Tectonophysics 880 (2024) 230317

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

Invited Research Article

The remarkable parallels between the North East Atlantic and Arctic regions

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ARTICLE INFO

Keywords:
Northeast Atlantic
Arctic
Iceland
Continental crust
Oceanic crust
Hybrid crust
SDRs
Passive margins
LIPs
Microcontinents

ABSTRACT

Geological understanding of the NE Atlantic and Arctic regions has increased greatly over the last two decades, revealing remarkable similarities. Continental extension in both regions onset during pausing or cessation of adjacent orogenies – the Verkhoyansk-Chukotka and Alpine orogenies – which relaxed compressional stresses and permitted extension. Severe extension accompanied by high-volume magmatism did not onset abruptly but was the culmination of long-term, regional tectonic and magmatic unrest. It was complex and piecemeal, with extension and volcanism occurring along multiple axes simultaneously, a process still ongoing in Iceland today. Large Igneous Province emplacement did not drive breakup but occurred as a consequence of continental extension. The High Arctic Large Igneous Province did not progress to breakup. As a result, much of the Arctic Ocean is floored by hyper-extended continental crust overlain by seaward-dipping reflectors. This crust resembles the passive margins of the NE Atlantic. The Alpha-Mendeleev Rise in the Arctic Ocean is a double-sided passive margin underlain by hyper-extended continental crust draped with seaward-dipping reflectors. A similar structure has been proposed for the Greenland-Iceland-Faroe Ridge. If correct, present-day volcanism in Iceland is building SDRs today. Up to ~50% of the NE Atlantic Ocean oceanward of the continental shelves is likely underlain by at least some continental crust. For the Arctic Ocean this figure is ~80%. Similar structures are found elsewhere, including the Madagascar Channel, the NW Indian Ocean, and the South Atlantic. These new ideas suggest promising directions of future study including assessing the true extent of continental crust in the oceans globally.

1. Introduction

The NE Atlantic and Arctic Oceans together comprise a ~ 6000-km-long region that represents the latest phase of Pangea breakup. It formed North America, Greenland, Scandinavia and Russia (Fig. 1). Over the last two decades of study of these complex regions major advances have been made which are significantly influencing preferred working hypotheses. The research approach in the two regions has been different because the climate becomes progressively more hostile farther north, but despite this, ideas concerning structure and processes are converging.

Recently, sufficient information has accrued for new models to be developed for the structure, tectonics and magmatism of these adjacent oceanic regions. This has raised first order questions and inspired new ideas concerning how oceans form. Many things remain to be clarified, however, in particular the extent of both continental- and hybrid/transitional crust in the oceans.

In the present paper, we briefly describe the two oceans, compare and contrast them, and discuss wider implications. We highlight the many similarities, and discuss these in the context of recent new models that propose a larger role for continental crust in the oceans than has hitherto been generally assumed. We highlight analogous parts of Earth's oceans and remaining unknowns that can point the way to future potentially fruitful research goals.

2. Geological overview

The NE Atlantic region lies between the Charlie-Gibbs Fracture Zone in the south and the Fram Strait in the north, and between Newfoundland, Labrador and Baffin Island west of Greenland and Scandinavia in the east (Fig. 1). The ocean is bordered by extensive regions of submerged continental shelf including the ~1000-km-broad North Sea/

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https://doi.org/10.1016/j.tecto.2024.230317
Received 28 August 2023; Received in revised form 9 April 2024; Accepted 11 April 2024
Available online 18 April 2024

British Isles plateau, the Rockall-Hatton plateau, and the ~500-km-wide Vøring Plateau. To the south it is open to the Central Atlantic Ocean, and to the north it connects with the Arctic Ocean.

The Arctic region comprises the ocean itself and surrounding continental margins. It includes the Beaufort, East Siberian, Chukchi, Kara, and Barents Seas and Arctic Greenland, Canada, Alaska, Russia and Scandinavia (Fig. 1). The continental shelves are broad (up to ~1500 km) along the coasts of northern Russia and NW Norway but narrower (up to ~150 km) along the north coasts of Canada and Greenland. In addition to connecting with the NE Atlantic Ocean *via* the Fram Strait, the Arctic Ocean is open to the Pacific Ocean *via* the Barents Strait between Alaska and Russia.

Development of the oceanic region began in the Early Cretaceous with opening of the Canada Basin, the most easterly unit in the Arctic Ocean (Table 1, Fig. 2). Following this, polyphase continental rifting formed the majority of the Amerasian Basin (see Nikishin et al., 2021a for a review). Away from the Canada Basin, extension is not thought to have matured to full seafloor spreading and oceanic crust formation (Nikishin et al., 2021a). Instead, when ocean opening became established in the NE Atlantic in the Late Paleocene and Early Eocene (*e.g.*, Gernigon et al., 2003), seafloor spreading in the Arctic Ocean onset along the Gakkel Ridge, forming the Eurasian Basin (Michael et al., 2003). Today, the mid-ocean ridge extending through the NE Atlantic Ocean, including the Reykjanes, Kolbeinsey, Mohns and Knipovitch

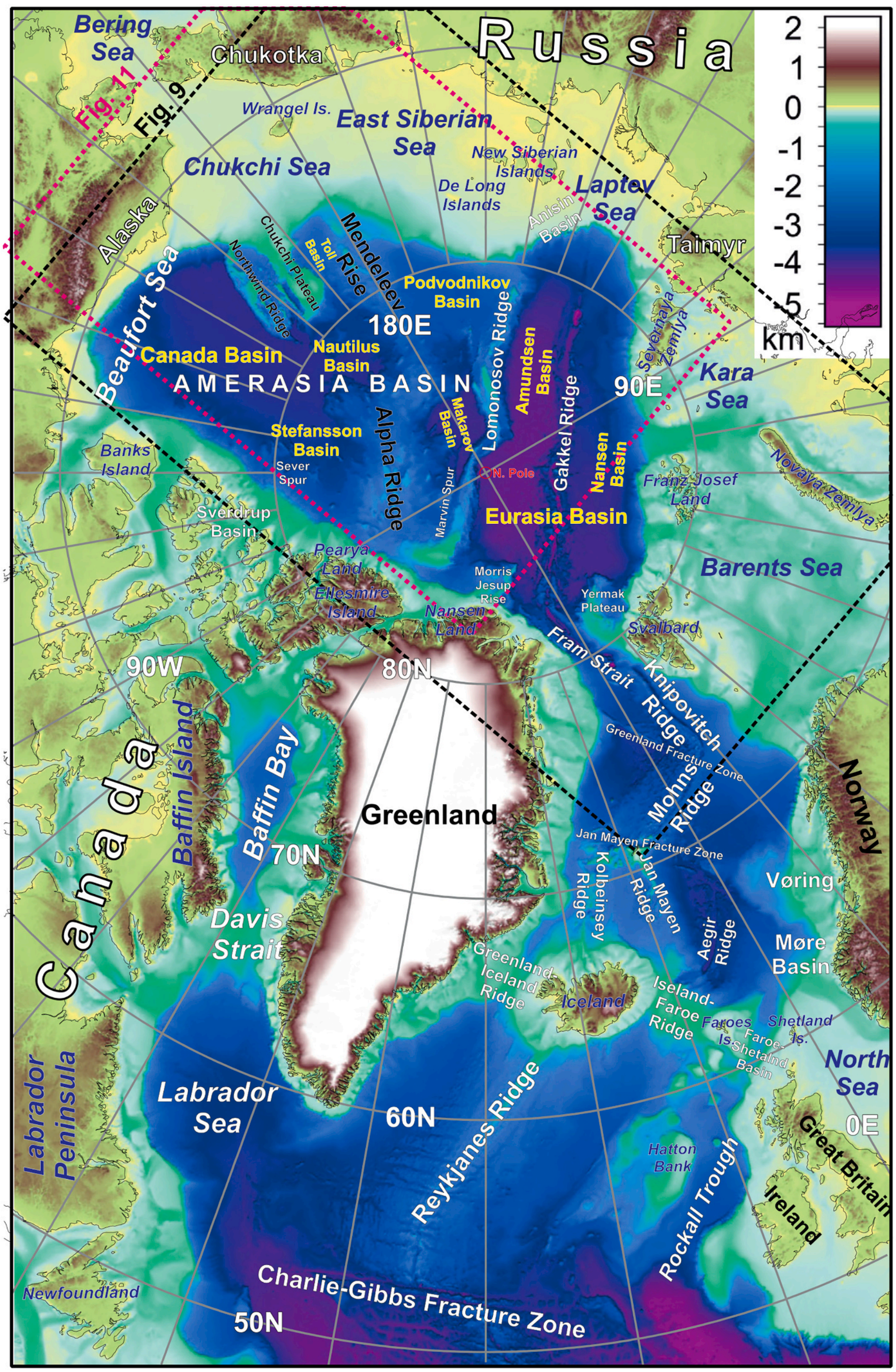

Fig. 1. Geographic map of the NE Atlantic-Arctic region showing features and place-names mentioned in the text. Topography and bathymetry are after Jakobsson et al. (2020).

