Circum-Arctic lithosphere evolution

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Abstract: This book is the final product of the Circum-Arctic Lithosphere Evolution (CALE) project. The project’s ultimate goal is to link the onshore and offshore geology in order to develop a self-consistent set of constraints for the opening of the Amerasia Basin. The circum-Arctic is divided into seven regions, each with its own research team; the teams included geophysicists and geologists working together to integrate geological and geophysical data, from onshore to offshore. This work is summarized in the 18 papers contained in this volume.

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The Arctic Ocean can be divided into two primary basins with distinct ages and physiographies. The Eurasia Basin (Fig. 1), north of the Barents Shelf, was formed in the Cenozoic by the propagation of seafloor spreading across the Barents Shelf. The remainder of the deep Arctic Ocean is the Amerasia Basin (Fig. 1). Indirect evidence, largely from the continents surrounding this basin, suggests that it formed during the Mesozoic Era.

Plate boundaries form continuous networks that span the globe, linking zones of crustal creation and destruction, driving plate motion across the Earth’s surface. The propagation of the Mid-Atlantic Ridge into the Arctic Ocean separated the Lomonosov Ridge (Fig. 1) from the Barents Shelf. We can connect the Cenozoic history of the Eurasia Basin to the global network of plate boundaries through the Gakkel Ridge (Fig. 1). This is not possible for the Amerasia Basin, where a single plausible plate boundary has been identified. This mid-ocean ridge, which bisects the Canada Basin (Fig. 1), must link to other contemporary plate boundaries, but no connecting plate boundary has been identified. Without direct evidence, we remain reliant on the margins of the Canada Basin to infer the events that created it.

The Arctic Ocean basins (Fig. 1) have been relatively inaccessible to direct sampling and the techniques used elsewhere in the world’s oceans due to drifting sea ice. To a great extent, the Arctic Ocean is known mostly from geophysical methods. For example, the Amerasia Basin at c. 3800 m below sea-level was until recently virtually unexplored. Its age and history have been inferred from structural and stratigraphic relationships observed on the basin margins. These inferences are unconfirmed by observations within the basin. Onshore, the Arctic region is a remote wilderness far from supporting infrastructure. As a consequence, it has been mapped mostly at a reconnaissance scale. Without age controls on the stratigraphic units, structural fabrics and the history of deformation, it is difficult to correlate the geology from one region to another, to extrapolate onshore to offshore, and to constrain the development of Arctic Ocean basins using continental circum-Arctic geological data.

Constraints on the tectonic evolution of Arctic lithosphere are necessary to complete our understanding of global tectonics and to understand the framework of the known and estimated oil and mineral resources of the Arctic, the Earth’s climate system, the distribution of flora, fauna and, ultimately, the migration of humans. The morphology and sediment thickness of the Arctic continental shelves and slopes are directly relevant for claims to define the seaward limit of territories of the circum-Arctic states under Article 76 of the United Nations Law of the Sea (UNCLOS; MacNab 2006). Under UNCLOS, nations conducted extensive marine seismic reflection and refraction, gravity anomaly and bathymetric surveys to document their claims. These new data acquired by the Arctic Coastal States have illuminated poorly known parts of the Arctic Ocean.

This Special Publication is the final product of a five-year research programme on Circum-Arctic Lithosphere Evolution (CALE). The CALE project, supported by industry and academia, involved more than 30 scientists from 10 different countries. The project’s ultimate goal was to link the onshore and offshore geology to develop a self-consistent set of constraints for the opening of the Amerasia Basin. Teams of geophysicists and geologists worked together to integrate geological and geophysical data, from onshore to offshore, in each region (Fig. 2).
We anticipated being able to synthesize both within and across these sectors to establish inter-regional linkages to constrain the opening of the Amerasia Basin. In retrospect, this was an ambitious aim given the heterogeneity in the types and distribution of data across the Arctic region. When the CALE project ended in 2015, some geographical regions, such as the Barents/Kara shelf regions,
were incredibly well studied and had access to a wealth of new geophysical and geological data that allowed the development of sophisticated three-dimensional, lithospheric-scale models. At the other end of the spectrum – for example, across the Siberian shelf area – there was much new data from Russian UNCLOS efforts, but it remains proprietary and unavailable to the general scientific community. Consequently, some of the CALE sectors lack adequate data to develop the regional transect as initially envisaged. These gaps continue to hinder our full understanding of the Arctic region and, ultimately, our ability to apply constraints to the tectonic evolution of the Amerasia Basin. Nevertheless, significant advances have been made during the CALE project.

