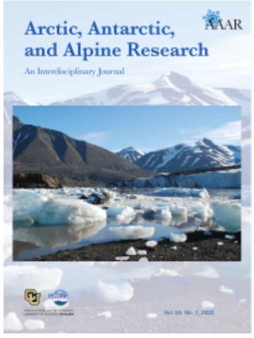

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Introduction: Processes and Palaeo-Environmental Changes in the Arctic from Past to Present (PalaeoArc) special issue

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Introduction: The PalaeoArc network and its predecessors

PalaeoArc (Processes and Palaeo-Environmental Changes in the Arctic: From Past to Present) is an international network research programme, the aim of which is to understand and explain the climatically induced environmental changes in the Arctic that have taken place throughout the Quaternary and continue in the present-day (see http://www.palaeoarc.no/). This network builds on and extends the impressive legacy of previous palaeo-Arctic network programs and projects extending back to the 1980s. This began with the "Polar North Atlantic Margins—Late Cenozoic Evolution" project (PONAM: 1990–1994; Hjort and Persson 1994; Landvik and Salvigsen 1995; Elverhøi et al. 1998), which was followed by the "Quaternary Environment of the Eurasian North" project (QUEEN: 1996–2002; e.g., Larsen, Funder, and Thiede 1999; Thiede et al. 2001, 2004; Kjær et al. 2006). These were then followed by the "Arctic Palaeoclimate and Its Extremes" project (APEX: 2004–2012; Jakobsson et al. 2008, 2010, 2014) and the "Palaeo-Arctic Spatial and Temporal Gateways" project (PAST Gateways: 2012–2018; Ó Cofaigh et al. 2016, 2018).

The latest incarnation of the network—PalaeoArc—was conceived at the final meeting of the PAST Gateways project in Durham, UK, in April 2019, when a new international steering committee was appointed to organize a series of activities and annual conferences for the following six years (2019–2024). The new international network held its first meeting in Poznań (20–24 May 2019), hosted by the Faculty of Geographical and Geological Sciences, Adam Mickiewicz University, Poznań (see Lyså et al. 2019), comprising the usual mix of talks, posters, discussions, workshops, and a field excursion. The network planned to organize a conference hosted by the Department of Earth Sciences at the University of Pisa in May 2020, but this had to be postponed due to the COVID-19 pandemic and was eventually held online in May 2021, endorsed by the International Arctic Science Council, Italian Geological Society, and Italian Association for the Study of the Quaternary. The meeting proved incredibly popular and was "attended" by over 250 Arctic scientists from twenty-six different countries over a four-day period, allowing glacial and marine geologists, palaeoceanographers, palaeoecologists, and specialists in permafrost and numerical modeling to discuss records of Arctic environmental change over decadal to millennial timescales. The collection of articles in this special issue stems from this second PalaeoArc International Conference and encompasses the diverse range of topics presented at the meeting, each of which addresses the overarching aims of PalaeoArc (detailed below). The third international PalaeoArc conference took place (in person) in Rovaniemi in August 2022. The network has been extended for a year, with further meetings planned in Akureyri (2023), Stockholm (2024), and Tromsø (2025).

A changing Arctic and Palaeo-Arctic

On a warming planet, the Arctic stands out for the rapidity of change that is currently occurring due to increased anthropogenic greenhouse gas emissions. Surface air temperatures in this region have increased far more than at lower latitudes (Meredith et al. 2019), with recent work suggesting that Arctic amplification

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may have been almost four times higher than the global average for the period 1979 to 2021 (Rantanen et al. 2022). Future projections indicate that even if global temperature increases are limited to below 2°C by the end of the century, environmental changes in the Arctic will be considerable and long-lasting, with significant loss of sea ice and glacier ice on land, permafrost thaw, and increasing precipitation where a larger fraction falls as rain rather than snow (Arctic Monitoring and Assessment Programme 2017; Allen et al. 2018; Turetsky et al. 2020; Fox-Kemper et al. 2021; Francis, Scambos, and Tedesco 2021; Vavrus and Holland 2021; Scambos and Moon 2022). It is also being increasingly recognized that in order to understand a rapidly changing Arctic and the complex feedbacks that occur there, palaeo records can provide a longer-term perspective and context in addition to new insights into climate states and transitions that are not necessarily captured by more recent observational records.