Table 1
Chronology of major tectonic events in the NE Atlantic and Arctic regions. See text for references and sources.

Date (Ma)	Magnetic chron	NE Atlantic	Arctic Ocean
133–125		Polyphase continental rifting	Canada Basin opens as a back-arc basin
125–100		Polyphase continental rifting	End of Verkhoyansk-Chukotka orogenic collision, start of collapse and rift-valley formation; HALIP Stage 1–formation of tholeiite trap plateaus; HALIP Stage 2–Alpha-Mendeleev rise formation accompanied by synrift & postrift tholeiitic & alkali SDR emplacement; *syn*-extension granitoid magmatism & volcanism
100–80		N-propagating mid-Atlantic Ridge reaches latitude of future Charlie-Gibbs FZ (86.3–83.6 Ma); Rockall Trough forms	HALIP Stage 3–formation of large Fedotov-type volcanoes in Alpha-Mendeleev region
80–66		Continental rifting in Baffin Bay	Sever Spur intraplate rifting – extension that did not mature to full continental breakup
66–58		Mid-Atlantic Ridge propagated W of Greenland (~63 Ma); magma-poor margins of Labrador Sea formed; continuation of continental rifting in Baffin Bay	Start of continental rifting between Lomonosov Ridge and Barents Shelf; volcanism in N Greenland and possibly Laptev Sea tip of future Gakkel Ridge
58–52	C24–22	Beginning of opening of Labrador Sea/Baffin Bay; first magnetic anomaly on proto-Reykjanes Ridge	Start of slow spreading on Gakkel Ridge; start of Eurekan orogeny in N Greenland
54–45	C24r-21	Spreading propagated from Greenland fracture zone S to Jan Mayen FZ; beginning of opening of NE Atlantic Ocean on Aegir Ridge & its propagation south over ~2 Myr; onset of fan-shaped spreading on Aegir Ridge balanced by extension in south JMMC; rift-to-drift transition on Faroe-Shetland and Hatton margins; no major change south of GIFR; 30–40° clockwise rotation of direction of plate motion	Slowing to ultra-slow spreading along Gakkel Ridge (~45 Ma); start of intraplate transtension and transpression
40	C18	Counter-clockwise rotation of direction of plate motion	Transtension on Alpha-Mendeleev Rise and transpression on Barents-Kara shelves
38–36	C17–13	Reykjanes Ridge becomes stair-step; pulse of elevated magmatism propagates from Iceland south along Reykjanes Ridge forming first chevron ridge of thickened oceanic crust; cessation of spreading in Labrador Sea.	
34			End of Eurekan orogeny; further slowing of spreading on Gakkel Ridge to ultra-ultra-slow
33–28	C12–10	Counter-clockwise rotation of direction of plate motion; extinction of ultra-slow Aegir Ridge; second chevron ridge begins to form about Reykjanes Ridge	Alpha-Mendeleev Rise subsidence; rifting between NE Atlantic and Eurasia basins
24	C6–7	First unambiguous magnetic anomaly about Kolbeinsey Ridge.	
20–0		Development of current tectonic conditions; Thulean land bridge breaches; multiple rift jumps in Iceland, several of which coincide with onset of chevron ridge propagators on Reykjanes Ridge which return it to its original oblique-spreading state	Connection of NE Atlantic and Eurasia Basins; stable tectonics in Eurasian Basin up to the present day; local intraplate volcanism

Ridges, connects with the Gakkel Ridge *via* the Fram Strait and is considered a continuous plate boundary (see Foulger et al., 2020a for a review).

Both oceans contain major Large Igneous Provinces (LIPs) – the North Atlantic Igneous Province (NAIP) (see Wilkinson et al., 2017 for a review) and the High Arctic Large Igneous Province (HALIP; Fig. 3) (see Dockman et al., 2018 for a review). Both LIPs were associated with phases of extreme extension of the continental lithosphere. In the NE Atlantic Ocean NAIP magmas include widespread, distributed, small-volume igneous rocks, extensive flows, and thick sequences of seaward-dipping reflectors (SDRs) (*e.g.*, Peace et al., 2020). If current magmatism in Iceland is included, then NAIP construction is still ongoing. In the Arctic, HALIP magmas comprise a similar suite but ceased to form considerably before extension onset on the Gakkel Ridge, forming the Eurasian Basin (Nikishin et al., 2021a).

Both oceans contain regions of continental crust and oceanic crust, and also areas floored by stretched, magma-inflated continental crust – so-called "hybrid" or "transitional" crust (*e.g.*, Geoffroy et al., 2022a) (Fig. 4). Much, if not all, of the Amerasian Basin appears to be floored by this kind of crust and it may also comprise parts of the Eurasian Basin (Nikishin et al., 2021a). We suggest that this type of crust also characterizes the Greenlandic and Norwegian borders of the NE Atlantic Ocean, and the shallow bathymetric ridge that comprises the Greenland-Iceland-Faroe Ridge (the GIFR). Ambiguities in the interpretation of seismic and density data make characterization of this type of crust challenging and its true extent is currently a matter of intense scrutiny.

3. Data and methodology

Extensive databases exist for both the NE Atlantic and the Arctic Ocean. In this section we briefly review existing data, results and published material.

The NE Atlantic has been extensively researched for many decades. It borders on Europe and Scandinavia, is valuable for hydrocarbons and fishing, and the unique geological environment of Iceland is of great scientific interest. The last two decades in particular have witnessed a surge in the data available which has radically advanced understanding of previously enigmatic features.

Much marine research has focused on the shallow continental shelves. There, extensive seismic reflection data have been acquired, supplemented by gravity, magnetic and electrical survey data and samples from drilling. This work has been extended, in some areas, into the deep ocean. For example, a recent, high-resolution magnetic survey

