas in the White Sea Ice Lake are not as common as in the Salpausselkä zone but the highest shoreline (i.e. chronostratigraphic marker horizon) just prior to the water drop was possible to trace and map in the eastern part of the Kola Peninsula.

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Terrestrial biomarkers in sediments from northern Svalbard reveal unprecedented subglacial meltwater drainage during the Last Termination

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Marine-based ice sheets, and their contribution to global-mean sea level changes, are particularly susceptible to dynamical instabilities triggered by both oceanic and atmospheric processes (Thomas, 1979). Collective evidence suggests the subglacial environment exerts a first-order control on the rapid grounding line retreat although the fundamental mechanisms remain elusive (Bell, 2008; Stearns et al., 2008). A sediment core, collected in northern Svalbard, at the edge of the Barents Sea Ice Sheet (BSIS), provides new insights into the connection between the BSIS retreat during the Last Deglaciation and subglacial processes. Analysis reveals an unprecedented release of biospheric terrestrial carbon along the Arctic margins, in phase with Meltwater Pulse 1A (MWP-1A, ~14,600 years ago). The organic matter fingerprint suggests the existence of an unidentified proglacial lake, located in the White Sea/Pechora Basin region, close to the southern margin of BSIS. We infer the existence of a large and interconnected subglacial drainage network beneath the BSIS and that the accumulation of water-saturated sediments could have directly contributed to the fast retreat of the BSIS arctic margins. Our findings provide evidence for the direct contribution of the northern sector of the BSIS to MWP-1A, through a new mechanism, connecting proglacial lakes to the ice sheet subglacial environment.

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Comparing geochronological tools for dating Quaternary Arctic Ocean sediments

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Large uncertainties in Arctic Ocean age models severely limit our ability to interpret paleo-environmental conditions, and effectively integrate these with global paleoceanographic and paleoclimatic data. Outside of biostratigraphy, common techniques for dating Arctic Ocean sediments include paleomagnetics, orbital tuning, amino acid geochronology, optically stimulated luminescence dating, and uranium-thorium dating. Age differences derived from these techniques can exceed several hundred thousand years when applied to the same sedimentary record. No consensus exists on which methods are the most robust or return the most accurate ages. Here we illustrate and emphasize the similarities and differences in the ages obtained by these methods when applied to sediment records from the Lomonosov Ridge in the central Arctic Ocean. The aim is to document the methods that return comparable results and to explore how close we are to a consensus view on the late Quaternary age models of Arctic Ocean sediments.

Multiproxy paleoenvironmental reconstruction of the Ross ice shelf retreat and sea-ice dynamics in the Joides Basin, Ross Sea, Antarctica

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The last deglaciation (ca. 18-11.5 ka) represent a major reorganization of climate and carbon cycle. Many studies on this timeframe focus on high latitude regions because they have exerted a first-order control on the atmospheric composition by releasing GHGs, accelerating, thus, climate change. However, many questions remain regarding the pathways of carbon release, in particular through the Southern Ocean, which is believed to be one of the major upwelling regions that outgassed CO2 during such major climatic reorganization.

Here we present preliminary results from the Joides Basin in the Ross Sea (Antarctica), one of the depressions located on the continental shelf adjacent to the Ross Ice Shelf (RIS) edge during the Last Glacial Maximum. We studied a sedimentary core collected at the very center of the Joides Basin (74° 01.9995' S; 175° 04.0752' E), at 584m water depth, in order to reconstruct the past-LGM evolution.

We used a combination of techniques that include grainsize, XRF and a suite of organic biomarkers, such as Highly Branched Isophrenoid (HBIs), Phytosterols and Glycerol dialkyl glycerol tetraethers (GDGTs), in order to reconstruct the sea ice and open water dynamics, and paleo seawater temperatures. These results are framed by a set of radiocarbon dates from bulk OC and foraminifera, laying the foundation of an age model.

Our results detect the transition from a LGM sub-ice shelf environment to a distal ice sheet system throughout the last deglacial period.

During the retreat of the RIS, the Joides Basin was characterized by open water conditions dominated by strong upwelling of warm, nutrient rich waters (presumably paleo CDW impinging branches), which caused persistent blooming of both heterotrophic and autotrophic organisms throughout the whole deglaciation, stabilizing during the Holocene.

We provide new information to improve our understanding of the RIS retreat and the related effects to the surrounding marine and glacio-marine environment during the last deglaciation and Holocene. Our findings allow us to detect massive algal blooming likely driven by upwelling and potentially associated carbon release, shedding new lights in regards to the Ross Sea CO2 contribution during this time interval.

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Equating, analysis, and modelling of pre-glacially weathered bedrock composition with till unit geochemistry – application to mineral exploration

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Lapland has been glaciated several times during the Quaternary period during which six stratigraphically significant till beds were deposited in the area (Hirvas, 1991). An ice divide zone existed in central Lapland several times during glacial phases and the cold-base ice conditions without significant basal erosion enabled the preservation of multiple till sequences and weathered bedrock underneath.

Both, weathered bedrock, and till are well suited for geochemical mineral exploration and the aim of the present work is to utilise a geochemical dataset, compiled by the Geological Survey of Finland (Gustavsson et al., 1979) to create prospectivity maps for the area.

Prospectivity maps were created using fuzzy logic. Fuzzy logic is a set theory proposed by Zadeh (1965). Fuzzy logic assigns a membership value for a datapoint. This value is between 0 and 1 ($0 \leq x \leq 1$), non-member and member, respectively. A value of 0.5 is said to be random. Fuzzy logic maps were created for both till and weathered bedrock. Till was further divided by one-meter intervals, to see the membership change with depth. Elements used for the fuzzy calculations were Fe, Cu, Ni, Pb, and Ag. Weathering indices were also used. These indices were Parker's weathering index (WIP) (Parker, 1970) and chemical alteration index (CIA) (Nesbitt & Young, 1982). Subsequently, the elements fuzzy map and the weathering indices fuzzy map were combined.

The results show potential areas for ore exploration. However, these results should be further validated by considering the glacier dynamics and direction of the ice movement. In other words, moving the results "up-ice" direction. Furthermore, receiver operating characteristics (ROC) (Egan, 1975) could be used to determine which of these 'data signals' is better for mineral exploration purposes.

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Mid-Pleistocene to Holocene calcareous nannofossil taxonomy and biochronology in the central Arctic Ocean

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A half-century of research (since the 1970s) indicates that accurate dating of sediments in the Arctic Ocean is not straightforward due to puzzling magnetic polarity patterns, lack or scarcity of microfossils, and discontinuous oxygen isotope records in Arctic marine sediments. Recently two important bio-horizons of calcareous nannofossils, including the first occurrence of Emiliania huxleyi (291 kyr, Raffi et al., 2006) and the last occurrence of Pseudoemiliania lacunosa (436 kyr, Raffi et al., 1977) were reported for the first time in the central Arctic (LRG12-3PC, O'Regan et al., 2020). In order to study the taxonomic composition and abundance of calcareous nannofossil taxa and expand on the results provided by O'Regan et al. (2020), a high-resolution stratigraphic analysis of upper Quaternary sediments has been undertaken on three cores from the Lomonosov Ridge (LRG12-7PC, LRG12-9PC, and AO16-5-PC1) and one core from the Makarov Basin (AO16-8GC) in the central part of the Arctic Ocean. Although our studies confirm the presence of the two bio-events across the central Arctic, the extremely low abundances and variable preservation can make it very difficult to confidently resolve their stratigraphic position. Through detailed sampling and cross-verification using LM and SEM imaging, a new stratigraphic framework in support of key bio-events is emerging. This would signifcantly change the geochronological framework for central Arctic Ocean sediments – implying that what were identified as sub-stages (inter-stadials) within Marine Isotope Stage 5 are actually separate interglacials. The presence and absence pattern of nannofossil markers in the studied cores follows the nannofossil zones NN19, NN20, and NN21 of standard biozonation of Martini (1971) and would place the Mid-Pleistocene to Holocene in the upper 2-3 meters of the cores.

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Development of geochemical and indicator mineral on-site research techniques - in connection to professional competence for ore exploration

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The mining industry is growing business in Finland. The most significant growth and strongest investment are focusing on northern Finland and especially in the Central Lapland area. At the same time, there is increasing demand on developing services for the on-site indicator mineral concentration and analytical techniques as well as educating staff for the exploration companies need for the northern, Arctic or sub-Arctic conditions. To response the demands, there two parallel projects going on: the project 'Pilot testing and demonstrating on-site methods for mineral exploration in Sodankylä' (Indika Au) funded by European Research Develop Fund and lead by the Sodankylä municipality, and the project 'Development of competence for ore exploration and research' (METSO) funded by the European Social Fund and lead by the Lapland Education Centre REDU, Sodankylä. Partners are the Geological Survey of Finland and the Oulu Mining School.

An aim of the Indika Au project is to produce practical information on new on-site mineral exploration methods to develop the service offering and new operation opportunities in the exploration business and to reduce the environmental impact in the sensitive environments. The project will produce experimental data for the assembly of a mobile unit suitable for mineral exploration with a view to on-site pre-treatment and analysis of soil and pre-glacial weathered bedrock samples related to indicator mineral exploration directly in the field or at a field camp. The methodological development is focusing especially on techniques suitable for gold prospecting, but also the methods which can be used for several other ore types, such as battery and other critical metals. Sample pre-processing and analytical testing directly on the exploration site reduces the need to transport samples, enables a rapid and resource saving research process, lower environmental impact, and provides an opportunity for new business and operating models in a key exploration area, in Central Lapland.

An aim of the METSO project is to increase the technical know-how of subcontractors doing simple ore exploration, for example by providing sampling services, field pre-processing and analyses, to improve and expand their product range and thus add value to their products. In addition, REDU will develop educational packages to further educate people in some related field, such as the civil engineering side of the business. By that way they could develop their services to suite better for the ore exploration and thus expand their service offerings extractive industries or, at best, create a whole new SME business in northern Finland. During the project, the readiness of teachers at REDU will be increased by giving professional geoscience education and producing teaching materials in the field of modern ore exploration, and by planning and piloting exploration projects and equipment procurement. Based on the competence needs of companies, locally offered degree components or entities consisting of already existing degree components are planned. The project will create and pilot at least two training modules including research assistant and technician who have readiness to work in challenging Arctic conditions and are experienced in modern field techniques in ore exploration.

Occurrence of the subglacial ring-ridge-shaped moraines in the interlobate zones of the central part of Fennoscandian Ice Sheet

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There are several areas in northern and south-eastern Finland where relatively small landforms composed semi-linear to ring-shaped moraines occur. These moraines, named Pulju moraines in Finland, were mapped, and investigated using Light Detection and Ranging (LiDAR) imagery interpretation. The ring-shaped, linear, and non-linear Pulju moraines are often overlain by the streamlined glacigenic features.

Pulju moraines were first described by Kujansuu (1967) from around Pulju village, NW Finnish Lapland, which gave the name to this moraine type. Based on earlier observations, these moraines were found especially north of the late Weichselian ice-divide zone, in Inari, in Enontekiö and in northern Kittilä (Aartolahti 1974, Aario 1990, Johansson & Nenonen 1991). The Pulju moraines occur and/or are best preserved in the supra-aquatic area typically close to ice-divide zone or at the interlobate zones of the Fennoscandian paleo-ice sheet.

