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Preface

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The Mesozoic Arctic: warm, green, and highly diverse

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The Arctic is disproportionately affected by current and forecasted anthropogenic climate change (ACIA, 2005). As a consequence, sensitive ecosystems are suffering from rapid and enduring changes in, for example, sea ice volume, permafrost stability, precipitation, sea surface and air temperatures, and biodiversity (Sommerkorn *et al.*, 2019). Long time perspectives can help us to better understand the response of high northern latitude environments to the consequences of climate forcing in the future. Sediment and bedrock archives can inform us of past conditions of climate, sea level, and fauna and flora that existed and even thrived in Arctic regions despite the long polar night. The Mesozoic Era, in particular, offers a view into the fascinating world of the past, when dinosaurs and diverse forests existed in polar regions during a time typically thought of as a climatic greenhouse. During the Mesozoic, atmospheric CO_2 concentrations were much higher than today, over 1000 ppm (as compared to the pre-industrial average of 280 ppm). Sea-surface temperatures may have exceeded 32°C at 15–20° N, while averaging 26°C at ~53° S (Littler *et al.* 2011). Thus, looking to the past offers the potential for insight into what the planet may look like in the future if greenhouse gas emissions continue unabated.

In this special issue we have collected an eclectic set of papers on Mesozoic sedimentary archives stretching from Ellesmere Island in Canada to eastern Siberia in Russia, and ranging in age from the Early Triassic to the Late Cretaceous. A key proxy record, palynology, takes centre stage, with a number of contributions on pollen, spores and dinoflagellate cysts. Palynology is enormously important for the study of Arctic sedimentary rocks, as these are often carbonate-poor and contain abundant organic matter. Hence, palynomorphs are in many instances the only fossil group present that can be used for dating as well as for palaeoenvironmental reconstructions. Several contributions on macrofossils, including invertebrates, vertebrates and plants, further underpin the generally well-preserved nature of fossils that are a rich source of information on past climate and terrestrial and marine ecosystems. Together with organic and inorganic geochemical proxy records, the wealth of microfossil data presented herein paints a picture of the Arctic as a warm and green place with thriving and diverse marine and terrestrial ecosystems.

Today, the remote Arctic land areas provide excellent exposures of sedimentary rocks, complemented by data from exploration and research drillings in the high-latitude seas, allowing investigations into palaeoclimatic changes during the Earth's past and the responses of the biota. However, Arctic archives are also key ways into understanding palaeogeographic reconstructions and the impact of opening and closure of seaways between polar and lower-latitude waters on palaeoclimate and ocean circulation, as most areas in the high Arctic today were at lower palaeolatitudes during much of Earth history.

Peary Land in North Greenland, one of the most remote stretches of land on the planet today, located at 82° N, is an excellent example of an Arctic area that was further south during the Mesozoic. Lindström *et al.* (2019) report on a palynological study of the Smithian Thermal Maximum from Peary Land. During the Early Triassic this area was part of a shallow marine basin located at 45° N and therefore can inform us about mid-latitude vegetation and climate via the palynomorphs that were washed or blown in from the continent. Supported by rigorous biostratigraphic data provided by ammonites, the authors use carbon isotope records to correlate sections across Greenland and further afield to Tibet and even Australia. The main find of the study is a major shift in vegetation across the Smithian–Spathian boundary that is driven by an increase in conifer tree abundance at the expense of lycophytes. In contrast to previous studies, where an abundance of lycophytes during the Late Smithian has been interpreted as indicating increased humidity, Lindström *et al.* (2019) instead interpret the lack of gymnosperms and proliferation of xerophytic lycophytes as evidence of an extremely arid climate unable to sustain large stands of trees. The increase in gymnosperm vegetation at the Smithian–Spathian boundary is instead interpreted as a shift from periods with extreme droughts towards more regularly occurring wet seasons. The mid-latitude forestation event is accompanied by a large positive excursion in C-isotope records, suggesting that carbon burial increased under high pCO_2. Whereas the carbon isotope excursion occurs synchronously in all sections, the vegetation shift in Greenland takes place later than in the southern hemisphere, congruent with the climate shift.