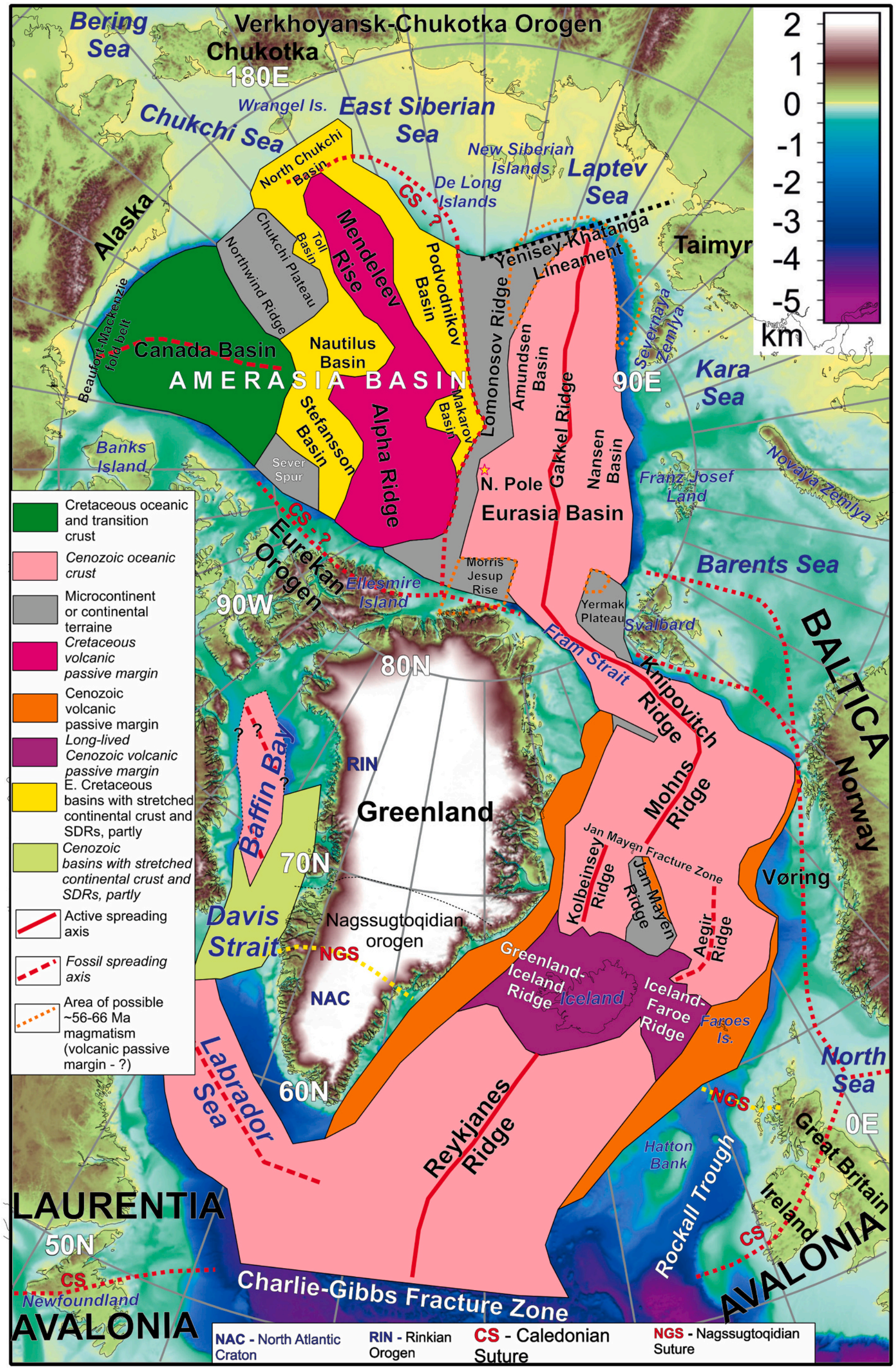

Fig. 2. Same area as shown in Fig. 1 but showing tectonics. Arctic region features are mainly after Nikishin et al. (2024), Nikishin et al. (2021a), Nikishin et al. (2021b), Nikishin et al. (2021c) and references within. Paleocene (66–56 Ma) magmatic province on the Morris Jesup Rise and Yermak Plateau is after Kristoffersen et al. (2021) and Brotzer et al. (2022). Data for Atlantic region from published literature (*e.g.*, Gernigon et al., 2020).

of the Norway Basin (Gernigon et al., 2012) has revealed in detail the history of development of this unusual, ocean-crust-floored basin.

The existence of the large landmass of Iceland has enabled detailed, land-based geological and geophysical work there also. Numerous seismic lines have been measured, including land-sea profiles up to ~350 km long (*e.g.*, Angenheister et al., 1980; Menke et al., 1996). Excellent gravity and magnetic datasets exist for the island and geological mapping and sampling, geochemical work and age-dating have revealed the tectonic and volcanic history in detail (*e.g.*, Sigmundsson et al., 2020). Seismic lines have also been shot along the bathymetrically shallow Greenland-Iceland and Iceland-Faroe ridges (*e.g.*, Bott and Gunnarsson, 1980; Staples et al., 1997; Yuan et al., 2020) (see Foulger et al., 2003 for a review).

Data from Iceland and the marine parts of the NE Atlantic Ocean are supplemented by detailed geological knowledge of Scandinavia and Britain. Geological mapping and sampling of the ice-free coastal regions of Greenland has also been conducted for many years, though less is known about this continent because of the difficulty of access, limited ice-free areas, and the short summer field seasons. The NE Atlantic is thus well-illuminated by extensive research work deploying diverse marine- and land-based methods in all branches of Earth science.

The situation in the Arctic Ocean is somewhat different. There,

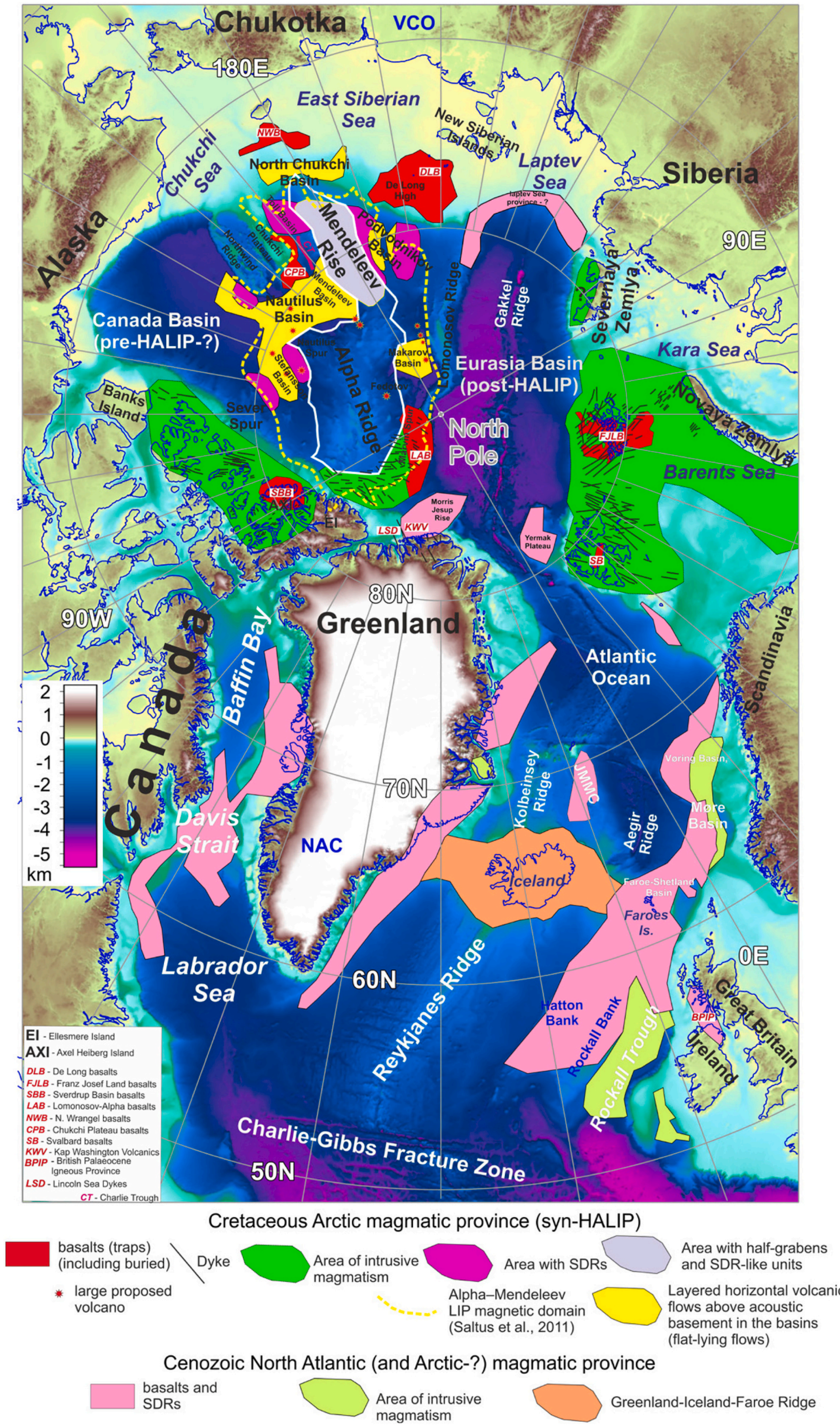

Fig. 3. Same area as shown in Fig. 1 but showing igneous features. NAC: North American Craton; VCO: Verkhoyansk-Chukotka Orogen. Data for Arctic region mainly after Nikishin et al. (2023), Nikishin et al. (2021b), Nikishin et al. (2021c) and references within. For the Atlantic region data are mainly after Gernigon et al. (2020), Chauvet et al. (2019), Foulger et al. (2020a) and Funck et al. (2017).

hostile environmental conditions have limited the geological and geophysical data that can be gathered and the methods that can be used. Geological mapping of land exposures on the margins is also challenging. These circumstances have resulted in less information being available from the Arctic Ocean compared with the NE Atlantic. Nevertheless, over the last two decades, technological advances have enabled accelerated progress. In particular, adoption of the United Nations Convention on the Law of the Sea (UNCLOS) in 1982 encouraged renewed research by Arctic- and European nations.