Landform mapping indicates that Pulju moraines occur in fields where individual moraine ridges stand out from the ground as various type of horseshoe-shaped features, 1-5 metres high. For example, in the Kemijärvi ja Salla areas south from the latest ice divide zone, Pulju moraines occurr as a distinct moraine field with hundreds of individual landforms (Korkala 2020). Typically, there are also separate linear and non-linear moraine ridges between the ring-type moraine features and in places there seems to be a continuum from ridge-shaped into ting-shaped moraines. Stratigraphical results show that Pulju moraines are composed of 2-3 subglacial sandy till units with strong till clast fabrics orientation parallel to last ice flow direction. The moraines seem to have been formed in supra-aquatic areas void of major subglacial glaciofluvial landforms such as eskers but relatively close to ice interlobate area between the Kuusamo and Salla ice lobes. In places, the ring-shaped moraines are superimposed by the streamlined moraines such as drumlins and flutings.

In SE Finland, these moraine fields currently under investigation occur between the former Lake District and the Karelian Ice Lobes adjacent to the interlobate complex. Moraines in this area cover more than 300 km2 on both sides of an interlobate formation. The moraines are composed of till. Their shape varies from ring-shaped to straight ridge-type moraines, commonly 1-3 metres high. Also here, Pulju moraines are in places overlain by fluted surfaces, indicating partial deformation and morphological re-modification. Thus, this indicates the origin to be in the subglacial conditions under influence of fractional, moving ice sheet.

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Fluvial and permafrost history of the lower Lena River, NE Siberia, over the glacial-interglacial cycle

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Arctic warming and permafrost thaw visibly expose changes in the landscape of the Lena River delta, the largest Arctic delta. Determining the past and modern river regime of thick deltaic deposits shaping the Lena River mouth in NE Siberia is critical for understanding the history of delta formation and carbon sequestration. Using a 65 m long sediment core from the delta apex a set of sedimentological techniques is applied to aid reconstructing the Lena River history. The analysis includes (i) grain-size measurements and the determination of the bedload composition, (ii) XRF, XRD, and magnetic susceptibility measurements and heavy mineral analysis for tracking mineral change, (iii) pH, electrical conductivity, ionic concentrations, and the δ18O and δD stable isotope composition from ground ice for reconstructing permafrost formation. In addition, (iv) total and dissolved organic carbon is assessed. Chronology is based on (vi) radiocarbon dating of organic material (AMS and conventional) and is complemented by two IR-OSL dates. The record holds transitional periods from traction, over saltation, to suspension load sedimentation and the postglacial delta growth in the course of the sea level rise. Minerogenic signals do not indicate provenance change over time. They rather reflect the change from high energy to a lower energy regime after LGM time parallel to the fining-up grain-size trend. A prominent minimum in the ground ice stable isotope record at early Holocene highlights that a Lena River branch migration and an associated refreeze of the underlying river talik has altered the isotopic composition at that time. Fluvial re-routing might be explained by internal dynamics in the Lena River lowland or due to a tectonic movement, since the study area is placed in a zone of seismic activity. At the southern Laptev Sea margin onshore continental compressional patterns are bordering offshore extensional normal faults.

India in the Changing Geopolitics of Arctic region

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The Arctic region has recently assumed importance due to melting of ice, climate change, global warming and other environmental vulnerabilities. However, the region is witnessing a considerable amount of focus from the global players. Primarily due to the presence of two major powers in the region, it is moving to play a greater role in the world affairs and in redefining the global perspective of the Arctic region. According to recent studies, the Arctic region may experience ice free summers by 2050's which will open various economic pathways such as opening of new shipping/transportation routes, opportunities for energy exploration of various resources, minerals, oil, gas etc. With the increased importance of the region all the states, especially the Arctic states, are introducing their policies, plans and strategies for the engagements in the region.

Considering all the factors, it is important for a country like India which is the third largest energy consuming nation in the world to play a greater role in the international arena and register its presence in the region.

However, in order to pursue these goals India needs partners who can help to advance Indian goals in the region. India's engagement in Arctic region can provide a ground for natural extension of India's Act East Policy which has been recently signalled by PM Modi in his Speech in 20th India-Russia Annual Summit 2019.

The Arctic region can also help in strategically manoeuvring both USA and Russia. India is working with USA in the Indo-Pacific region already through its political, economic and military engagements, and therefore an Indo-Arctic construct would complement India's Indo-Pacific strategy and can help India to work also closely with Russia. The active presence of India in the Arctic region is also necessary as India foresees the expanding Chinese interest in the region.

The influence of proglacial lakes on climate and surface mass balance of retreating ice sheets – An Investigation of the Laurentide and Fennoscandian ice sheets, 13 ka BP

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This study investigates the effect of ice-contact lakes on regional climate and surface mass balance (SMB). For this purpose, the atmospheric general circulation model ECHAM6 was extended by a novel subroutine, which considers proglacial lakes and their specific characteristics. Other lakes still evolve freely according to a mixed layer scheme.
As a first application the impact of proglacial lakes during the Allerød interstadial 13 ka BP (ka BP is thousand years before present) was studied for the Laurentide (LIS) and Fennoscandian (FIS) ice sheets. To achieve this, the following three scenarios were taken: i) 13 ka BP land surface boundary conditions (GLAC-1D, Ivanovic et al., 2016) and a modern lake configuration, ii) same as (i) but with additional lakes around LIS and FIS, iii) same as (ii) but additional lakes are treated with new proglacial lake approach.
All simulations used a hybrid setup with ocean boundary conditions taken from a 15ka coupled climate simulation. They were evaluated with respect to the regional climate response and the surface mass balance was calculated using the diurnal Energy Balance Model (dEBM, Krebs-Kanzow et al., 2021). Preliminary results indicate an overall positive effect of regular lakes, and in particular proglacial lakes, on the SMB of the great ice sheets over Northern America and Scandinavia during the Allerød interstadial.

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Coal particles in Arctic deep-sea sediments: Origin, composition and potential significance for paleo-ice drift reconstructions

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Coal particles have been found occasionally in deep-sea sediment cores from the Eastern Arctic Ocean, the Fram Strait, and the Nordic Seas. Based on coal petrographic studies and the geographical distribution of coal-bearing and non-coal-bearing cores, it was concluded that the encountered input of coal grains most likely stems from a source in northern Siberia (Bischof et al., 1990). To better constrain and distinguish its potential source areas, coal petrological and organic geochemical investigations were performed on coal particles found in deep-sea sediment cores from the Vilkitsky Strait (northernmost Siberia), the outer Voronin Trough (northern Kara Sea), the central Fram Strait, and the NE Greenland continental margin.

The results reveal a certain variability of data (vitrinite reflectance, Rock-Eval hydrogen and oxygen indices, hydrocarbon biomarkers) even among samples from the same core, suggesting that the coal grains do not stem from one restricted area. Data clusters and comparison with published information on coals from circum-Arctic continents, however, allow a tentative discrimination of our samples. The coals from the Vilkitsky Strait, the Voronin Trough and the central Fram Strait show relatively high oxygen indices, in opposite to coals from the NE Greenland margin. The latter resemble coals from the Cretaceous/Tertiary basins on Svalbard and NE Greenland.

While the coal grains found in the Vilkitsky Strait core were deposited during the last deglacial, available stratigraphic data from our cores suggest that the coal-bearing layers in cores from the Voronin Trough, the central Fram Strait, and the NE Greenland margin are from the Saalian glaciation (marine isotope stage 6, MIS 6). We conclude that during MIS 6 coal-bearing layers in the NE Greenland Wandel Sea Basin were eroded by an expanded North Greenland Ice Sheet and transported by icebergs southward along the adjacent continental margin. At the same time, icebergs breaking off from the large northern Eurasian Ice Sheet drifted from northern Siberia across the Eurasian Basin towards the central Fram Strait. Our results generally support the hypothesis of a cross-Arctic iceberg transport in MIS 6 but show that caution must be applied when conclusions are made on the sources of individual coal particles.

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Reconstructing the evolution of the Laurentide and Innuitian ice sheets prior to the Last Glacial Maximum (115 ka to 25 ka): recent progress and future challenges

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The Laurentide Ice Sheet was the largest global ice mass to grow and decay during the last glacial cycle (~115 ka to ~10 ka). Despite its importance for driving major changes in global mean sea level, long-term landscape evolution, and atmospheric circulation patterns, the history of the Laurentide (and neighbouring Innuitian) Ice Sheet is poorly constrained owing to sporadic preservation of stratigraphic records prior to the Last Glacial Maximum (LGM; ~25 ka) and a case-study approach to the dating of available evidence. In this paper, we review recent progress towards reconstructing the pre-LGM evolution of the ice sheet, including previously published geochronological data, together with published stratigraphic and geomorphological data, as well as numerical modelling output. This has culminated in 19 hypothesised reconstructions of the Laurentide and Innuitian ice sheets from 115 ka to 25 ka at 5-kyr intervals, with uncertainties quantified to include best, minimum, and maximum ice extent estimates at each time-step. This work suggests that, between 115 ka and 25 ka, some areas of North America experienced multiple cycles of rapid ice sheet growth and decay, while others remained largely ice-free, and others were continuously glaciated. Key findings include: (i) the growth and recession of the Laurentide Ice Sheet from 115 ka through 80 ka; (ii) significant build-up of ice to almost LGM extent at ~60 ka; (iii) a potentially dramatic reduction in North American ice at ~45 ka; (iv) a rapid expansion of the Labrador Dome at ~38 ka; and (v) gradual growth toward the LGM starting at ~35 ka. Some of these reconstructions are only loosely constrained and are therefore highly speculative (especially prior to 45 ka). Nevertheless, this work represents our most up-to-date understanding of the build-up of the Laurentide and Innuitian ice sheets during the last glacial cycle to the LGM based on the available evidence. We consider these ice configurations as a series of testable hypotheses for future work to address and refine, noting the large uncertainties on most age constraints and current over-reliance on a small number of constraints older than 45 ka. Nonetheless, these results are important for use and testing across a range of disciplines including ice sheet modelling, palaeoclimatology and archaeology and are available digitally.

Quantitative mineral analysis for revealing Arctic Ocean sediment provenances and transport history: review and outlook

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In-situ micro-analytical automated techniques enable presently a quick identification the most useful provenance indicator minerals and quantify their relative abundances in sediments. Developments in single grain analytical techniques have provided a new dimension to heavy mineral provenance studies by enabling geochemical characterization of individual mineral populations. All factors controlling the compositional modifications need to be always clarified when a parent rock transform to a final deposit. Data acquisition in quantitative provenance analysis should include analysis of bulk mineralogy and the selective analysis of heavy minerals as well as important varietal geochemical analysis of single grain populations. For Arctic Ocean sediments this technique can provide critical data for evaluation of possible source areas, consider deglaciations and for discuss on ice rafting. There is a specific need to evaluate a possible involvement of marine sediments recycling in forming the complete heavy mineral assemblages. Example for complexity comes from the glacial and ice-rafted diamicts in the East Siberian continental margin and the southern Lomonosov Ridge, respectively. Heavy mineral assemblages were needed to be identified for prominent parent rocks in hinterland and other sediment source areas, as well. The presence of glacial sediments on the East Siberian continental shelf and slope, along with the results from heavy mineral analysis implicate that glacial ice not only grew out from the East Siberian shelf but also from the De Long Islands. There was, however, at the same time a clear ice-rafting related sediment transportation to the southern Lomonosov Ridge from other, westerly sources, such as the Laptev Sea.