This Special Publication summarizes our current understanding of the tectonic development of the Arctic region, sector by sector, through the integration of geological and geophysical data. The volume consists of 17 papers organized geographically into five sections (locations shown in Fig. 1). The first four sections are based on the CALE regional sectors (Fig. 2; Sector A, Greenland and Canada; Sector B, Alaska and Chukotka; Sector C, Laptev Sea region; and Sectors E, F and G, Barents/Kara shelf region). The first paper in each section presents the regional integrated onshore–offshore lithospheric-scale transect. Subsequent papers in each section represent contributions that address the science behind the synthesis and interpretation(s) associated with each transect. The fifth and final section addresses pan-Arctic theme(s) that are relevant to all the CALE regions. Areas of future research beneficial to resolving the Amerasia Basin conundrum are highlighted throughout the book.

**Greenland–Canada**

This section begins with a 400 km long crustal seismic velocity model across Ellesmere Island in Arctic Canada (Stephenson et al. 2017), which builds strongly on the new maps of Moho depth, depth to basement and crystalline crustal thickness of Ellesmere Island in Schiffer & Stephenson (2017) and

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**Fig. 2.** An Eocene (c. 55 Ma) Arctic reconstruction (after Pease 2011). The Eurasia Basin has not yet opened and Svalbard restores adjacent to north Greenland. The white transparent regions represent the seven regional teams of CALE. Tectonic elements of the circum-Arctic region shown. OCVB, Ohotsk–Chukotka Volcano-Plutonic Belt; OM, Omolon Massif; SAS, South Suture.
the structural synthesis presented by Piepjohn & von Gosen (2017). Piepjohn & von Gosen (2017) present the first structural cross-section of the North American continental margin and confirm the superposition of Cenozoic deformation on Palaeozoic structures.

Alaska and Chukotka

The paper by Miller et al. (2017b) leads this section with an impressive synthesis of recently published seismic reflection data and interpretations, integrated with regional geological constraints, and presents a new crustal transect (>5000 km long) stretching from the Lomonosov Ridge to the Aleutian Islands. The authors are able to define the crustal identity, limits and history of the Arctic Alaska–Chukotka microplate and, together with regional geological constraints, provide a tectonic framework to aid in establishing its pre-Cretaceous restoration. This work, in part, builds on the other papers presented here. In Holland et al. (2017), detrital zircon isotopic data are used to place constraints on the Neoproterozoic to Cretaceous evolution of Arctic Alaska (a significant component of the Arctic Alaska–Chukotka microplate). Their data suggest that Arctic Alaska was only proximal to Laurentia after the early Devonian. Pease et al. (2017) present new geochronology from eastern Chukotka, which suggests that palaeo-Pacific plate subduction was initiated by at least 120 Ma. Gottlieb et al. (2017) present new data from Neoproterozoic basement rocks of Wrangel Island and the Velitkenay massif; the Wrangel data are consistent with a Grenville–Sveconorwegian provenance for pre-700 Ma strata and allow correlation with Arctic Alaska and Pearya. The final paper in this section is on the deformational history of Wrangel Island; Miller et al. (2017a) combine deformational fabrics and thermochronology to assess the exhumation and uplift of the island. These authors conclude that the island was at low temperatures (<110°C) at c. 95 Ma due to north–south extension.