The most ambitious of these projects was the multi-expedition,

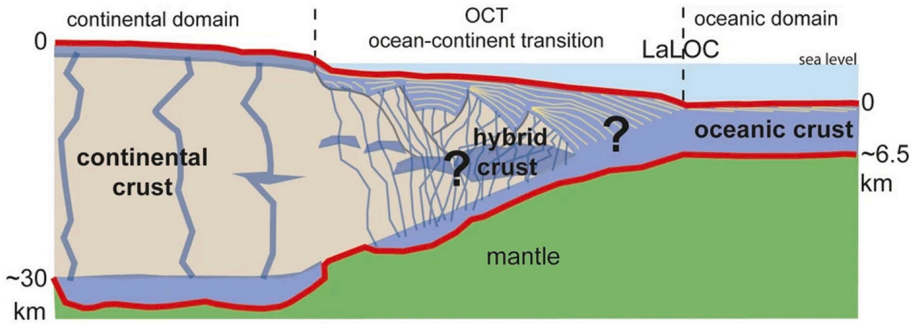

Fig. 4. Schematic cross section showing a model for hybrid crust at the volcanic margins of the NE Atlantic – crust intermediate between continental- and classical oceanic crust at magma-rich margins. LaLoc, Landward Limit of the Oceanic Crust (from Sauter et al., 2023).

extensively documented, Russian Arctic Ocean Mega-project (Kashubin et al., 2018; Mosher et al., 2023; Mukasa et al., 2020; Nikishin et al., 2018; Nikishin et al., 2014; Nikishin et al., 2021a; Nikishin et al., 2021b; Nikishin et al., 2021c; Nikishin et al., 2022; Nikishin et al., 2023; Petrov et al., 2016; Petrov and Smelror, 2021; Piskarev et al., 2019; Shimeld et al., 2021; Skolotnev et al., 2019; Skolotnev et al., 2023). This project acquired >30,000 km of multi-channel seismic lines along with multi-beam bathymetry data, drilled rock samples, gravity, magnetic and geodetic data. Supporting geological surveys were conducted of several Arctic islands (Fig. 5). Rock samples were also taken by geologists in submersibles from the slopes of the Mendeleev Rise and many new dates have become available from seismic stratigraphy, paleontology and age-dating. New seismic, gravity and magnetic data were also gathered by organizations in North America and Europe (Bruvoll et al., 2010; Bruvoll et al., 2012; Chian et al., 2016; Coakley et al., 2016; Dove et al., 2010; Evangelatos et al., 2016; Funck and Shimeld, 2023; Gaina et al., 2011; Hegewald and Jokat, 2013; Hutchinson et al., 2017; Ilhan et al., 2018; Jokat and Ickrath, 2015; Jokat et al., 2013; Mosher et al., 2023; Mosher et al., 2012; Saltus et al., 2011; Shimeld et al., 2021; Weigelt et al., 2014). With the benefit of these data, knowledge of the stratigraphy and tectonic and magmatic history of the Arctic region has recently improved significantly.

4. The NE Atlantic region

Breakup in the NE Atlantic region was prolonged, diachronous and piecemeal. Formation of the ocean was preceded by multiple rifting pulses lasting from the Late Permian to the earliest Triassic (see Peace

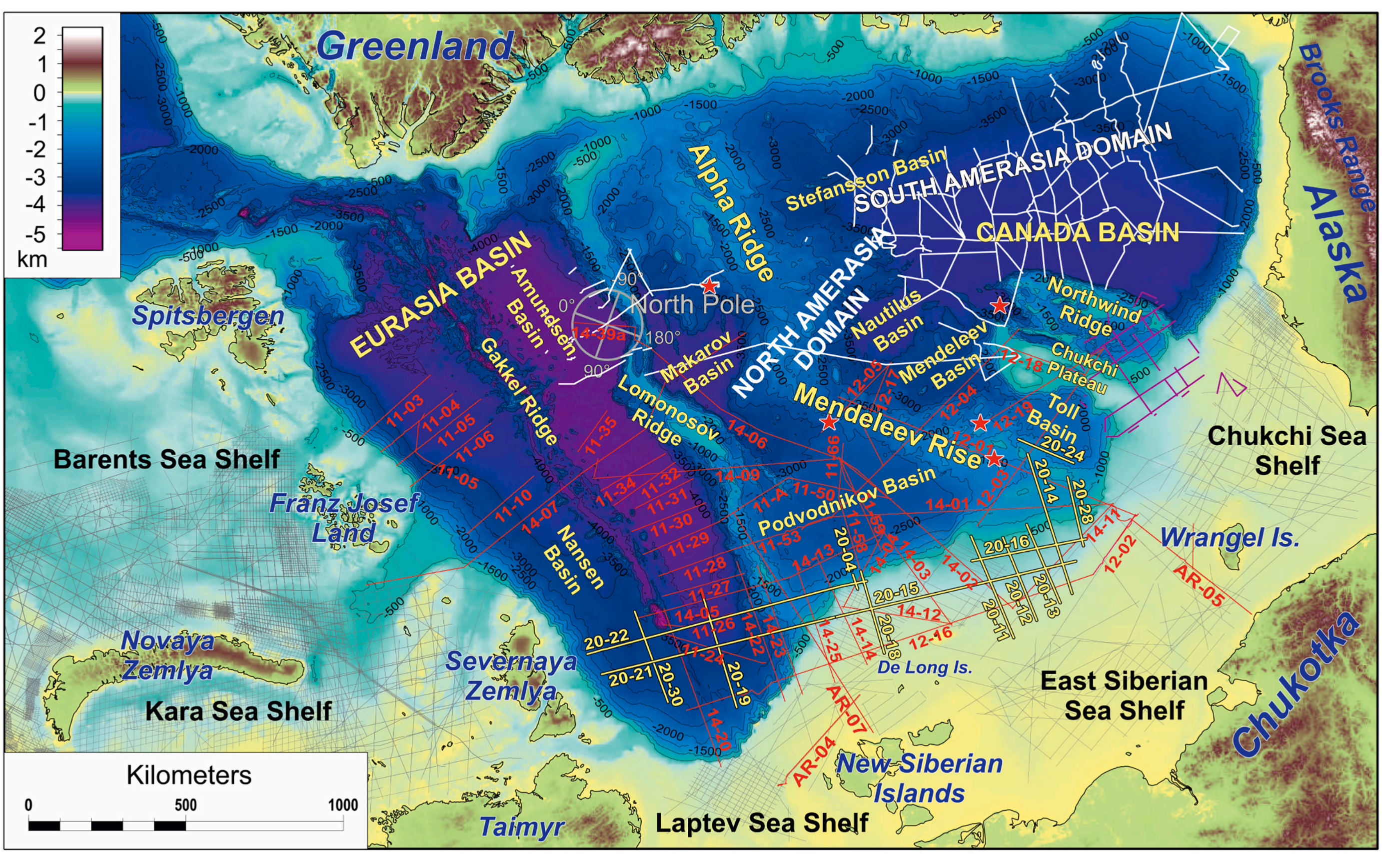

Fig. 5. Map showing the main seismic lines and sampling locations for expeditions in the Arctic Ocean including TransArctic-89-91, Arktika-2000 and expeditions in the period 2007–2020. Russian expeditions obtained over 30,000 km seismic lines (red and yellow lines), sub-bottom profiles of the Eurasia Basin and new bathymetric data for the Arctic Ocean. Red stars – main sampling locations of volcanic rocks. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

et al., 2016; Peace et al., 2020 for a summary). Prolonged unrest is recorded, for example, in the rich stratigraphic record of the Shetland-Faroe Basin (Stoker et al., 2017). In the early Paleocene, the Central Atlantic mid-ocean ridge propagated north to open a new rift west of Greenland, the Aegir Ridge formed north of present-day Iceland, and seafloor spreading onset (Gernigon et al., 2012; Keen et al., 2018).

The NE Atlantic is the type example of the Wilson cycle, the process whereby continents tend to break up by reactivating old sutures (Fig. 2) (Gernigon et al., 2015; Peace et al., 2018a; Peace et al., 2018b; Schiffer et al., 2020; Schiffer et al., 2019; Schiffer et al., 2015). Rift-tip propagation in the Labrador Sea was blocked at the EW trending Paleoproterozoic (1.86–1.84 Ga) Nagssugtoqidian orogenic belt (Fig. 2). There, the Davis Strait oblique transfer zone developed (Chalmers, 2012). This is now bathymetrically shallow and likely underlain by extended continental crust (Heron et al., 2019). Farther north, continental extension and minor seafloor spreading opened Baffin Bay (*e.g.*, Welford et al., 2018).