Trace element and isotope analyses of sulfide minerals as a fingerprinting tool for mineral exploration: Example from northern Finland

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Geochemical and indicator mineral research methods are commonly used in mineral exploration in northern, glaciated terrains. Transported cover sediments such as unconsolidated till and upper soils are typically used to target the source areas and detect sub-outcropping mineralizations. Sulfide minerals are common ore minerals and indicators in various mineral deposits. Pyrite is one of the most common sulfides and can be survived during the glacial transport. Trace element composition of pyrite varies in different geological and ore-forming processes, thus making it potential mineral for fingerprinting. Advanced analytical techniques such as LA-ICP-MS allow detailed trace element and isotopic analyses with a spatial resolution of a few microns.
The use of fingerprinting technique for pyrite characterization in gold exploration was tested in the Petäjäselkä study area in the Central Lapland Greenstone Belt, northern Finland. The study area was located in the centre of last glacial maximum during the Late-Weichelian glaciation. The till cover is relatively shallow in the area, generally 2-3 m. In-situ trace elements and sulfur isotope compositions of pyrite were analysed in heavy mineral separates of till and compared to the composition of known gold occurrences. Pyrite compositions from heavy mineral separates are compared with pyrites from the gold occurrences, and the capability of using pyrite for fingerprinting is evaluated. The results showed that well-preserved pyrite grains can be found from till in the study area, although quite big amount of them have been weathered and goethetized. Furthermore, the results of trace element analyses show variable source areas for the pyrite grains in the Petäjäselkä area.
The study is a part of the first author´s Ph.D. project within the EIT Raw Materials funded 'Enhanced use of heavy mineral chemistry in exploration targeting' (MinExTarget) project. The project aims to develop effective indicator mineral concentration procedures and fingerprinting techniques using various minerals in tills that can be used in the greenfield exploration stages. This aspect is important for the arctic region, potentially providing a low-impact, environmentally friendly prospecting application. Furthermore, the project develops a new service for mineral exploration through a novel combination of the available technologies of automated mineralogy and mass spectroscopy.

Oil slicks from natural seepage of oil and gas, a common occurrence on ice sheet influenced continental margins?

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Of the over 1000 x 106 litres of oil estimated to be released into the ocean each year, nearly half originate from natural seepage. Although the Barents Sea represents a well-studied petroleum system, with abundant gas seepage documented, the first oil slicks stemming from natural oil seepage have only recently been documented in the central Barents Sea (Ivanov, 2019; Serov et al., in review). We expand on this considerably, mapping abundant sea surface oil slicks across the Norwegian sector of the northern Barents Sea, from satellite SAR imagery.
The imagery covers a period from 2016-2021 and identifies a total of nearly 1000 individual slick segments, with segments reaching a maximum area of 130 km2. Oil slicks with known pollution sources account for 17% of the mapped slick segments; whilst the remaining are naturally occurring, representing either natural seepage of oil from the seafloor or look-alikes (low wind areas, biogenic slicks, ocean fronts). Field observations made by CAGE (Centre for Arctic Gas Hydrate, Environment and Climate) since 2016, and other published accounts, provide extensive evidence of natural seepage and confirm that many of these slicks are related to leakage of oil and oil-coated gas bubbles from subseafloor hydrocarbon reservoirs.
Across the Barents Sea, hotspots for the natural seepage of oil and gas from subsurface thermogenic reservoirs have been created by the repeated erosion of ice sheets, removing cap rocks, opening up migration pathways for hydrocarbons and over-pressuring petroleum reservoirs. Geologically analogous settings are found across many polar continental shelves where extensive thermogenic reservoirs have experienced intense glacial erosion, e.g. example offshore Greenland, North America and Russia, and making these likely hotspots for natural oil and gas leakage.
Natural seepage, in particular from marine sources, represents a poorly constrained component of the global carbon cycle. The widespread oil slicks documented across the Barents Sea confirm that oil droplets and oil-coated gas bubbles are reaching the sea surface. Assessing the impact of these on atmospheric methane concentrations and marine ecosystems must be a priority.

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Middle Conference Excursion in the Rovaniemi region

The 3rd PalaeoArc Conference in Rovaniemi, Finland, August 23.-26. 2022

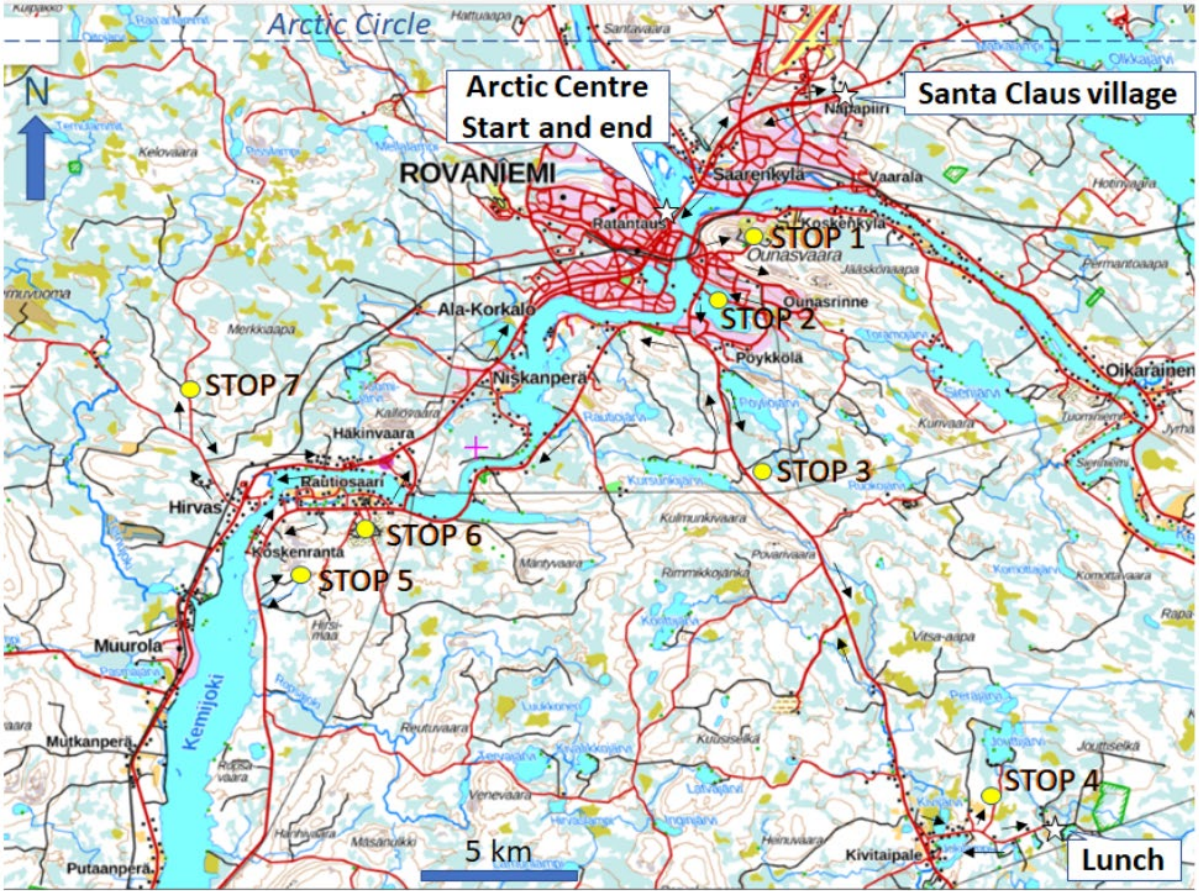
Edited by
Pertti Sarala and Peter Johansson

Organizers:

University of Oulu, Oulu Mining School and UniOGS
PalaeoArc international network research programme
the Finnish National Committee for Quaternary Research (INQUA)
University of Lapland, Rovaniemi-Lapland Congresses

Excursion route and stops

A map of the excursion route in the Rovaniemi region with the location of excursion stops 1-7 and Santa Claus Village on the Arctic Centre.



CONTENT

Introduction

Geological background and environments

Pertti Sarala and Peter Johansson

Northern Fennoscandia including western Finnish Lapland locate next to the centre of the former Fennoscandian Ice Sheet (FIS) (Fig. 1). The centre of the FIS situated in the Scandinavian Mountain range, and it covered Finland and the north-western Russian Plain several times during the Pleistocene glaciations (e.g., Svendsen et al., 2004; Johansson et al., 2011). It is not precisely known how many times Finland and the northern areas were covered by ice during the Pleistocene. This is because several ice advances eroded and deformed most of previously deposited interglacial and glacial sediments during the cold stages (Johansson et al., 2011).

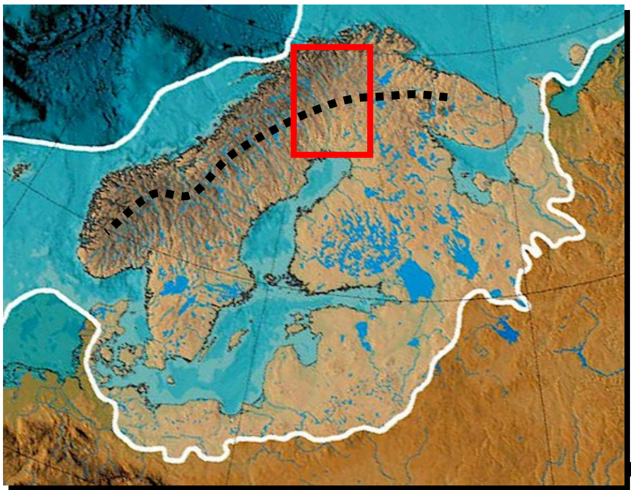


Fig. 1. A map of Fennoscandia and the location of western Lapland (red box). Dashed line shows the area of last ice divide zone. Modified after Svendsen et al. (2004).

m subglacial to ice-marginal depositional environments and from active, warm-based ice-lobe network in the south to cold-based, more passive ice in the ice-divide zone in the north (Johansson et al., 2011). Glacial deposits are related to several glacial phases with separate till sheets each associated with glacial striations and till fabrics with varying orientations (Hirvas, 1991; Sarala, 2005). Due to the glaciogenic nature of surficial sediments and their extensive cover (97 % of Finland's land area) (Johansson & Kujansuu, 2005), surficial geology and morphology form a foundation to nature and all human activities in northern environments.

In Finland, and particularly in northern Finland, pre-glacial, weathered bedrock has been largely preserved beneath glacial deposits (Hirvas, 1991; Nenonen, 1995; Hall et al., 2016). The ice divide zone of Central Lapland is the area where the remnants of weathered regolith from some tens of centimetres up to tens of metres thick are frequently found. The thickest weathering profiles are found in topographic depressions under the till cover. Typically, only the saprock has been preserved, but in places also the lower saprolite (Sarala & Ojala, 2008; Hall et al., 2016), and parts of the upper saprolite are still present displayed as kaolinite deposits. The saprock horizons are strongly fractured and therefore are zones of preferential groundwater movement with enrichment of secondary iron minerals like goethite and some clay minerals (Sarala, 2015). Weathered bedrock has also been served as a ground for glacial erosion and a source for till material reflected in till composition.