Past climate variations in Arctic areas, especially those of the Quaternary period, have caused major environmental changes, resulting in significant impacts in marine and terrestrial environments and, in particular, the cryosphere that have led to sea-level changes of several tens of meters. Stratigraphic records and imprints on both land and the sea floor bear witness to the processes and changes that have taken place during this period, often very rapidly. Palaeo records, for example, provide a long-term perspective on the recent decline of Arctic sea ice that was unprecedented in the last 1500 years (Kinnard et al. 2011). Ocean sediment records also attest to rapid iceberg discharge events (Heinrich 1988; Hemming 2004) that have been linked to abrupt changes in temperature recorded in Greenland ice core records (Bond et al. 1993). The growth and decay of the North America and Eurasian Ice Sheet complexes also provide new constraints on the rate and magnitude of both meltwater runoff and sea level rise from ice sheets during a warming climate (Tarasov and Peltier 2005; Tarasov et al. 2012; Gowan et al. 2021; Kirkham et al. 2022), including rapid sea level rise (Gregoire, Payne, and Valdes 2012). Reconstructions of former Arctic ice shelves have also highlighted the sensitivity of marine-based ice sheet margins to abrupt climate change (England et al. 2022; Jennings et al. 2022).

With this in mind, PalaeoArc seeks to strengthen recent advances in a number of key areas by connecting those with expertise from a range of disciplines, including those working in both marine and terrestrial environments, those using numerical modeling, and those using and refining geochronological methods. For example, recent work has seen the compilation of impressive new syntheses of geochronological data to produce refined reconstructions of both the Eurasian (Hughes et al. 2016) and Laurentide-Innuitian Ice Sheet complexes (Dalton et al. 2020) during the last deglaciation that will require updating and testing as new data become available. These empirically derived ice sheet outlines also provide crucial data to both calibrate and test numerical ice sheet models (e.g., Tarasov et al. 2012), and recent efforts have been targeted at developing more robust and quantitative methods to combine geomorphological and geochronological data with ice sheet modeling output (Ely et al. 2021).

Following the landmark paper by Svendsen et al. (2004) that emerged from the QUEEN program, there has been continued interest in reconstrutions of the Eurasian Ice Sheet (Hughes et al. 2016; Sejrup et al. 2022) as well as renewed interest in the evolution of Arctic ice sheets prior to the Last Glacial Maximum, using both empirical evidence (Batchelor et al. 2019; Dalton, Stokes, and Batchelor 2022) and numerical modeling (Gowan et al. 2021). This work has highlighted key uncertainties, such as palaeoenvironmental change in the Arctic and associated sea level changes during the last deglaciation (cf. Brendryen et al. 2020) as well as the stadials and interstadials of Marine Isotope Stage (MIS) 5 (Barlow et al. 2018), which many view as an analogue for the Arctic over the next few centuries. Indeed, the response of the Arctic to earlier and globally strong (warm) interglacials, such as MIS 11 (Past Interglacials Working Group of PAGES 2016), is also required to help inform its response to future warming. Recent work has also focused on the buildup of ice sheets toward the Last Glacial Maximum and their extent during MIS 3 (e.g., Dalton et al. 2016, 2019; Sarala et al. 2016; Pico, Creveling, and Mitrovica 2017; Helmens 2019; Miller and Andrews 2019; Kleman et al. 2021). The penultimate deglaciation and the distribution of circum-Arctic ice sheets during earlier Late Pleistocene glaciations are also subject to large uncertainties (Niessen et al. 2013; Colleoni et al. 2016), including the extent and timing of an Arctic ice shelf (Jakobsson et al. 2016). These are just some examples of themes that PalaeoArc seeks to address, including some of the articles in this special issue.

PalaeoArc themes and overview of articles

There are four major themes to the PalaeoArc programme, each of which are represented by the articles in this special issue:

(1) the dynamics of Arctic ice sheets, ice shelves, and glaciers;

(2) the dynamics of high-latitude oceans and sea ice;
(3) the dynamics of the terrestrial environment and landscape evolution; and
(4) the climatic response to, and interaction between, these different parts of the Arctic system.