East of Greenland, prolonged extension formed a northeast-trending chain of Mesozoic rift basins that now comprise the Vøring-, Møre-, Faroe-Shetland- and Hatton-Rockall Basins (*e.g.*, Cole and Peachey, 1999; Gernigon et al., 2021; Hitchen and Ritchie, 1987; Japsen et al., 2023; Mudge and Rashid, 1987; Stoker et al., 2018; Zastrozhnov et al., 2020). Full breakup and onset of seafloor spreading there started at 54–52 Ma (*e.g.*, Gernigon et al., 2020; Lundin and Doré, 2019; Nirrengarten et al., 2018). The GIFR sector, and the regions to its south and north, developed in different ways (Gaina et al., 2017). North of the GIFR the Aegir ridge grew by southerly propagation along the Caledonian suture over ~2 Myr (Gernigon et al., 2015; Gernigon et al., 2020; Schiffer et al., 2019). Where the tip of this ridge encountered the western frontal thrust of the Caledonian suture it was unable to progress, curved ~70° to the west, and stalled.

At approximately the same time, continental extension transitioned to seafloor spreading south of the GIFR along the proto-Reykjanes Ridge (*e.g.*, Barnett-Moore et al., 2018; Geoffroy et al., 2022b). That ridge

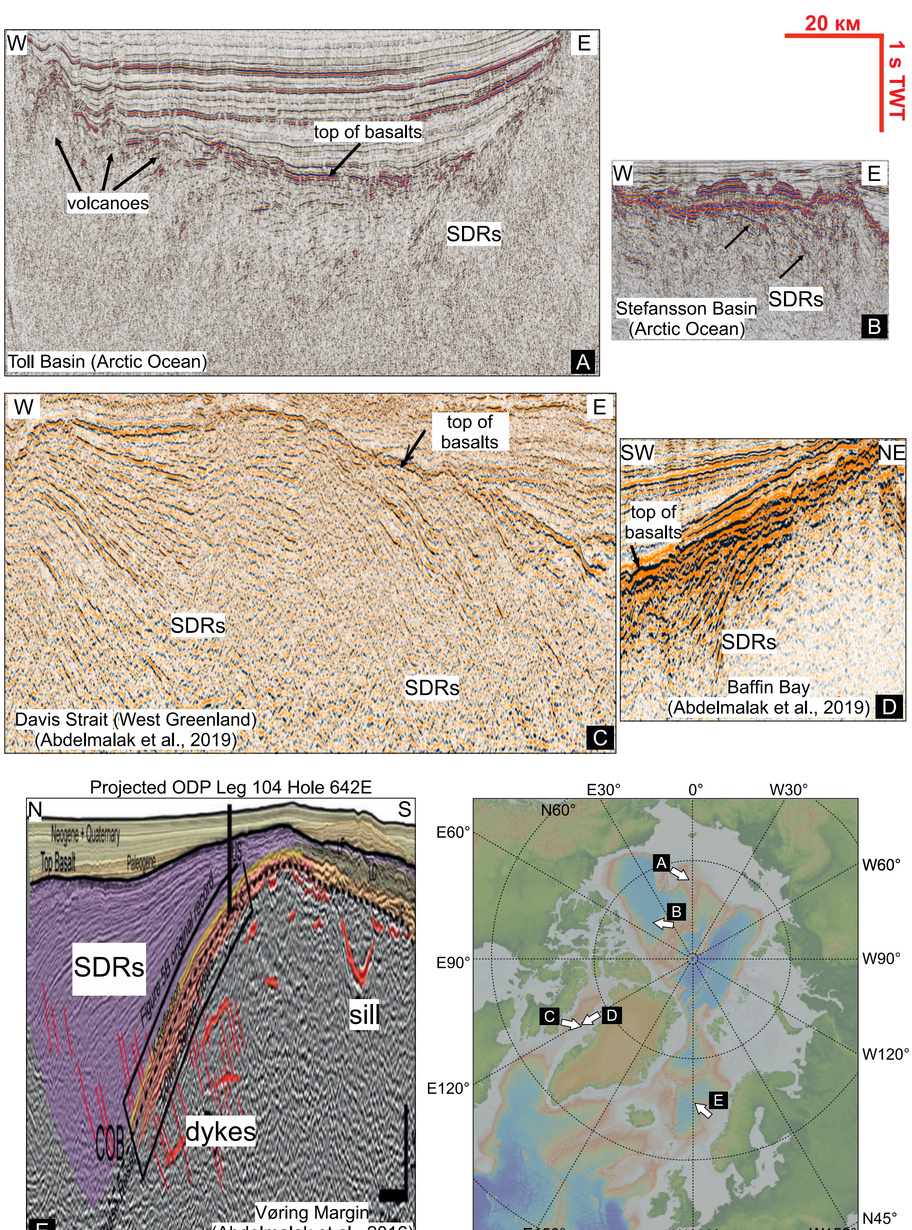

Fig. 6. A selection of seismically imaged SDRs in the Arctic and NE Atlantic Oceans. The vertical and horizontal scales are shown at top right and are the same for all panels. A,B – adapted from Nikishin et al. (2021c, 2023); C,D,E, adapted from Abdelmalak et al. (2016, 2019).

terminated at the confluence of the Nagssugtoqidian and Caledonian orogenies, ~ 400 km south of the Aegir Ridge tip. Spreading ceased west of Greenland at ~36 Ma, likely in response to a major change in the direction of plate motion (Gaina et al., 2009; Martinez and Hey, 2022; Martinez et al., 2020).

Fan-shaped spreading occurred about the Aegir Ridge until ~30 Ma when it became extinct (Bott, 1985). Thereafter, spreading north of the GIFR was taken up ~400 km farther west where the Kolbeinsey Ridge developed (*e.g.*, Franke et al., 2019; Gaina et al., 2017; Gernigon et al., 2020). This split off a block which thereafter became the Jan Mayen Microcontinent Complex (JMMC; Fig. 3) (Blischke et al., 2022; Blischke et al., 2017; Brandsdóttir et al., 2015; Schiffer et al., 2019).

Ocean development south of the GIFR along the Reykjanes Ridge was, to a first order, simpler, with no large or abrupt rift jumps (Gaina et al., 2017). It experienced reorganization at ~30 Ma, however, and thereafter small-offset, south-travelling ridge propagators formed, coincident with lateral rift jumps on the GIFR (Hey et al., 2010). These ridge propagators progressively transported the Reykjanes Ridge to the east (Jones et al., 2002; Martinez et al., 2020; Vogt, 1976).

Opening of the NE Atlantic was highly magmatic and produced the NAIP (Hole and Natland, 2020; Wilkinson et al., 2017). Magmas conventionally assigned to this province occur in and around the Davis Strait, along the margins of east Greenland, Norway and Britain, and on the GIFR including Iceland (Clarke and Beutel, 2020; Peace et al., 2020) (Fig. 3). Where volcanism occurred during rifting and subsidence on major faults, SDRs formed (Fig. 6). SDR sequences are divided into Inner- and Outer-SDRs (Figs. 4 and 6) (Planke et al., 2000). Inner-SDRs, which comprise flow-stacks up to ~10 km thick, are thought to overlie magma-injected, mid-to-lower continental crust necked at an advanced stage of extension (Geoffroy, 2005; Geoffroy et al., 2015; Geoffroy et al., 2022b; Paton et al., 2017; Tard et al., 1991). Such crust underlies much of the Greenland and Norwegian coastal regions (*e.g.*, Eldholm and Grue, 1994; Geoffroy et al., 2015; Gernigon et al., 2020).

Outer-SDRs overlie thinner crust of uncertain provenance but with similar seismic properties to Inner-SDRs (*e.g.*, Geoffroy et al., 2020). The underlying crust may be magmatic (*e.g.*, Voss and Jokat, 2007) or stretched, ductile continental mid- and lower-crust, with or without intrusions (Geoffroy et al., 2022a; Geoffroy et al., 2022b). Discriminating between these two interpretations on the basis of geophysical data is difficult. The magmatic rate dwindled following NE Atlantic breakup and basaltic oceanic crust with normal thickness and cooling/subsidence profile began to form except beneath the GIFR (Huismans and Beaumont, 2008; van Wijk et al., 2001).

The crust beneath the GIFR is unlike classical oceanic crust (Foulger et al., 2003). The GIFR comprises a ~ 1200-km-long, 300–400-km-wide swathe of crust 30–40 km thick that stands ~1 km higher than thermal models predict for typical oceanic crust (Clift, 2005; Detrick et al., 1977). It comprised a subaerial landbridge connecting Greenland to Europe until 15–10 Ma, only foundering when the NE Atlantic Ocean had attained a width of ~1000 km (Denk et al., 2011; Ellis and Stoker, 2014; Scharff, 1909; Stoker et al., 2005). Submarine parts lie only a few hundred meters below sea level, in stark contrast to the adjacent, >2000-m-deep ocean basins. The only remaining subaerial part of the GIFR is the 500-km-wide island of Iceland across which Holocene volcanism is distributed over a ~ 400-km-wide region in the direction of plate motion (*e.g.*, Sigmundsson et al., 2020).