Glacigenic sediments are dominant in most of the northern areas (Johansson & Kujansuu, 2005). The Quaternary cover is thickest in depressions and river valleys, thinning out on hill slopes. Till is the most widely spread sediment-type and is formed different landform associations in the areas of active ice sheets. Morphologies include~~s~~ well-formed drumlin and ripped moraine fields but also flat or gently undulating basal till areas and hummocky moraine fields. Sorted sediments mainly related to ~~the~~ glaciofluvial and glaciolacustric activity and sediment deposition are less abundant than till but can form very distinct esker and delta formations in valleys. Typical feature in the depression of northern areas is the occurrence of large aapa mire areas which cover underlying sediments and large/long river valleys and lake bodies. In the northernmost fell and mountain areas rocky surface and bedrock outcrops as well as boulder fields are dominant landscape elements.

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Late Pleistocene glacial history and stratigraphy

Pertti Sarala, Peter Johansson and Juha Pekka Lunkka

Most of the Quartenary sediments are glacigenic in origin and were deposited during the last cold stage (Weichselian) directly on the fresh or pre-glacially weathered Pre-Cambrian bedrock. Except for some scattered remnants of the Saalian esker ridges (Kujansuu & Eriksson, 1995) in the ice-divide zone of northern Finland (Finnish Lapland) and in the major river valleys in the Pohjanmaa area, in western Finland, there are no distinct geomorphological landforms related to pre-Weichselian glaciations. However, there are several sites where Middle and Late Pleistocene organic and glacial sediments have been preserved, particularly in northern Finland and in Ostrobothnia, western

Finland (cf. Hirvas, 1991; Nenonen, 1995). These sites provide the basis for the general Quaternary stratigraphy of Finland and at the same time of northern Fennoscandia.

According to the Finnish till stratigraphy, there are six, stratigraphically significant till beds in Finnish Lapland. The key site for the till stratigraphy is the Rautuvaara area in western Finnish Lapland (Hirvas et al., 1977; Hirvas, 1991). The three uppermost till beds are thought to represent Weichselian-age tills (Till Beds I – III), two of these (Till Bed I and II) are thought to have been deposited during the Late Weichselian. The so-called Till Bed IV was laid down during the Saalian glaciation. The two lowermost till beds (Till Beds V-VI) that occur beneath the Holsteinian peat horizon may represent Elsterian or pre-Elsterian tills (cf. Hirvas and Nenonen, 1987; Hirvas, 1991). However, recent revision of some important key sites in northern Finland has led to the revision of the chronology and ages of key sections (Helmens et al., 2007; Helmens & Engels, 2010; Salonen et al. 2014; Howett et al., 2015; Lunkka et al., 2015). Based on new OSL dates of inter-till stratified sediment layers from different key sites, it is most evident that the till beds even in the thickest sequences have been formed during the Weichselian ice age and only in places, the oldest till beds have been deposited during the Saalian glaciation (Lunkka et al., 2015).

Southern Finnish Lapland

Based on stratigraphical and morphological evidence, two glaciation phases of the Weichselian age have been observed in southern Finnish Lapland (Sarala, 2005). The bluish grey Kemijoki Till is representing the Middle Weichselian glacial advance phase and the greyish or brownish grey Tervola Till with three till units represents the Late Weichselian glaciation phase. The glacial morphology is dominantly composed of the assemblage of drumlins, flutings, and ribbed moraines. These forms exist as fields in the area and indicate active ice-lobe formation during the late stage of the last deglaciation. Active-ice landforms dominate in the areas of Kuusamo and Oulu ice-lobes. The Ranua interlobate area in between those ice-lobes and with the north-northwest to south-southeast oriented drumlin field is a relic of the older glacial phase, which is correlative with the Middle Weichselian glaciation. Older drumlin field has preserved under cold-based subglacial conditions under central part of the Late Weichselian glaciation. Recent (OSL) dating results show that the Middle Weichselian glaciation was the first one to cover the southern Finnish Lapland after the Eemian interglacial.

The development of active-ice landforms from east to west in the area of Kuusamo ice-lobe indicates fast-flowing ice streams during deglaciation. The warm-based subglacial conditions prevailed at the marginal zone of the glacier during the formation of large Kuusamo drumlin field in the east. In the central and western parts, closer the glacier centre, the ribbed moraines with the ribbed moraine fields of Ranua, Tervola and Kemijärvi are common. The ribbed moraine formation is related to the retreating boundary of cold- and warm-based glacier, in an internal part of the glacier margin during deglaciation (Sarala, 2005). An existence of those landforms indicates cold-based subglacial conditions still prevailed in an internal part of the ice-lobe, while the marginal parts were warm-based. The most probable starting point for the ice-lobe separation and the development of fast-flowing ice streams during deglaciation was rapid climate warming at the end of the cold, Younger Dryas period, about 11,600-11,800 years ago.

Middle Weichselian interstadials in Lapland

Recent sedimentological, palaeontological, and geochronological results from Lapland and adjacent areas have increased knowledge on the interplay and timing of the stadials and interstadials/-glacial during the Middle and Late Pleistocene and led to a revision of former stratigraphical schemes. For example, the major revision to the previous stratigraphy of Lapland is that in addition to the Early Weichselian interstadials (115-70 ka, MIS 5b and 5d), there have been several, relatively short, warm stages during the Middle Weichselian (MIS3) even in Lapland (Johansson et al., 2011; Salonen et al., 2014; Lunkka et al., 2015) as well as in central and southern part of Finland (Nenonen, 1995; Mäkinen, 2005; Sarala, 2005; Sarala et al., 2005; Helmens et al., 2000, 2007a, 2007b; Auri et al., 2008; Salonen et al., 2008; Helmens and Engels, 2010; Sarala et al., 2010, 2016; Sarala and Eskola, 2011; Salonen et al., 2014; Lunkka et al., 2015).

For example, the recent study in the Kaarreoja river in northern Finland revealed inter-till gyttja − silt deposit with organic material, wood pieces and a well-preserved peat layer (Sarala et al., 2016). The peat deposit is composed of Betula-Salix dominant pollen taxa and macrofossils and includes pieces of well-preserved birch and willow wood particles. The age of the peat is c. 36,000 years BP (14C, cal) for the bulk sample and >45,000 BP (AMS) for the wood pieces. OSL age of the sand under the organic sediment deposit is 52 ± 12 ka. The interstadial deposit in the Kaarreoja sequence is interpreted to represent almost the entire length of the depositional and vegetation history of MIS3. Furthermore, it shows that present-day like, stabile ice-free period existed for a long time during the MIS3 in northern Finland before the onset of the Late Weichselian cold stage. This interpretation strongly supports the observations made from the large areas in northern Finland as well as northern Sweden.

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Southern Lapland region

Glacial morphology and stratigraphy in southern Finnish Lapland

Pertti Sarala

Both parallel and transverse elements are present in the glacial morphology of southern Lapland area. Under the active glacial flow, the glacier eroded bedrock and deposited morainic landforms. The erosion forms, like rock drumlins and large, streamlined hills, indicate the main glacial flow from the west to the east. Active ice forms like transversal ribbed moraines are the most dominant landforms in the area (Fig. 2). Ribbed moraines exist as uniform fields in lowland areas and are mainly composed of Rogen moraine or hummocky ribbed moraine types (cf. Hättestrand, 1997; Sarala, 2003) (Fig. 3). Furthermore, a small area of minor ribbed moraines occurs in the Sihtuuna area (cf. Aario et al., 1997). Ribbed moraines form together with drumlins and flutings assemblages of active ice morphology (cf.

Aario, 1977a, 1990; Lundqvist, 1969, 1989). Quartzite hills or hill areas occurring transversal to the general glacial flow break the uniformity of the ribbed moraine-drumlin field.

The ice-lobe system formed during the latest ice-retreat phase is clearly seen in the glacial morphology. Based on the interpretation of glacial landforms, there were two active ice lobes, i.e. Kuusamo and Oulu ice lobes in the area during the last deglaciation and one passive ice flow area, so-called Ranua Interlobate area. Drumlin-ribbed moraine associations indicating active ice-flow occur in the Kuusamo Ice-lobe area and in the southern part of the Kuusamo Ice-Lobe (Fig. 2). Similar associations can also be seen in the Oulu Ice-lobe area where the last active ice-flow was towards the east. Between the active lobes, the Ranua Interlobate area the older northwest-southeast oriented drumlin morphology around Ranua, south to the Kivalot hill chain and Portimojärvi area have been preserved due to less active ice flow during the latest ice-retreat phase. Meltwater streams were followed the lobate structure including some larger channel systems like the one in the area of Korouoma valley (Fig. 2).

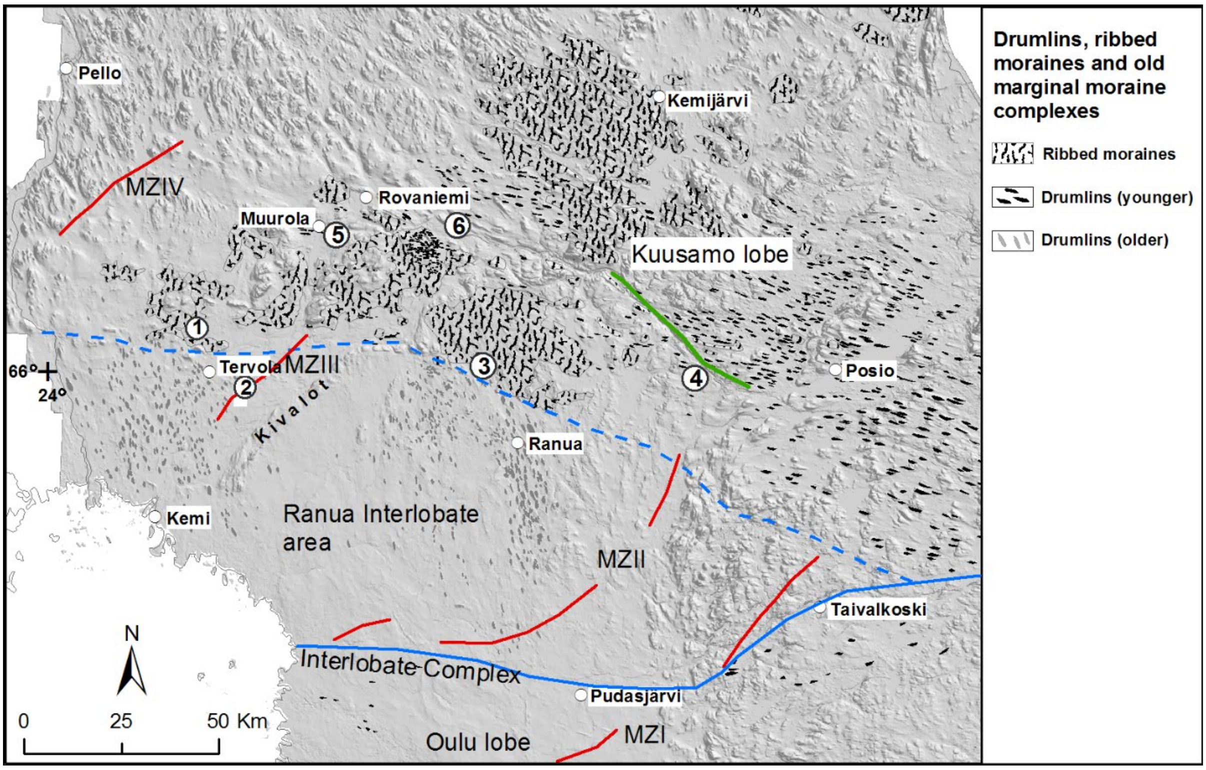

Fig. 2. The occurrence of drumlins, ribbed moraines, old marginal zones MZI-MZIV (red) and Pudasjärvi-Taivalkoski-Hossa Interlobate Complex (blue) in southern Finnish Lapland. The places mentioned in text are: 1) Sihtuuna, 2) Kauvonkangas, 3) Portimojärvi, 4) Korouoma Valley Complex (green), 5) Sukulanrakka and 6) Jokkavaara. Digital elevation model © National Land Survey of Finland.