In the low latitudes, the Triassic was a time of extreme aridity within the interiors of Pangaea (Parrish, 1993), but around the margins of the supercontinent, large fluvial systems were draining at times of increased humidity. Many are familiar with the Carnian humid episode ('Carnian Pluvial Event') that triggered large river systems to drain south into the northern Tethys (Roghi, 2004), but at the northern end of Fennoscandia a vast humid coastal belt developed during the Triassic in what is now the Barents Sea. The study by Paterson and Mangerud (2019) uses palynology to refine the biostratigraphy of the Anisian to Rhaetian portion of this very expanded Triassic deep marine to paralic succession, which they had worked on previously (Paterson and Mangerud, 2015), also linking palynology to the original plant communities. Interestingly, the palynofloras from this region differ markedly from those reported from the Alpine and Germanic realms. The Barents Sea area, including Svalbard, is characterized by relatively continuous sedimentation and thus represents a key area for understanding Triassic climate and ecosystem evolution in the northern Pangaea margin.

Palynological records tell a striking story of a warm, green and diverse Mesozoic polar world. The Early Jurassic Toarcian Oceanic Anoxic Event (T-OAE) is a case in point. Work by van de Schootbrugge *et al.* (2019) on the first detailed dinoflagellate cyst record from two outcrops in Siberia spanning the Toarcian OAE shows rapid diversification of cyst-producing dinoflagellate species during the large carbon cycle perturbation that marks the T-OAE (Suan *et al.*, 2011). Highly diverse assemblages of dinoflagellate cyst species represent phytoplankton communities close to the North Pole during one of the warmest periods of the Mesozoic, as Siberia was located at a palaeolatitude of 85° N. Comparison with records from offshore Norway and the European Epicontinental Seaway (United Kingdom) indicate that the sudden appearance of two major lineages of dinoflagellates (*Parvocysta* and *Phallocysta*) following the T-OAE was not an origination event in Europe but rather a migration event from high to mid-latitudes. This migration event occurred in conjunction with a waning of the euxinia in NW Europe, and could signal the arrival of colder, more oxygenated waters. Perhaps more significant, though, is that these results provide a glimpse of the evolution of phytoplankton in the Arctic during one of the most extreme greenhouse episodes of the past 200 Ma. Could the Arctic have acted as a refuge and seeded other regions after global temperatures declined after the T-OAE?

High phytoplankton diversity and abundance in the mid- to northern high latitudes likely supported diverse communities of invertebrates, fish and large marine vertebrates at the top of the food chain, such as ichthyosaurs and plesiosaurs. Delsett and Alsen (2019) describe a large haul of skeletal remains of these two groups of marine reptiles from the Oxfordian (Late Jurassic) of East Greenland. The newly described material adds to an increasing amount of records from across the Arctic including from Svalbard and Arctic Canada and contradicts the previous notion that ichthyosaurs were in decline during the Late Jurassic.

Long periods of elevated primary production in the high northern latitudes across the J/K boundary are also postulated (Rogov *et al.* 2020). The authors compile and discuss a large body of sedimentary and organic geochemical data on the occurrence of dysoxic to anoxic conditions on the Arctic shelves in Russia and compare those to similar occurrences at low latitudes and even in the southern hemisphere. These so-called Shelf Dysoxic–Anoxic Events (SDAEs) that span the Late Jurassic to Early Cretaceous are only marginally comparable to better-known OAEs as they are of very long duration; in some regions SDAEs lasted for 20 Ma. The exact forcing mechanisms are up for debate: was it widespread changes in hydrography and oceanography, perhaps related to global warming following cooler conditions during the Middle Jurassic, or was it related to profound biotic changes, including the proliferation of newly evolved phytoplankton groups?