Historic models for the GIFR have included both continental crust (Bott, 1985; Zverev et al., 1977) and unusually thick oceanic crust resulting from exceptionally high temperatures in the melt source (*e.g.*, Bjarnason et al., 1993; Darbyshire et al., 1998; Ribe et al., 1995). The latter model suffers from conflicting geological and geophysical observations, for example:

1. Petrological, seismological, bathymetric and vertical-motion indicators are inconsistent with high melt-source temperatures (Borchardt and Lee, 2022; Clift, 2005; Foulger et al., 2020a; Gudmundsson, 2003; Hole and Natland, 2020; Menke, 1999).
2. Seismic data suggest the lower crust is cooler than the gabbro solidus and devoid of distributed partial melt (Menke and Levin, 1994; Menke et al., 1995).
3. Linear magnetic anomalies observed on the GIFR resemble those seen over transitional crust on passive margins, not over classical oceanic crust (Bott, 1974; Geoffroy et al., 2022b; Nasuti and Olesen, 2014) (Fig. 7).
4. Crustal extension on the GIFR has always been distributed across two or more subparallel rift zones connected by complex shear zones (Einarsson, 1988, 1991; Hjartarson et al., 2017; Saemundsson, 1979) (Fig. 8).

Structure, and the past and present mode of deformation on the GIFR, resemble the *syn*-breakup structure and style of distributed extension, rifting and volcanism elsewhere in the NE Atlantic. The loci of rifting have been chronically unstable throughout the >50 Myr period of NE Atlantic opening, migrating to new positions typically on a time scale of ~5 Myr (Helgason, 1984). The lower crust beneath the GIFR may thus be magma-inflated continental crust – hybrid crust – and not oceanic crust (Fig. 4) (Amundsen et al., 2002; Bohnhoff and Makris, 2004; Bott, 1985; Foulger, 2006; Foulger et al., 2020a; Foulger et al., 2020b; Paquette et al., 2006; Peace et al., 2023; Prestvik et al., 2001; Schaltegger et al., 2002; Torsvik et al., 2015; Yuan et al., 2020; Zverev et al., 1977). The 6–8-km-thick GIFR upper crust would then comprise a

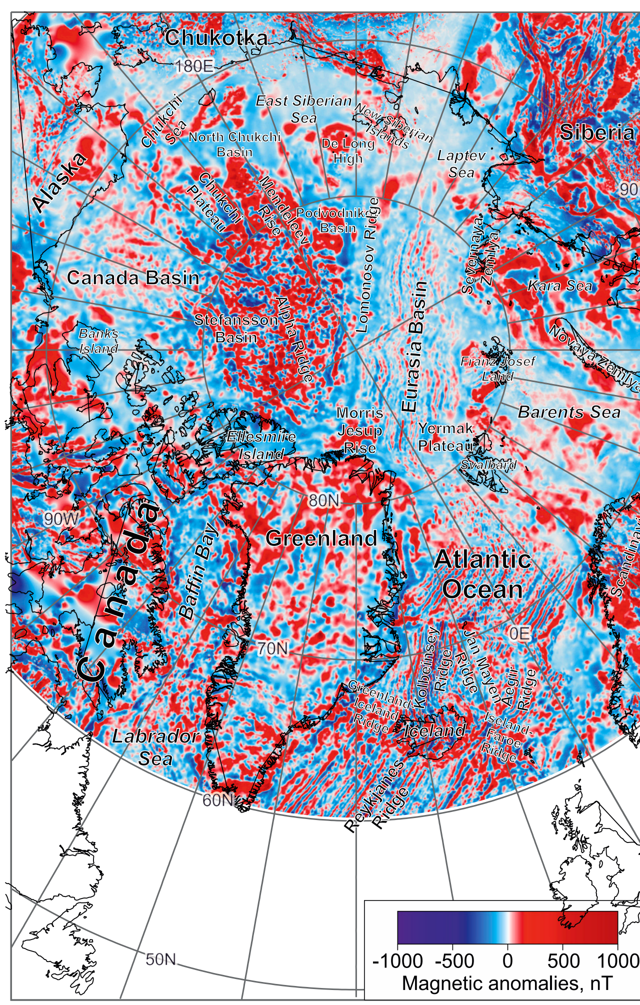

Fig. 7. Magnetic anomalies in the NE Atlantic and Arctic regions (from Gaina et al., 2011; Glebovsky et al., 2002; Piskarev et al., 2019).

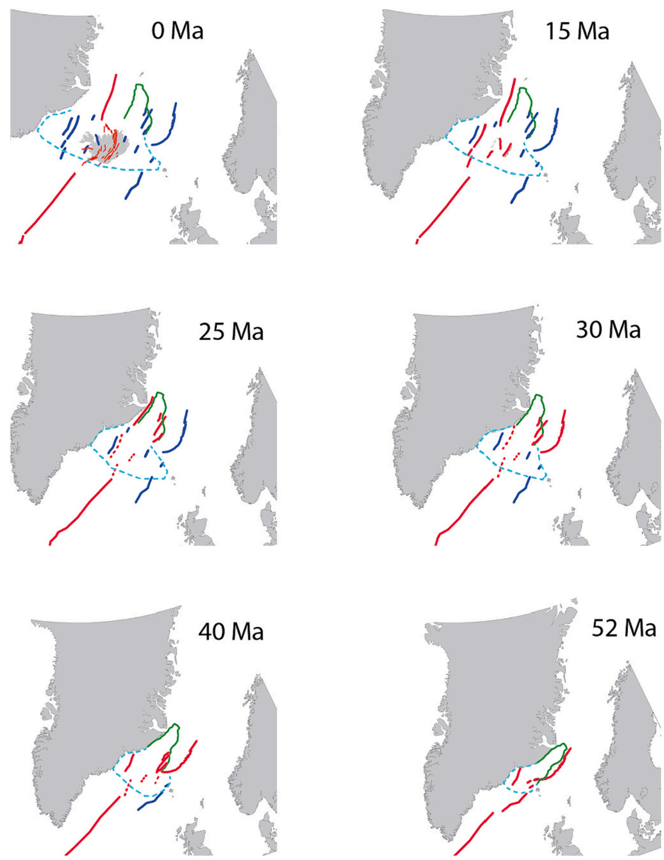

Fig. 8. Tectonic evolution of the GIFR region. Red: active rifts, blue: extinct rifts, dashed lines: speculative, green solid line: approximate boundary of JMMC, pale blue dashed line: approximate boundary of Iceland Microcontinent (from Foulger et al., 2020a). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

basaltic cap analogous to the SDR sequences mapped offshore Norway and Greenland (Fig. 9).

Such a structure could account for the low crustal- and mantle-melt-source temperatures, the absence of classical linear magnetic anomalies, the chronically unstable axes of extension and the anomalously high hypsometry of the GIFR (Clift, 2005; Denk et al., 2011; Ellis and Stoker, 2014; Stoker et al., 2005). If the GIFR comprises hyperextended continental crust, tectonic decoupling of the ocean-crust-floored regions to the south and north is unsurprising. Palinspastic reconstructions and geochemistry suggest that the JMMC continues under eastern Iceland, so a full-thickness continental block may also lie there (*e.g.*, Bjarnason and Schmeling, 2009; Bott, 1985; Foulger, 2006; Gernigon et al., 2020; Paquette et al., 2006; Peace et al., 2023 and references therein; Prestvik et al., 2001; Torsvik et al., 2015).

How could such a structure form? Numerical modelling has shown that, for originally thick orogenic crust and reasonable temperatures and compositions, ductile crustal flow to the degree required to build the 1200-km-long GIFR is possible (Petersen et al., 2018) (Section 6.2). Most of the continental crust beneath the GIFR is envisaged to comprise hyper-extended, magma-inflated mid- and lower continental crust and not full-thickness continental microcontinents broken off the conjugate margins, which is ruled out by palinspastic reconstructions (Gaina et al., 2017).