Fig. 3. Ribbed moraine ridges in Petäjäskoski, western Rovaniemi. Ice-flow has been from west to east (upper left corner to right down). Photo R. Aario.

The Quaternary lithostratigraphy of southern Finnish Lapland consists of three till beds and two inter-till, stratified minerogenic sediment layers containing organic material in places, and is proposed to be named as the *Peräpohja Group* (Sarala, 2005b, c; Table 1).

Table 1. Quaternary lithostratigraphy, unit descriptions and formal names in Rovaniemi-Tervola area. A whole stratigraphic sequence is proposed to be named as the Peräpohja Group. After Sarala (2005c).

Formation	Member	Depth	Description	Interpretation	Chrono-stratigraphy	Type section
Suolijoki Formation		0.5 - 2 m	Stratified sand and gravel	Shore deposit	Holocene	N7345.5 I2561.5 M118, Vammavaara
Tervola Till Formation	Korttelivaara Till Member	0.1 - 1.5 m	Brownish grey sandy diamict	Melt-out, flow or waterlain till	Late Weichselian	N7334.0 I3444.6 M90, Korttelivaara
	Petäjävaara Till Member	1 - 3 m	Brownish grey or grey gravelly diamict	Lodgement or basal melt-out till		N7358.5 I2564.1 M1, Petäjävaara
	Vammavaara Till Member	1 - 4 m	Grey sandy diamict	Lodgement till		N7346.2 I2561.2 M25, Vammavaara
Sihtuuna Sands		1 - 2.5 m	Horizontally or cross bedded sand	Subaquatic fan	?	N7344.6 I2529.6 M124, Sihtuuna
Kemijoki Till Formation		1 - 2 m	Bluish grey, compact sandy/silty diamict	Lodgement till	Early or Middle Weichselian	N7345.9 I2562.2 M21, Vammavaara
Saarenkylä Gytja		2 - 3 m	Organic gytja, silt and sand	Lacustrine or marine deposit	Eem Interglacial or Early Weichselian	N7382.5 I3447.6 Saarenkylä (Sutinen 1992)
Saarenkylä Till Formation		> 1 m	Grey, compact sandy diamict	Lodgement till	Saalian	N7382.5 I3447.6 Saarenkylä (Sutinen 1992)

The lowermost till unit, Saarenkylä Till, correlative with Till Bed IV after the nomenclature of Hirvas (1991) is interpreted as being deposited during the Saalian Stage. The Saarenkylä Gyttja is thought to have been deposited either during the Eemian Interglacial (Sutinen, 1992) or possibly during the Early Weichselian Interstadial. Kemijoki Till above is known as dark till in literature (e.g., Ber and Kujansuu, 1974; Kujansuu et al., 1982) and is correlative with Till Bed III of Hirvas (1991). It has been deposited during the first Weichselian glaciation that covered the southern Finnish Lapland area. The Sihtuuna Sands stratigraphically above the Kemijoki Till represents an ice-free interstadial phase of the Middle Weichselian substage. The Tervola Till Formation including members of Vammavaara Till, Petäjävaara Till and Korttelivaara Till represents the Late Weichselian glaciation including the till units from an ice-advance phase to a melting phase with the redeposited unit related to ribbed moraine formation in between. The Korttelivaara Till is rare and has seldom preserved, because the upper parts of morainic landforms were washed during the later Ancylus Lake and Litorina Sea stages and changed to shore deposits of the Suolijoki Formation.

Based on studies in southern Lapland, the glacial morphology and till stratigraphy were developed during the two Weichselian glacial phases (Sarala, 2005c). There is evidence of three glacial advances during the Weichselian glaciation, but the first glacial stage was quite modest in extent and covered only the area of northernmost Finland. The glacier reached southern Finnish Lapland (and maybe whole Finland) for the first time during the Middle Weichselian. The marginal formations in the Pudasjärvi area and from there to northeast (MZI-MZIV in Fig. 1) deposited during the melting phase. Series of marginal deposits described by Sutinen (1992) is now completed with a fourth zone MZIV in Fig. 1), which runs through the Kauvonkangas ice-marginal formation (Fig. 1). An interstadial in the Middle Weichselian (MIS 3) age-bracketed to 40-55 ka with C-14, OSL and TL (the Peräpohjola Interstadial described by Korpela in 1969) confirms that the ice-free interval(s) existed in Lapland during the Middle Weichselian (Sarala, 2005b; Sarala et al., 2005; Mäkinen, 2005). Finally, the interstadial was followed by the relatively short but very intensive and large Late Weichselian glaciation.

Excursion sites in the area

STOP 1. Highest shoreline on top of the Ounasvaara Hill, Rovaniemi

Peter Johansson

The Ounasvaara Hill is situating 3 km east of the centre of the Rovaniemi city (Fig. 4). Marks of the glacial erosion can be seen on the barren bedrock top of Juhannuskallio (in English: Mid-Summer Rock), the second highest point (203 m) of the hill. The bedrock is approximately 2000 Ma old and characterized by pale grey quartzites varying in composition from well-sorted orthoquartzite to poorly sorted arcosite and sericite quartzite. Mica schist, calcium silicate rich interbeds and white quartz veins also occur. Quartzite is more resistant to the erosion than the rock types in the surrounding area. That is the main reason, why Ounasvaara stands out as a prominent hill. The shape of the polished rocks, striae and grooves on the bedrock surface demonstrate that in its final stage the flow direction of the ice was from WNW (=285°) (Fig. 5).

After the deglaciation, about 10 300 years ago, large areas in the Rovaniemi area were covered by the waters of the Ancylus Lake (The ancient Baltic Sea). The highest shoreline reached the elevation of 212 m at the Rovaniemi area. Only the highest point of the Ounasvaara Hill (213 m) was an small,

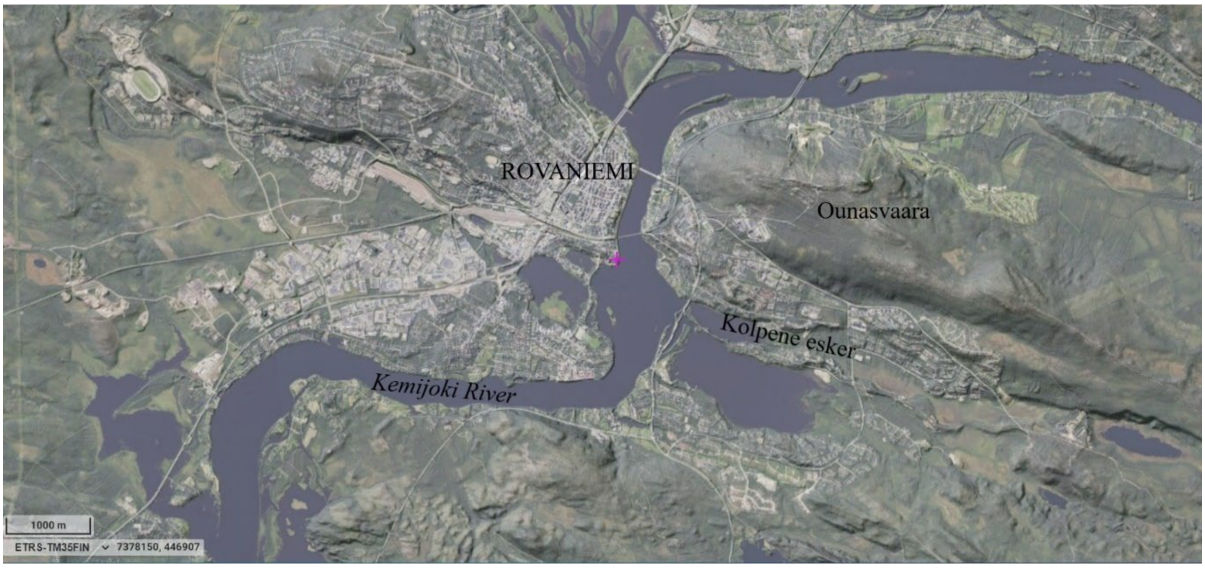

Fig. 4. Location of the Ounasvaara Hill on eastern side of the Rovaniemi centre. The glaciofluvial esker system goes through the town including Kolpene esker on the eastern side of the Kemijoki River. Digital elevation model and topographic map © National Land Survey of Finland.

isolated island above the water level. The highest shoreline reaches its maximum height, 219 m, at the Vammavaara Hill, 40 km south of the city. From there, it descends towards the north and northeast and it is about 186 m - 189 m at Sodankylä.


Fig. 5. Glacially eroded and polished bedrock surface, i.e., roches moutonnée on top of the Ounasvaara Hill. Photo P. Johansson.

Around the hilltop there are bedrock outcrops and associated block field caused by shore processes. The waves and the ice in winter turned the stones and boulders around and formed a gravelly beach ridge on the slopes of Ounasvaara. On the lower levels there are sandy littoral deposits. As a result of the isostatic uplift the land rose and the areas covered by the waters of Ancylus Lake diminished. The highest Littorina shoreline is approximately 90 metres above the present sea level. Littorina Sea withdrew from the area some 7 000 years ago. Large deltaic formations deposited in the valleys of the rivers Kemijoki and Ounasjoki.

Raised littoral formations have been an important target of research in attempts to unravel the history of the Baltic Sea. By mapping the area in which raised beaches occur, it has been possible to establish the extent and elevation reached by the waters of the Baltic Sea basin at different times and in different areas (Fig. 6). The elevations of the raised beaches have been used in attempts to determine the varying rates of uplift (Saarnisto, 1981; Fig. 7).

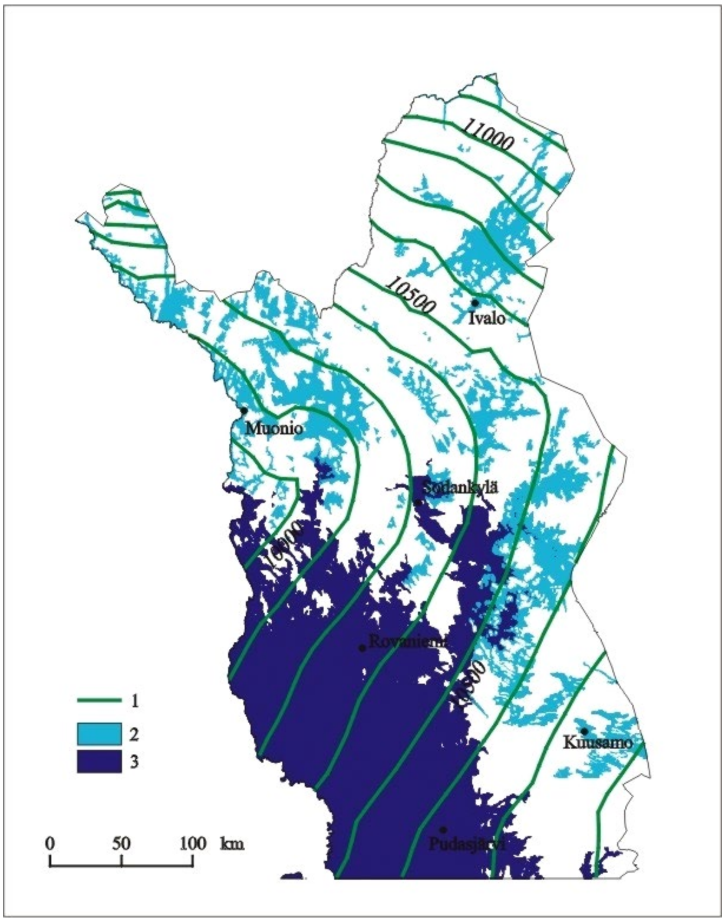

Fig. 6. Recession of the margin of the glacier in northern Finland towards the end of last glaciation. 1 = position of the ice margin, 2 = areas covered by ice-dammed lakes and 3 = Ancylus Lake. After Johansson and Kujansuu (2005).