The overarching rationale for PalaeoArc is that knowledge of past environmental processes and change in the Arctic are key to understanding the present and future of the Arctic and vice versa. PalaeoArc also strives for inclusivity and aims to bring together and build bridges between scientists from different countries and career stages and from different disciplines in Arctic science, which we hope is exemplified by the diverse authorship of articles in this special issue. This includes marine and terrestrial researchers, working with field data on numerical modeling approaches and from across the Arctic and sub-Arctic (Figure 1).

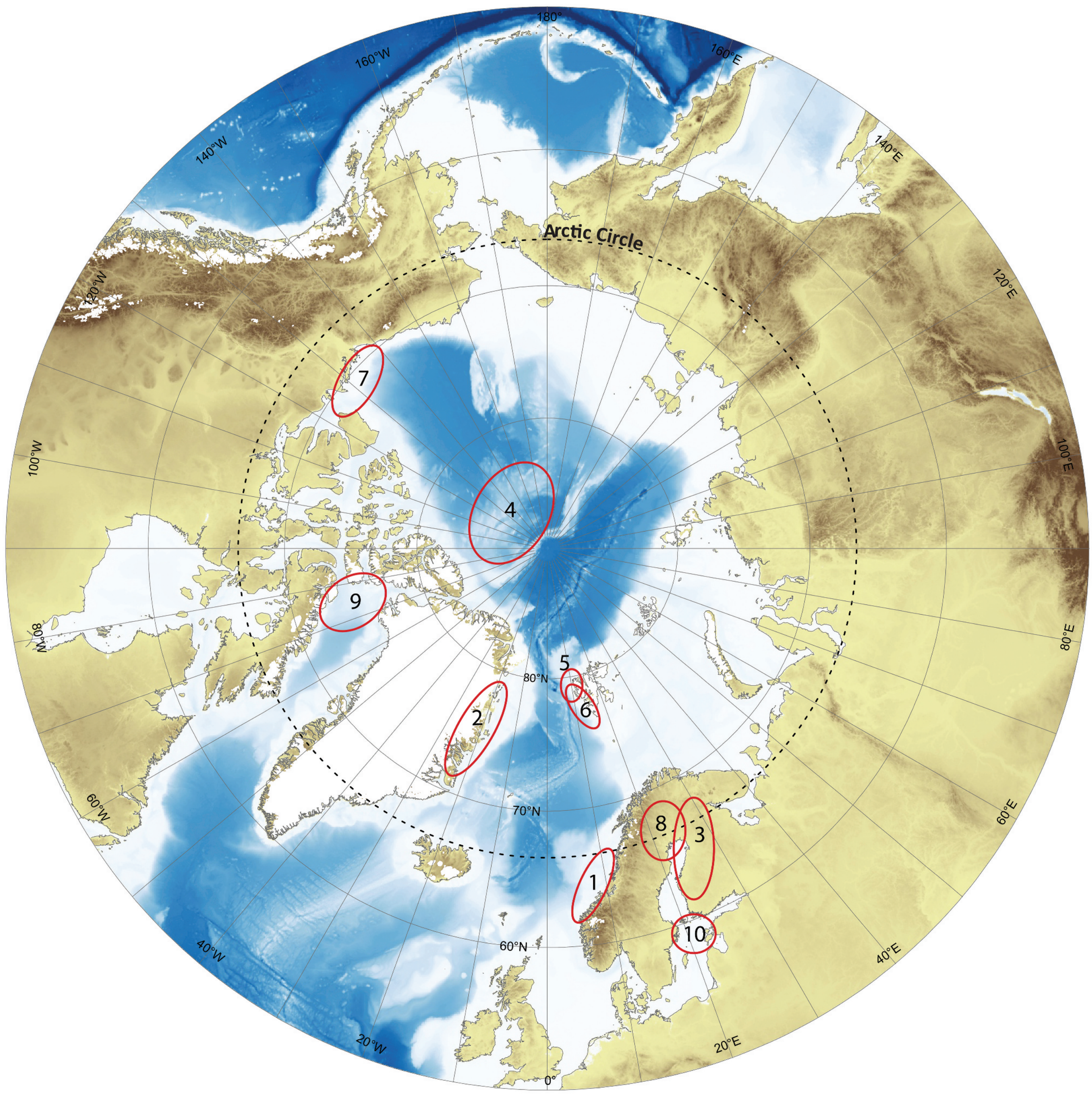

Figure 1. Location of Palaeo-Arctic studies represented in this special issue (red marked areas): Theme 1: The Dynamics of the Arctic Ice Sheets, Ice Shelves, and Glaciers: (1) Ottesen and Dowdeswell 2022; (2) Larsen et al. 2022; (3) Sarala et al. 2022. Theme 2: The Dynamics of High-Latitude Oceans and Sea Ice: (4) Vermassen et al. 2021; (5) Gamboa-Sojo et al. 2022; (6) Torricella et al. 2022; (7) Swärd et al. 2022. Theme 3: The Dynamics of the Terrestrial Environment and Landscape Evolution: (8) Alexanderson et al. 2022. Theme 4: The Climatic Response to, and Interaction between, These Different Parts of the Arctic System: (9) Kelleher et al. 2022; (10) Alatarvas et al. 2022.

The dynamics of the Arctic ice sheets, ice shelves, and glaciers

The dynamics of the former Fennoscandian Ice Sheet on the mid-Norwegian continental shelf is investigated in the article by Ottesen and Dowdeswell (2022). They use high-resolution multibeam bathymetric data to describe the morphology and origin of distinctive iceberg ploughmarks on the upper continental slope. The ploughmarks are distinguished by chains of well-defined and regularly spaced pits. The orientation and morphology of the pits indicate formation under a tidal influence, with each pit coinciding with a low tide and the distance between pits recording the distance of iceberg drift between successive low tides as the icebergs were transported northeastwards along the margin by the Norwegian Atlantic Current. It is inferred that the ploughmarks likely date to retreat of the Norwegian Channel Ice Stream from the outer shelf c. 19,000 years ago, and this article offers a useful template to interpret similar features elsewhere, with important implications for ice stream activity and iceberg drift patterns.