Such a structure is unusual but not without analogies. Extended continental shelves up to ~200 km wide are reported for Baffin Bay (*e.g.*, Welford et al., 2018). The Vøring Plateau is underlain by thinned continental crust and the entire rifted margin extends for ~400 km toward the ocean (Gernigon et al., 2020). The width of the NE Atlantic passive margins away from the GIFR is controversial and depends on whether the distal Outer-SDRs are underlain by crust that is partly continental or entirely magmatic. If the former is correct then passive margins 200–300 km wide are common throughout the NE Atlantic Ocean (Geoffroy et al., 2022b). If a full-thickness continental block underlies Iceland then the GIFR may comprise two pairs of conjugate rifted margins, one pair extending from Iceland to Greenland and the other pair extending from Iceland to the Faroe Islands (Geoffroy et al., 2020). Thus, simplistically, the GIFR may essentially comprise four aligned passive margins.

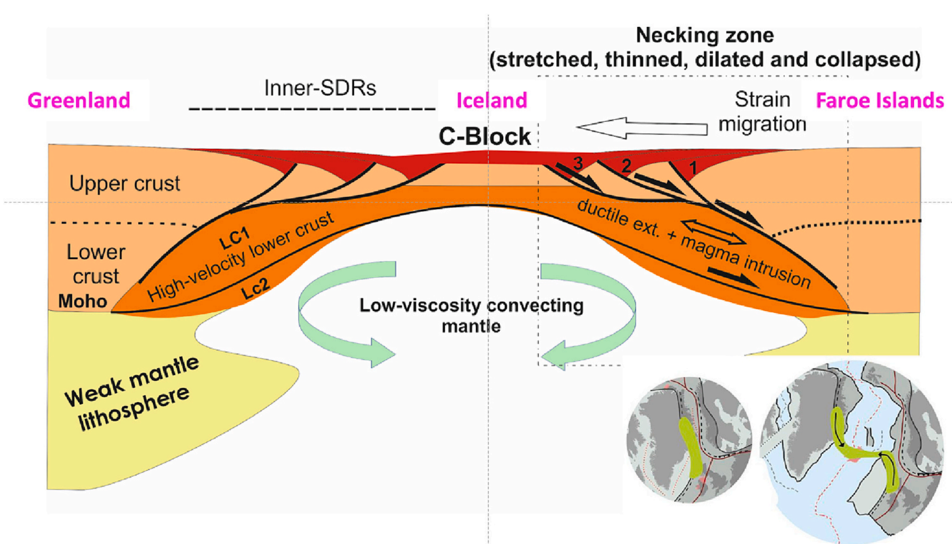

Fig. 9. Schematic figure showing a model for the GIFR and Iceland. The conjugate volcanic passive margins are at the necking stage, with a central horst-like core and Inner-SDRs. The central core – the "C-Block" – is likely currently fragmented, buried deeply under Iceland and blanketed by lava flows. The SDRs develop sequentially (1 to 3, right side) such that two main extensional axes are generally active simultaneously, one on each side of the central block. Lower crust 1 (LC1) is magma-injected mid-to-lower continental crust. Lower crust 2 (Lc2) is a mafic lower crust overlying the convecting mantle. Main figure is adapted from Geoffroy et al. (2020). Inset at lower right shows schematically how ductile stretching of Caledonian orogenic front crust could build the GIFR and is adapted from Petersen et al. (2018) and Foulger et al. (2020a).

The total volume of the NAIP has been estimated at ~4.4×10^6 km^3 making it one of the largest LIPs in the world (Coffin and Eldholm, 1992, 1993, 1994; Eldholm and Grue, 1994). Confirming this is nevertheless difficult because the quantity of intrusions and deeply buried extrusives is unknown (Gallahue et al., 2020) and the composition of the lower crust beneath the Outer-SDRs and the GIFR is controversial. The volume of the latter alone is ~3.6×10^6 km^3 and it is as yet unclear how much of this is magmatic (Foulger et al., 2022).

5. The Arctic region

The Arctic Ocean comprises the Amerasia and Eurasia basins which are separated by the Lomonosov Ridge, a submerged ribbon-continent (Figs. 1 and 2). The Amerasia Basin is geographically complex. It comprises several, separate, deep-water basins of which the Canada Basin is the largest. Others comprise the Podvodnikov-Makarov- and Toll-Mendeleev-Nautilus-Stefansson belts of basins. The basins are separated by bathymetric highs, the largest of which is the Alpha-Mendeleev Rise. The Eurasia Basin was formed by the Gakkel ultra-slow spreading ridge which connects with the mid-Atlantic Ridge. Gakkel Ridge spreading split the Lomonosov Ridge off the northwestern Russian continental shelf (Jokat et al., 2019; Jokat and Schmidt-Aursch, 2007; Nikishin et al., 2018).

Events in the northern Pacific subduction system, and the Verkhoyansk–Chukotka orogeny, have both been influential (Fig. 2). The latter orogeny involved essentially all Russia east of the Siberian craton where multiple terranes united to form NE Asia (*e.g.*, Akinin et al., 2020). The end of Verkhoyansk–Chukotka compression marked the beginning of extension, rifting and accompanying magmatism in the Arctic region, including HALIP magmatism (Nikishin et al., 2024; Nikishin et al., 2021a; Nikishin et al., 2022) (Fig. 3).

Major seismic boundaries have been identified on the basis of drilling (the ACEX Project; Backman et al., 2005) and onshore-offshore stratigraphic correlations (Nikishin et al., 2021c). The first basin to form was the Canada Basin which opened *via* a now-extinct Cretaceous spreading plate boundary (Mosher et al., 2023; Nikishin et al., 2021a). Magnetic anomalies suggest this occurred at 133–125 Ma (Alvey et al., 2008; Døssing et al., 2020; Nikishin et al., 2023). It may have comprised a back-arc extensional feature of the North Pacific subduction zone that consumed Pacific sea floor along a zone extending from the southern margin of Chukotka to the southern margin of Arctic Alaska. That convergence is now taken up along the Aleutian arc (Døssing et al., 2013a; Døssing et al., 2013b; Mosher et al., 2023; Nikishin et al., 2021a; Zhang et al., 2019). The Canada Basin is thus affiliated to Pacific tectonic activity. True oceanic crust within it is probably limited in extent, and peripheral parts of the basin are likely floored by hyper-extended continental crust.

Apart from the central part of the Canada Basin, the Amerasia Basin, including both shallow regions and deep-water basins, appears to be devoid of classical ocean-crust-type linear magnetic anomalies (Fig. 7). The Alpha-Mendeleev Rise features very-high amplitude "chaotic" magnetic anomalies (the High Arctic Magnetic High Domain or HAMH; Oakey and Saltus, 2016). These are believed to be associated with the HALIP and aged 125–100 Ma (*e.g.*, Buchan and Ernst, 2018; Coakley et al., 2016; Deegan et al., 2023; Dockman et al., 2018; Døssing et al., 2013b; Mukasa et al., 2020; Nikishin et al., 2021a; Nikishin et al., 2021b; Nikishin et al., 2021c; Oakey and Saltus, 2016).

The HALIP was the most voluminous magmatic event to occur in the Arctic Ocean (Coakley et al., 2016; Mosher et al., 2023; Oakey and Saltus, 2016) (Fig. 3). It involved the emplacement of three main units (Bédard et al., 2021; Dockman et al., 2018; Døssing et al., 2013b; Funck and Shimeld, 2023; Minakov et al., 2018; Mosher et al., 2023; Mukasa et al., 2020; Nikishin et al., 2023; Oakey and Saltus, 2016; Petrov et al., 2016; Polteau et al., 2016; Saltus et al., 2011; Shipilov, 2016). These are (1) intraplate basalt trap-type plateaus with tholeiitic lavas, (2) intraplate intrusives, and (3) synrift and postrift basalts in the Alpha-Mendeleev region overlain by SDRs. Large volcanoes (*e.g.*, the Fedotov seamount (100–80 Ma); Funck and Shimeld, 2023) formed last. Isotopic U/Pb ages of the basaltic lavas and intrusions, and one volcanic bomb from this region, have yielded dates in the range 125–100 Ma (Nikishin et al., 2021a; Nikishin et al., 2023; Saltus et al., 2011; Skolotnev et al., 2019; Skolotnev et al., 2023; Skolotnev et al., 2022). A possible later magmatic event is suggested by zircons aged 87–83 Ma (Skolotnev et al., 2023). Volcanism also occurred on the Chukchi Borderland, with ^{40}Ar/^{39}Ar ages of 118–70 Ma (Mukasa et al., 2020).