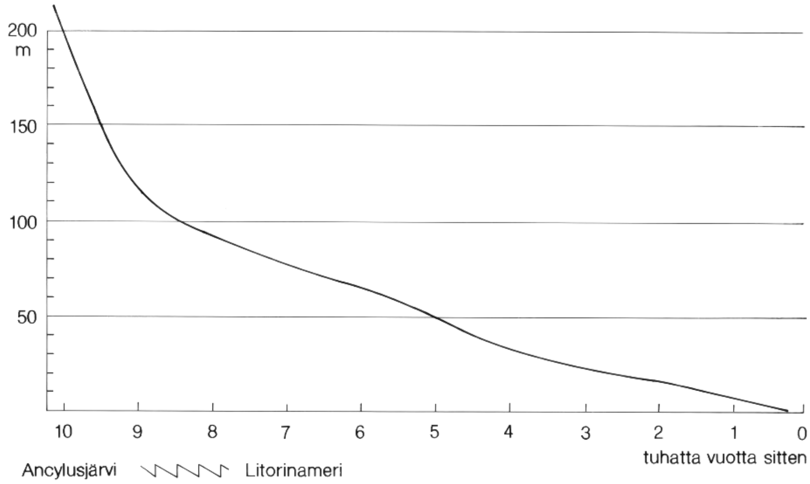

Fig. 7. Displacement curve showing the shoreline elevation of the ancient Baltic Sea above the current sea level in southern Finnish Lapland after deglaciation. The time scale shows calendar years. Ancylusjärvi = Ancylus Lake, Litorinameri = Litorina Sea and tuhatta vuotta sitten = thousands of years ago. After Saarnisto (2005).

STOP 2. Kolpene esker on the centre of Rovaniemi

Peter Johansson and Pertti Sarala

The Kolpene esker (Kolpeneenharju in Finnish) is an approx. 6 km long glaciofluvial ridge composed of sand and gravel and formed in a bedrock fracture. It is a part of longer W-E-oriented esker system (Fig. 4). On the western part of the esker the ridge is bordered by the Lake Keinuvuopaja on the northern side and Lake Salmijärvi on southern side (Fig. 8).

Fig. 8. Glaciofluvial Kolpene esker, which is a part of glaciofluvial system that go through the town Rovaniemi in W-E direction. Photo P. Sarala.

The thickness of the loose soil cover varies greatly, being at its thickest over 45 m in the actual groundwater formation area. In this area, the height level of the bedrock surface is also at its lowest at a little over 30 m a.s.l. and, on the other hand, groundwater near the ground surface, so the thickness of the loose soil cover saturated with groundwater is large. Likewise, the thickness of the soil cover above the groundwater level is at its greatest in the actual groundwater formation area. Groundwater level in the formation area varies between 74 and 80 m a.s.l. The main groundwater flow direction is west towards the Kemijoki River.

There is a groundwater pumping area for the town Rovaniemi in the uninhabited, eastern end of the Kolpene esker. The water pumping station was completed in 1959, and the water treatment plant was built in 1965.

The earliest Stone Age settlement in Rovaniemi is estimated to date back to 8000–7000 BC. According to some estimates, on the shore of Lake Salmijärvi, on southern side of the esker, there was a turning point of the Menolithic and Neolithic era between 6000 and 5000 BC. stone age settlement. It is thought that the dwelling sites were chosen not only because of the fishing opportunities, but also because of the sheltered southern slope of the Kolpene esker, where the nearby Ounasvaara weakened the bite of the north winds. It has been assumed that Kolpene has been inhabited even in winter and that there have been settlements in several places.

STOP 3. Bouldery field, shoreline, and glacial erratics in Sapilasselkä, Rovaniemi

Pertti Sarala

On the southern side of Rovaniemi centre, there is a boulder field with large glacial erratics (Fig. 9). The boulder field is situated over the moraine ridge and the origin of the boulders is in glacial transportation related to ribbed moraine formation in the area. An enrichment of boulders on the surface is due to wave action on the shoreline and washing the fine material away by the Ancylus Lake after the dropping of water surface to the level 145-150 m a.s.l. during the post-glacial time.

Fig. 9. Boulder field and large glacial erratics on the top of moraine ridge on the southern side of town Rovaniemi. Photo P. Sarala.

Furthermore, close to this location, there is a deep erosional channel. It was formed during the last deglaciation phase as a subglacial meltwater channel, which is continuing towards the east as a depositional esker formation (Fig. 10). In addition, in the up-ice direction, the channel was filled by sands forming ice-marginal delta. This type of transitional subglacial meltwater channel pattern is common in this region and there are several parallel channels having the same structure. This is probably caused by cyclic meltwater pulses in the marginal zone of melting and at the same time floating icesheet. It has caused erosion dominated, subglacial meltwater channel network in southern Finnish Lapland.

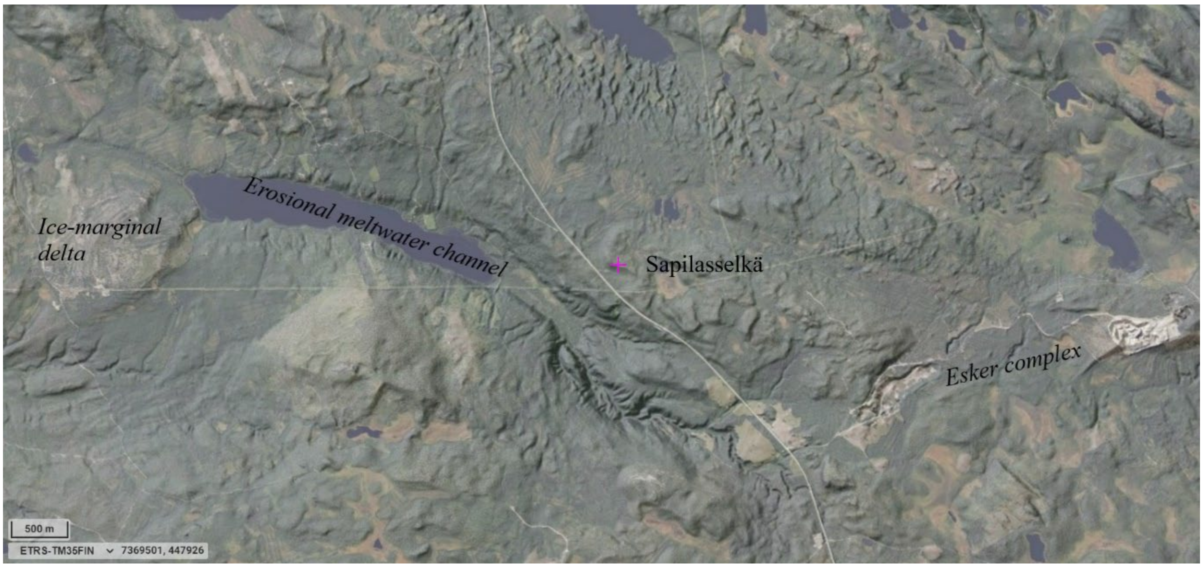

Fig. 10. Location of Sapilasselkä and the complex erosional-depositional system forming cyclic W-E oriented meltwater channel. Digital elevation model and topographic map © National Land Survey of Finland.

STOP 4. Ribbed moraines in Kivitaipale, Rovaniemi

Pertti Sarala

Ribbed moraines in Kivitaipale are part of the Ranua ribbed moraine field. It is one of the three large ribbed moraine areas in southern Finnish Lapland. It is composed of transversal moraine ridges, which are usually 5-15 m high, 100-150 m wide and up to one kilometre long (Fig. 11). The form of the ridges is often crescentic where the edges are pointing into the down-ice flow direction. These forms represent Rogen moraine type described by Lundqvist (1969). Hummocky ribbed moraine type (cf. Hättestrand, 1997; Sarala, 2003, 2006) is also common, although having not so clear indication of the ice-flow direction. Characteristically, mires and little lakes exist in between the ridges and the ridge surface is mostly covered with boulders (Figs. 12-13).

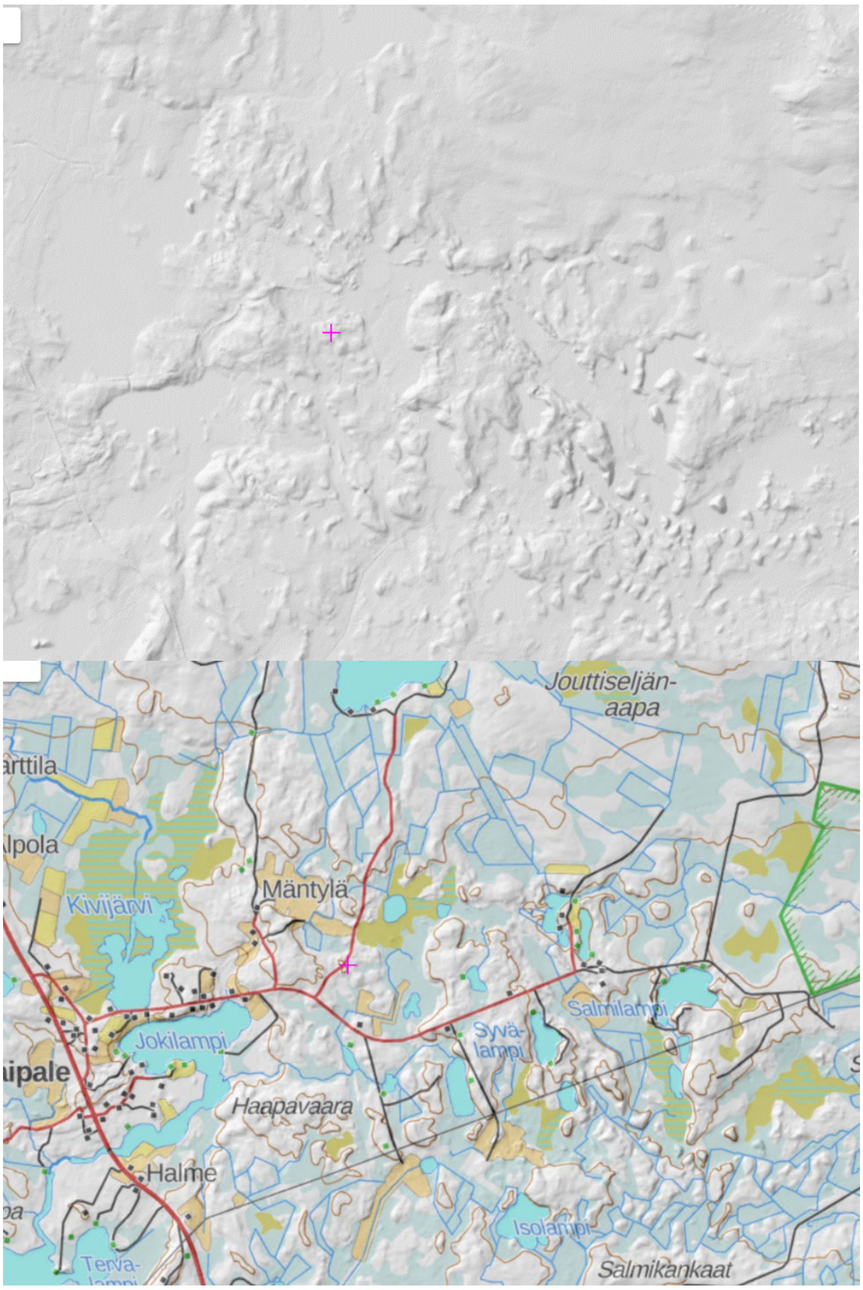

Fig. 11. A pair of maps of the ribbed moraine ridge topography in the north of Kivitaipale village in southern Rovaniemi. Upper part is a LiDAR based elevation model and lower map topographic map showing transversal moraine ridges which are separated by mires or small ponds/lakes. Digital elevation model, topographic features and roads © National Land Survey of Finland.