Laptev Sea region

Piepjohn et al. (2017) start this section and present new evidence for dextral transpression along north–south-trending faults in the New Siberian Islands, which they correlate with the Laptev Sea segment of the Amerasia Basin Transform Fault in pre-Aptian–Albian times. Drachev & Shkarubo (2017) follow with interpretations of new long-offset seismic profiles to unravel the structural and seismic stratigraphic characteristics of the Laptev Rift System. They recognize four tectonic phases in the development of the Laptev Rift, initiating with an early rifting or stretching phase accompanied by brittle normal faulting in Late Cretaceous(?)–Paleocene(?) time. This pair of papers seems to verify older models for the rotational opening of the Amerasia Basin.

Barents/Kara shelf region

As a result of extensive and successful oil exploration in this region, this is perhaps the best known sector of the Arctic Ocean. The papers included in this section add unique data to the publically available exploration information, developing a more continuous representation of the structure and more complete history of the region. Faleide et al. (2017) use ‘all available’ deep seismic reflection and refraction data, aided by an existing three-dimensional model of the region, to construct a series of profiles that extends through the crust and lithosphere. These profiles are then used to constrain the near-surface geology with respect to the tectonic and basin history. Zhang et al. (2017a) relies on apatite fission tracks to constrain the thermal history of the Taimyr fold belt. With these data, they identify three phases of cooling in the Permian and Triassic. They integrate this history with the construction of two balanced cross-sections of the region. Zhang et al. (2017b) combine U–Pb detrital zircon geochronology with apatite fission track data from Precambrian to late Permian sediments to fingerprint the sediment sources and constrain the thermal exhumation history of Novaya Zemlya. They identify the Fennoscandian shield as a source area of detritus shed during Caledonian orogenesis. The apatite fission track data identify a rapid cooling event, which the authors’ associate with the late Triassic deformation of Novaya Zemlya. This timing agrees well with the work of Curtis et al. (2017), who document oblique, inclined sinistral transpression of late Triassic age associated with the western Main Pai-Khoi Thrust. The Main Pai-Khoi Thrust links the Polar Urals and southern Novaya Zemlya; consequently, this margin experienced deformation between the late Permian (continental collision in the Polar Urals) and the late Triassic (deformation in Novaya Zemlya).

Minakov et al. (2017) study the history of dyke emplacement within the Early Cretaceous large igneous province of the Northern Barents Sea. Using magnetic anomalies, multi-channel seismic reflection and seismic refraction data, they recognize offshore zones of concentrated dyke and sill intrusion that they link to similar magmatism onshore. They then interpret these intrusions in relation to the regional palaeo-stresses. The final paper in this section is a study of unique samples dredged from the central Lomonosov Ridge by Knudsen et al.
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(2017) Using $^{40}$Ar/$^{39}$Ar dating of metamorphic mica data, these workers conclude that thermal resetting of muscovite occurred in the mid-Ordovician. They correlate this with similar-aged accretionary events recognized in northern Ellesmere Island, Svalbard and other parts of the Caledonides.

Circum-Arctic themes

Using waveform tomography from large datasets, Lebedev et al. (2017) develop a tomographic model of the upper mantle in the Arctic region with improved resolution. They have some provocative results, which suggest that the mantle root beneath northern Greenland may extend as far west as central Ellesmere Island and that warmer and thinner lithosphere in the Arctic is associated with lithospheric erosion resulting from large igneous province magmatism. Schiffer et al. (2017) combine crustal structure and depth to the lithosphere–asthenosphere boundary to calculate geopotential energy and then determine the corresponding geopotential stress field for the Arctic region. After defining confidence criteria, the authors recognize three regions where the present day and palaeostress fields coincide. They are able to use this information to infer minimum ages for lithospheric stress in north Greenland (Cretaceous), western Siberia (Triassic) and the east Siberian shelf (Cenozoic).

Concluding remarks

The papers in this Special Publication are the state-of-the-art in our knowledge of circum-Arctic tectonics and lithospheric evolution. This book is relevant to geologists and geophysicists interested in tectonics, the Arctic and resource analysis, from both an academic and an industry point of view, and is anticipated to be a data resource as well as providing the foundation for the next generation of research investigations in the Arctic region.

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