One of the major debates regarding the Mesozoic is whether the climate was warm and equable with largely ice-free polar regions (Hallam, 1985), or whether periods of extreme heat were interrupted by brief episodes of cold or even glacial conditions, so-called 'cold snaps' (Herrle *et al.* 2015; Grasby *et al.* 2017). A series of cold events, based mostly on sedimentological evidence, is now proposed for the Early Jurassic (Ruebsam *et al.* 2019), Late Jurassic (Rogov and Zakharov, 2010) and the Early Cretaceous (Alley *et al.* 2019). However, most palaeotemperature proxy data, including new crenarchaeota lipid data (O'Brien *et al.* 2017), as well as clumped isotope data (Vickers *et al.* 2019), do not support very cold high-latitude conditions that would allow for the formation of ice caps. This debate can only be resolved by adding more high-resolution multi-proxy data from high-latitude archives. Galloway *et al.* (2019) present detailed C-isotope records integrated with ammonite biostratigraphy from Axel Heiberg Island, in the high Canadian Arctic. They improve the chronostratigraphy for the uppermost Jurassic and lowermost Cretaceous interval, a problematic time interval in need of chronological refinement. Their new carbon isotope record that spans the Jurassic–Cretaceous transition documents a large negative excursion in the middle Volgian Stage, followed by a return to less negative values and a small positive excursion in the Valanginian related to the Weissert Event. While the carbon isotope trends are consistent with other high-latitude records, the large negative excursion is absent from Tithonian carbonate strata deposited in the Tethys. This raises several questions: did Arctic seawater compositionally evolve away from open marine $\delta^{13}C$ values during the Volgian due to low global or regional sea level? While a geologically sudden increase in volcanism may be responsible, a lack of precise chronological control globally for the Jurassic–Cretaceous boundary interval precludes direct comparison with potentially coincident events.

Based on an extensive compilation of published data augmented with new analyses from more than 100 outcrops and cores, Nøhr-Hansen *et al.* (2019) present a state-of-the-art biostratigraphic framework for the entire Cretaceous of Greenland based on dinoflagellate cysts and accessory pollen and spores. This new palynozonation recognizes 15 palynozones that have been calibrated with a regional ammonite zonation and can be correlated to nearby zonations from the Barents Sea, the Norwegian Sea and the North Sea. Overall, more than 100 palynostratigraphic events have been recognized that will be of great importance for correlations of Cretaceous sedimentary successions in northern high latitudes with successions around the world.

Palynostratigraphy is also the central theme of the contribution by Śliwińska *et al.* (2020) who provide a detailed dinoflagellate cyst stratigraphy for several Cretaceous formations on Svalbard. Śliwińska *et al.* (2020) interpret a Valanginian to Hauterivian age for the Rurikfjellet Formation and a Hauterivian to Aptian age for the overlying Helvetiafjellet Formation using several cores and outcrop sections from central and eastern Spitsbergen. These two formations are important archives for understanding Early Cretaceous climate evolution. Interestingly, both the Valanginian Weissert Event and the Early Aptian OAE1a on Svalbard occur within major transgressive sequences that appear similar to sea level changes in low latitudes. Such correlations will be crucial for testing the driving mechanisms behind global eustasy during the Cretaceous, whether through ice or increases in mid-ocean ridge volumes.

Biostratigraphy of Early Cretaceous successions on Svalbard is very much dependent on well-preserved microfossils, because most Arctic successions suffer from a general lack of macrofossils, apart from some special cases, for example where methane seeps are concerned (Hryniewicz *et al.* 2015). Alsen *et al.* (2019) present a new species of belemnite *Arctoteuthis bluethgeni*, which appears to be endemic to Svalbard and could serve as a useful macrofossil marker species for Valanginian–Hauterivian Cretaceous sediments in the Barents Sea region.

Macrofloral remains from NE Russia and northern Alaska provide evidence of a generally warm Arctic during the Late Cretaceous. By using leaf form and tree ring data, Spicer *et al.* (2019) demonstrate a thermal regime at latitudes as high as ~80° N characterized as temperate, with only limited periods of freezing temperatures. The data indicate that most of the studied sites experienced summer precipitation around 0.5 m, and that neither drought nor cold periods were long enough to limit growth or freeze the soil below tree rooting depth, respectively. This study has implications for future Arctic climate warming. Whereas the Arctic today is a place where precipitation is sparse under a cold strong polar high-pressure system, global warming will likely lead to an invigorated hydrological cycle when warming-induced evaporation and enhanced transpiration from an increased and more complex vegetation weaken the polar high.

The collection of papers presented here demonstrates the importance of Arctic geology and tells a tale of what the future may hold. The papers provide evidence of the importance of terrestrial vegetation for major carbon cycle fluctuations, for connectivity between the polar and more southerly oceans, and of the Arctic as a refuge for biota during global warming events.

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