Fig. 12. Two photos from Närhikkö (STOP 4) in Kivitaipale where the mire is seen occurring between the ribbed moraine ridges on the upper photo and typical boulder surface on the lower photo. Photos P. Sarala.

The ribbed moraines in the area have been studied since 1975 (Aario, 1977a, 1977b; Aario, 1990; Aario and Peuraniemi, 1992) in connection to Quaternary geomorphology and stratigraphy investigations and also, for ore prospecting purposes. The ridges are composed more or less regularly of two till facies, a more densely packed lodgement and melt-out till with fine-grained matrix at the base and homogeneous melt-out and flow till at the surficial parts. Pebble content increases upward while the roundness decreases. The transport distance of stone material is also highest at the basal part of till. On the surface and in the uppermost till, boulders are indicating local variation of the underlying bedrock composition. It is clearly coming out as short (some tens of meters wide and 200-300 m long) mineralized boulder trains traced in the area (Aario et al., 1985; Aario, 1990; Aario and Peuraniemi, 1992). Sandy layers or stone pavements exist sometimes in the boundary between the units but more often the contact is hard to distinguish.

Fig. 13. A couple of ribbed moraine ridges and a little lake between the ridges. It is a very typical scenery in many parts of the ribbed moraine field in southern Finnish Lapland. Photo P. Sarala.

In places, the third, bluish grey till unit is also found in topographic depressions, like in between the bedrock tops. The till is clay-rich, matrix supported, compact and homogenous in structure deposited most commonly as basal, lodgement till. Unfortunately, the surface of this till is at the level of 6-8 m from the top, so it is hard to reach during the studies. Different till units are seen in Half-Schlumberger sounding profile (Fig. 14) (see also Aario, 1990).

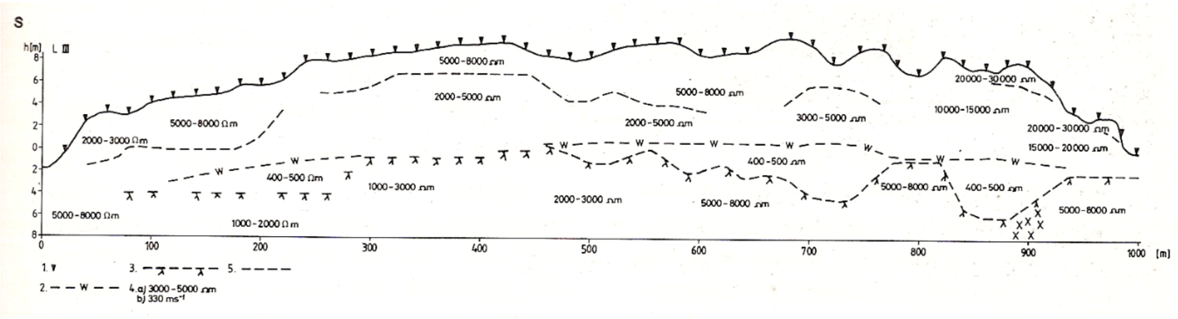

Fig. 14. Interpretation of Half-Schlumberger sounding profile measured along the ribbed moraine ridge in Portimojärvi. The sounding curves show ribbed moraines to be composed of three till units of which the lowest one only exists in topographic depressions in between the bedrock tops. After Aario (1990).

Ribbed moraine formation

Pertti Sarala

Ribbed moraines were initially descriped by Hughes (1964) in North America. After that a lot of papers have been published from Scandinavia and North America concerning the existence, morphology, composition and structure of those landforms. Many theories of the formation of ribbed moraines from for example end, push and squeeze to annual or dead-ice disintegration moraines have been presented over the years. Since the end of 1960's the formation was considered to be an active ice, subglacial process controlled by different pressure, tension and temperature conditions (e.g., Cowan, 1968; Lundqvist, 1969; Aario, 1977a). The latest theories presented by Hättestrand (1997), Lundqvist (1997), Sarala (2005b; 2006), Möller (2006, 2010), Stokes et al. (2008), Trommelen et al., (2014) and Möller and Dowling (2018) start with an assumption of multiphase formation controlled by the variable subglacial processes.

The observations made from the southern Finnish Lapland have proved that the formation process of ribbed moraines was a result of several subglacial stages (Sarala, 2006). During the early stage of deglaciation, on the retreating zone of subglacial frozen- and thawed-bed, pre-existing sediments and the lowermost part of the ice sheet formed a stagnant, stacked mass. Due to pressure and tension caused by the moving ice sheet, subglacial crack system was formed, and the stagnant mass was fractured (Fig. 15). When the zero-degree boundary was crossed the surface of bedrock or other weakness zone (e.g.,

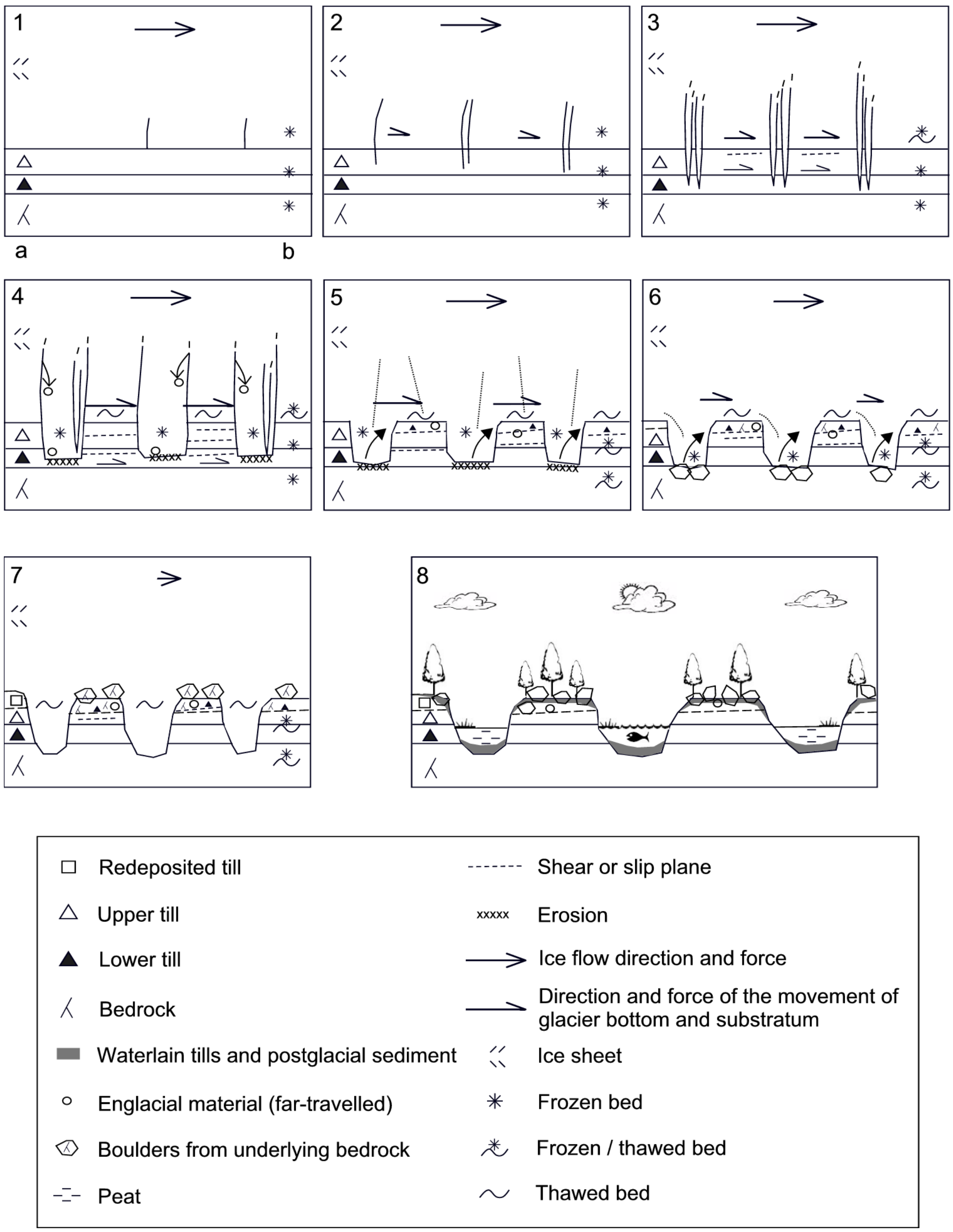

Fig. 15. Ribbed moraine formation as a result of subglacial fracturing, mass movement and followed quarrying. Variable pressure conditions under moving icesheet initiated the freeze-thaw process that caused the subglacial quarrying and deposition of local bedrock material on the ridge tops. After Sarala (2006).

till unit boundary, stratified layer, boulder pavement), fractured blocks were moved along the ice sheet forming rib-like morphology. Because of the prevailing cold conditions, followed freeze-thaw process was caused the quarrying in between the new-born ribs and a bit later, after the pressure increased on the proximal contact, the deposition of material (released from the ice bottom) on the surface of the ribs.

The formation process described above is a very general presentation but is relevant for all the ribbed moraine types observed in southern Finnish Lapland. For example, an inner structure and the short glacial transportation of till material and boulders on surficial parts of ridges, and the relation between shapes of parallel ridges indicate that ribbed moraines are depositional features.

Sarala (2005b, 2006) represented that quick and strong decrease of the air temperature and the subsequent imbalance between the surface and the base of the ice sheet might be the most suitable moment for the beginning of ribbed moraine formation in the early stage of deglaciation at the end of Younger Dryas. The climate change during that time was a global phenomenon and thus, explains the occurrence of ribbed moraines in the central areas of the former glaciated areas. It is worth noticing that ribbed moraine formation was not a sudden, explosive process but it continued several hundred or maybe over a thousand of years after the Younger Dryas. Rapid climate change during the Younger Dryas was only the starting point for the formation process. Suitable glacial conditions for ribbed moraine deposition could have varied both in spatially and temporally in different parts of continental ice sheets in Scandinavia and North America.

STOP 5. Potholes in Sukulanrakka, southern Rovaniemi

Peter Johansson

The number of documented potholes in Finland is about 2,000. Most of them have been found in southern Finland, especially in the southern coastal region, where the bedrock is better exposed than anywhere else in the country. In northern Finland only a few potholes are known. Sukulanrakka, one of the best-known pothole areas in Finland and northern Europe is located about 20 km southwest of Rovaniemi (Fig. 16). On this hill 14 clearly distinguishable potholes shaped like churns or pots can be found, among them three centrally situated, remarkable large and deep ones.