Larsen et al. (2022) also address the theme of Arctic ice sheets in a new study that presents 47 ^{10}Be cosmogenic exposures ages to constrain the timing of deglaciation of the Greenland Ice Sheet (GrIS) from the outer coast to the present glacier margin. Furthermore, these results are combined with previously published data from the region to review the broader ice sheet history since the LGM. It is reported that the shelf edge was glaciated during LGM and that the GrIS remained at the shelf until at least 26 and 20 cal ka. Though the onset of the deglaciation still is uncertain, it is suggested that the GrIS reached the outer coast between 12.8 and 9.7 ka and the present ice extent was reached between 10.8 and 5.8 ka. A further key conclusion is that the ice sheet likely retreated inside its present margin during the Middle Holocene before it readvanced during the Little Ice Age. A combination of increased atmospheric and ocean temperatures is thought to be the driving mechanisms of the deglaciation in North and Northeast Greenland. However, Larsen et al. (2022) suggest that local topography may have been of importance because the deep fjords were deglaciated faster than the shallower fjords and the terrestrial-based areas.

The third article in the special issue that addresses the theme of Arctic ice sheet dynamics is by Sarala et al. (2022), who established a new database of all of the published optically stimulated luminescence age results from different sediment sequences in Finland. The database includes ~180 ages, spanning the past 235,000 years, dating both Saalian and Weichselian sedimentary successions. Exploratory cluster analysis of the database reveals three primary age clusters representing Early and Middle Weichselian ice-free periods (115–70 ka and 55–22 ka, respectively) and the Late Weichselian deglaciation (16–10 ka). This new record highlights a record of pronounced stadial-intertstadial variations, and further demonstrates the prevalence of short ice advance phases and glaciations during much of Weichselian in Finland, with a transition to longer stadials during the final Middle and Late Weichselian periods.

The dynamics of high-latitude oceans and sea ice

The biostratigraphy of mid-Pleistocene high-latitiude ocean sediment records is the focus of the paper by Vermassen et al. (2021). This article provides new insight into the stratigraphic framework of the Arctic Ocean. Litho- and biostratigraphic correlations between Arctic Ocean sediment core AO16-8GC from the Alpha Ridge and the well-dated core LOMROG12-3PC from the Lomonosov Ridge suggest that the planktic foraminiferal species *Turborotalita egelida* may be a marker within MIS 15 or 17. If this biohorizon is supported by further study, then *T. egelida* arrived in the Arctic Ocean during the latest part of the mid-Pleistocene transition rather than within the superinterglacial, MIS 11, with important implications for the response of the Arctic Ocean to the change from 41 ka to 100 ka glacial–interglacial cycles.