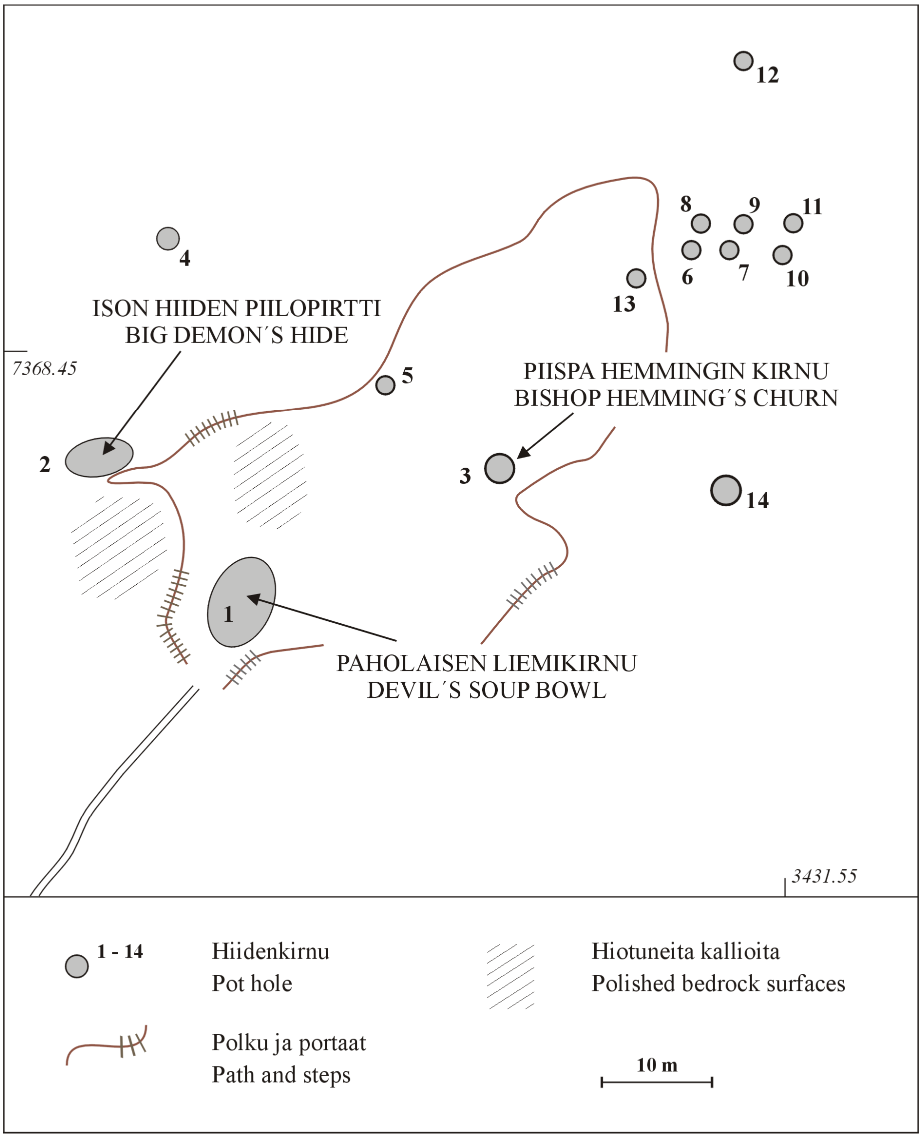

Fig. 16. Map of the Sukulanrakka potholes in Rovaniemi. After Johansson and Kujansuu (2005).

The largest pothole is known among the local people as the ”Devil's Soup Bowl”. With its depth of 15.4 m it is the largest pothole found in Finland. At the railing, its diameter varies between 8.0 m at its widest and 5.7 m. The southern wall is almost completely missing due to quarrying by the glacier. The bottom of the pothole is normally covered by water. In the spring 2002 it was pumped dry and cleaned and then two smaller potholes with a diameter of about 1.5 m were found at the bottom. Close to the largest pothole, in the hillside, there is another one with a depth of 8.7 m. It is called ”Big Demon's Hide” and is oval in shape with a diameter of 6.4-3.6 m. Spirals can be seen in its well-polished rock walls. The third of the large potholes,”Bishop Hemming's Churn” (Fig. 17), lies northeast of the other two. It is a 10.1 m deep hollow, this one, too, with rifle-like spirals on its walls. At the bottom its diameter is 2.4 m and at its narrowest it is at the mouth, only 1.5 m. By the pothole you can see some rounded grinding stones found on its bottom.

Fig. 17. The walls of the pothole "Bishop Hemming's Churn" are marked with spiral grooves formed by stones set into circular motion by strong meltwater currents. Photo P. Johansson.

The potholes of Sukulanrakka were formed during the last deglaciation, about 10,500-11,000 years ago, as the subglacial meltwater stream flowing northwest from the Muurola area towards Jokkavaara crossed the bedrock ridge of Sukulanrakka (see Fig. 2). At this ridge the highly pressurised meltwater stream formed eddies, which whirled around stones and finer sediment transported by the stream. Especially boulders loosened from the nearby diabase rock formed grinding stones, rounded and resistant to wear. As they rotated in the whirlpools, they bored into the rock on the tunnel floor, making potholes in it. The bedrock here contains cordierite-antophyllite rock, which is favourable to the formation of potholes, as it has low resistance to grinding. Potholes were formed until the glacier became thinner and the pressurized meltwater stream with its whirling water ceased. After the deglaciation, the potholes were partly filled with sediments and plant remains.

The Sukulanrakkka potholes are located in a small area of only about 0.3 hectares. The location forms a crossing point between the cordierite-antophyllite rock and the route of the glacial meltwater stream. Although the local people have known the place for centuries, it was not studied in detail until in the early 1960's. In times past, it was unknown how the potholes had actually formed. They were belived to be the work of giants, hence the fanciful names of the large potholes.

STOP 6. Subglacial glaciofluvial depositional formation at Hietavaara

Pertti Sarala

A large sand/gravel quarry is located at Hietavaara, about 20 km from Rovaniemi to SW. It is a part of a cyclic subglacial meltwater system that was discussed and described at the STOP3. At this stop, typical glaciofluvial sediment sections with different materials from sand to boulders can be seen (Fig. 18). It is good to notice that the quarry is under active production and the section conditions are variable.

Fig. 18. Hietavaara sand and gravelly quarry in south-western Rovaniemi. Digital elevation model and air photo © National Land Survey of Finland.

STOP 7. Streamlined subglacial (fluted) surface at Hirvas

Pertti Sarala

Streamlined drumlins and flutings on the northern side of Hirvas indicate fast, ice-tongue like movement over the bedrock dominated ground (Fig. 19). Particularly flutings are seen as shallow formations on the topography, and therefore hard to recognise without a LiDAR-based digital elevation model interpretation. On the northern side of the figure area, the landforms are changing to ribbed moraines and on the southern part to the Kemijoki River valley dominated by fluvial sediments (see the route map in the beginning).

At this stop, several examples of narrow and shallow flutings can be seen. Subglacially formed lineations are oriented almost W-E. The direction of the subglacial lineations and their shape becoming narrower towards the east (crag and tail type formations) which indicate that the ice flow direction across the area was from the west towards the east. On the southern part, larger drumlin type formation occurs being overlayed by some smaller flutings.

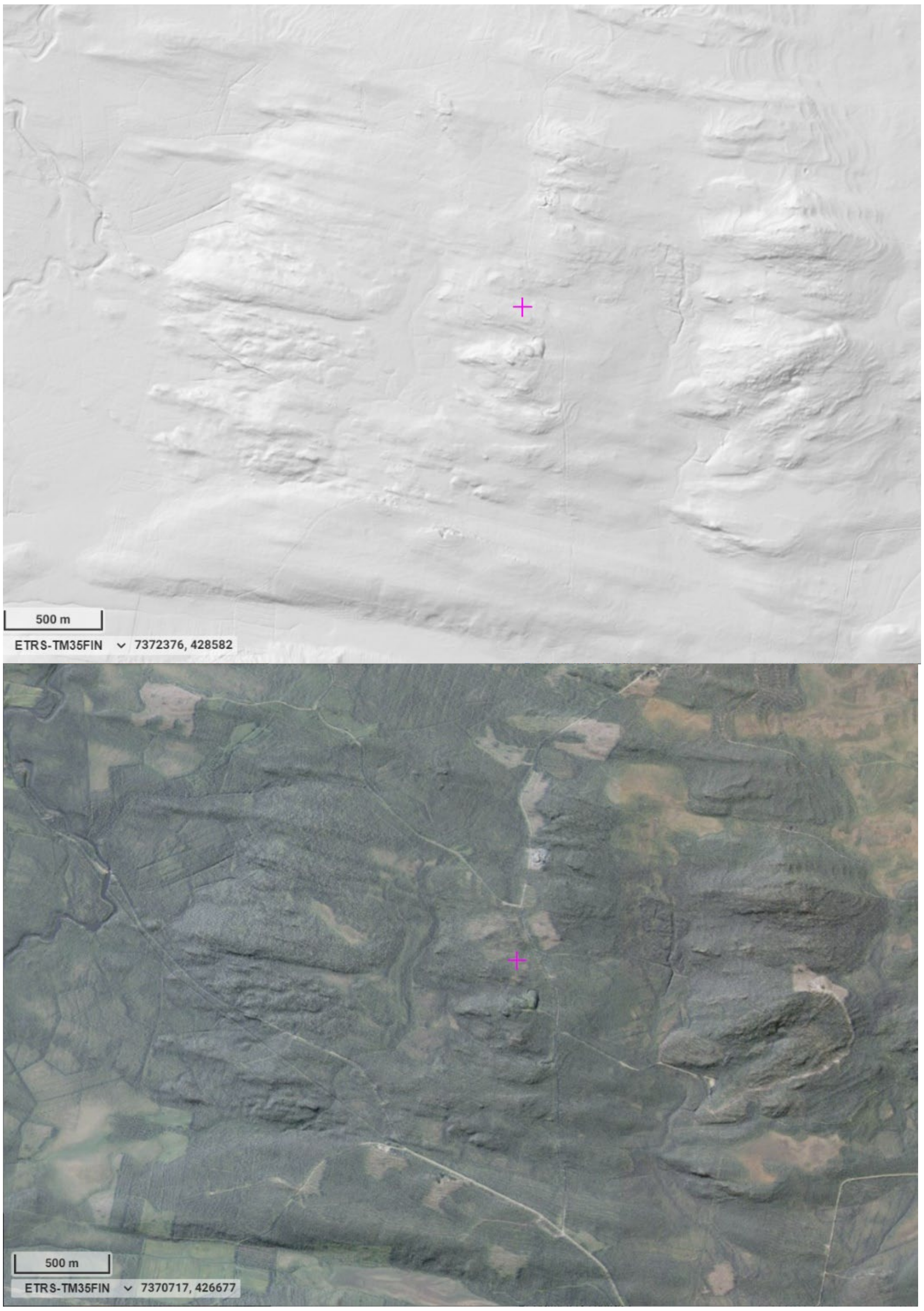

Fig. 19. Fluted surface at northern side of Hirvas in south-western Rovaniemi. LiDAR Digital elevation model and air photo © National Land Survey of Finland.

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