High-latitude oceanographic changes are investigated over much more recent and shorter timescales in the article by Gamboa-Soja et al. (2022). Foraminiferal assemblages and stable O and C isotopes in a sediment core from Krossfjorden, western Spitsbergen document the changing environments in the fjord driven by retreat of Lilliehöök glacier toward the fjord head and increasing core temperatures of Atlantic Water in the West Spitsbergen Current. Also, off Spitsbergen, Torricella et al. (2022) provide a multiproxy investigation of a sediment core from the Bellsund Drift spanning the 2,000 years. A study of biological proxies (calcareous nannofossils, diatoms, benthic, and planktic foraminifera assemblages) and lithological data, including X-ray fluorescence spectroscopy and clay mineral analysis by X-ray diffraction, provide new insights into the response of the marine environment to climatic changes associated with changing freshwater influx from melting glaciers on Svalbard and the strength of Atlantic Water carried by the West Spitsbergen Current. Changes in water column stratification and sea ice conditions are related to established warm and cold periods including the Roman warm period, the Dark Ages cold period, the Mediaeval warm period, and the Little Ice Age.

Holocene sediments from the Mackenzie Trough in Arctic Canada are the focus of the article by Swärd et al. (2022). They analyzed the mineralogy (X-ray diffraction) and isotopic (Sr and Nd) compositions of the fine fraction (<38 μm) of sediments from an 81.5-m deglacial-to-Holocene borehole (MTW01) recovered from 45-m water depth in the Mackenzie Trough. The goal was to identify the mineralogical and isotopic signature of Mackenzie River sediments as a basis for documenting past sediment contributions of Mackenzie River discharge to the Arctic Ocean.

The dynamics of the terrestrial environment and landscape evolution

A third theme of PalaeoArc is to examine the dynamics of terrestrial environments and/or the processes in terrestrial environments linked to ice sheet activity. This is the focus of the article by Alexanderson et al. (2022), who tested the age of formation of the Veiki moraine belt of northern Sweden using optically stimulated luminescence and radiocarbon dates. The landscape comprises plateaus formed by downwasting of debris-covered glacier ice near the ice sheet margin leading to formation of ice-walled depressions that subsequently filled with sediment. The landforms were largely preserved during later expansion of cold-based ice. Arguments are laid out that the age data support the assignment of the Veiki moraine formation to MIS 3 (best estimate 56–39 ka), during the Middle Weichselian, providing a significant advance in our understanding of an intermediate-sized ice sheet during MIS 3 conditions in Fennoscandia.

The climatic response to, and interaction between, these different parts of the Arctic system

Recognizing that the ice sheets and ocean and terrestrial environments are often intimately linked in the Arctic, the final theme of the PalaeoArc network address these often complex but nonetheless important linkages across these environments. The article by Kelleher et al. (2022), for example, combines themes 1 and 4. Sediment cores from Lancaster Sound and northwest Baffin Bay, Canada, reveal that the Lancaster Sound Ice Stream retreated into Lancaster Sound by ~15,300 years ago, initiating the massive calving events BBDC 1 and 0 into Baffin Bay, and show that Arctic Ocean freshwater via the Canadian Arctic Archipelago gateways began with Parry Channel opening 10,600 years ago followed 2,200 years later by the opening of Nares Strait.

The final article in the special issue is by Alatarvas et al. (2022), which reports sedimentary facies and clay mineralogy of the late Pleistocene Landsort Deep sediments in the Baltic Sea and explores the implications for the Baltic Ice Lake development. This is a part of the Integrated Ocean Drilling Program Expedition 347 core from the ice-marginal Baltic Ice Lake that is thought to have developed from ~13.5 to 10.5 ka. They used sedimentary facies, grain size, physical properties, water and carbon content, and detrital clay mineral assemblages to derive not only a palaeoenvironmental reconstruction but also the drainage condition of the palaeolake along with its termination.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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