Magmas of HALIP age are not confined to the Alpha-Mendeleev Rise. Geological mapping and geophysical data have revealed basaltic plateaus, traps, and associated intrusions with ages in the range 125–105 Ma in Franz Josef Land, Svalbard, the De Long Islands and the Canadian Arctic Archipelago (Corfu et al., 2013; Drachev and Saunders, 2006; Døssing et al., 2013a; Funck et al., 2022; Midtkandal et al., 2016; Nikishin et al., 2021c; Nikishin et al., 2022; Nikishin et al., 2023; Polteau et al., 2016; Senger et al., 2014). Canadian Arctic Archipelago basaltic plateaus in the Sverdrup Basin were emplaced at 128–77 Ma (*e.g.*, Buchan and Ernst, 2018; Dockman et al., 2018; Evenchick et al., 2015; Galloway et al., 2018; Kingsbury et al., 2018).

Deep seismic reflection surveys that penetrated up to ~30 km have revealed the sequence of events in considerable detail (Funck and Shimeld, 2023; Nikishin et al., 2021b; Shimeld et al., 2021; Skolotnev et al., 2023). Half-grabens formed and were overlain by SDR-like units and basaltic plateau eruptions on the horsts. Thereafter, horizontal volcanic flows formed on the Alpha-Mendeleev Rise and SDRs dipping toward the basin axes. Large volcanoes formed on the Alpha Ridge and in the Makarov Basin and trap volcanic plateaus on Marvin Spur and the De Long Islands. Magma-floored continental rifts developed. Toward the end of the HALIP period, magmatism occurred in northern Greenland that may have been associated with extension of the Baffin Bay/Sever Spur rift system – a precursor to later full continental breakup in the Arctic region (Buchan and Ernst, 2018; Dockman et al., 2018; Døssing et al., 2013a; Nikishin et al., 2024; Thórarinsson et al., 2015).

The deep seismic reflection survey data show that the Alpha-Mendeleev Rise comprises a double sided, volcanic passive margin underlain by stretched continental crust and capped with magmas (Figs. 10 and 11). The flanking deep-water basins comprise incipient, but now aborted, continental breakup axes that did not proceed to classical seafloor spreading and oceanic crust formation. Development of this region is dated to 125–100 Ma with local volcanism continuing up to 90–80 Ma (see reviews by Coakley et al., 2016; Funck and Shimeld, 2023; Mosher et al., 2023; Nikishin et al., 2021a; Skolotnev et al., 2023). A continental provenance for the deeper crust of the Alpha-Mendeleev Rise is also supported by xenogenic zircons with Paleozoic and Precambrian ages (2475–131 Ma) (Skolotnev et al., 2023) and composition-time relationships for Chukchi borderland lavas that are consistent with melting initiating in sub-continental lithospheric mantle (Mukasa et al., 2020).

The volume of HALIP magmas has been estimated at $<1 \times 10^6$ km^3 (*e.g.*, Dockman et al., 2018). However, recent results render this uncertain. The seismic data suggest a typical thickness of 1–3 km for SDRs on the Alpha-Mendeleev Rise, and similar estimates can be made for some of the traps. The thickness of underplated intrusions may be 1–7 km but these estimates are uncertain. The maximum volume of HALIP magmatism may be comparable with that of the NAIP, but further study of both LIPs is needed to refine estimates.

Tectonic connections with the NE Atlantic began at 80–66 Ma (Nikishin et al., 2024). At this time, regional extension propagated north from the Labrador Sea/Baffin Bay system into the Arctic region. Normal faults and grabens of the Sever Spur rift system formed in the Stefansson Basin and the Marvin Spur Basin (Døssing et al., 2013a; Funck and Shimeld, 2023; Hutchinson et al., 2017; Nikishin et al., 2024). This rifting did not mature to continental breakup.

Seismic data detect volcanic units between the Eurasia Basin and the Laptev Sea shelves immediately beneath the ~56-Ma rift/post-rift

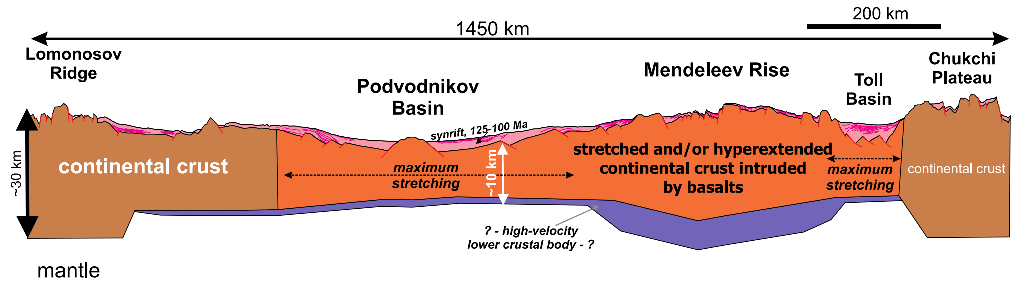

Fig. 10. Conceptual model of the crustal structure of the Mendeleev Rise and adjacent basins. Upper crust is from interpretation of seismic data (Nikishin et al., 2023). Model for lower crustal structure is after Kashubin et al. (2018).

breakup boundary (Nikishin et al., 2021b; Nikishin et al., 2021c). Immediately thereafter the Gakkel slow-spreading ridge began to form, simultaneously with onset of the Eurekan orogeny in north Greenland (Funck et al., 2022; Glebovsky et al., 2006; Lutz et al., 2018; Nikishin et al., 2018). The seafloor on either side of the Gakkel Ridge displays clear magnetic anomalies. Basalt productivity is low, however, and mantle peridotites are exposed on some parts of the ridge crest (Jokat et al., 2019; Michael et al., 2003). Eurekan orogenic compression continued throughout the period 56–34 Ma (*e.g.*, Piepjohn et al., 2016; Vamvaka et al., 2019) affecting the Barents Sea (Gac et al., 2020; Nikishin et al., 2021a), Kara Sea, and West Siberian Basin (Nikishin et al., 2021a).

Subsequent tectonic development of the Eurasia Basin was relatively uniform (*e.g.*, Funck et al., 2022; Jokat et al., 2019; Lutz et al., 2018; Nikishin et al., 2018; Piskarev et al., 2019). The Gakkel Ridge opened progressively with spreading slowing at ~45 Ma (Gaina et al., 2015). It now links with the NE Atlantic spreading axis *via* the Fram Strait. Away from the flanking seafloor featuring classical linear magnetic anomalies (Glebovsky et al., 2006) (Fig. 7), the crustal structure has yet to be clarified (*e.g.*, Jokat et al., 2019; Michael et al., 2003; Nikishin et al., 2018). The location and nature of the continent-ocean transition is unclear and proposals for the material beneath the thin surface basalts range from exhumed continental mantle to oceanic crust (*e.g.*, Jokat et al., 2019; Lutz et al., 2018). The Yenisey-Khatanga lineament between the Eurasia Basin and the Laptev Sea shelf (Fig. 2) has been proposed to be a large-scale transform fault (*e.g.*, Pease et al., 2014) but recent seismic data find no evidence for such a fault (Nikishin et al., 2018; Nikishin et al., 2021b; Nikishin et al., 2021c).

At ~34 Ma, the Yermak Plateau (Eurasian Plate) and the Morris Jesup Rise (North American plate) separated (Fig. 1). The Fram Strait opened magmatically at ~20 Ma (*e.g.*, Berglar et al., 2016; Ehlers and Jokat, 2013; Jokat et al., 2016; Kristoffersen et al., 2021).

6. Comparison of the NE Atlantic and Arctic regions

6.1. Structure and tectonics

The NE Atlantic and Arctic regions share numerous characteristics. Both oceans are triangular in shape, relatively narrow, and their deep-water portions cover approximately the same area (3–4 × 10^6 km^2; Fig. 1). Both are bathymetrically asymmetric, with the European/Scandinavian/Russian continental shelves being much wider and island-strewn than the North American/Greenland/Canada shelves. They both experienced extended histories of tectonic unrest and extension prior to breakup. When final breakup did occur it involved reactivation of pre-existing structures, asymmetric spreading, and LIP magmatism. Ultimate disintegration created continental fragments and extensive regions of stretched, magma-inflated continental crust, some blanketed with lavas. Volcanism included both long periods of widespread, scattered magmatism and relatively short periods of intense activity. Being adjacent, both oceans show a combination of independent and coordinated tectonic behavior (Table 1).

The Arctic region connects the Pacific and Atlantic Oceans and has been shaped by tectonic events in both. The extension that occurred in the Canada Basin at 133–125 Ma (Section 5) most likely comprised back-arc spreading behind the Beringian (N Pacific) margin where the Kula plate subducted up until the late Mesozoic. The much later formation of the Gakkel Ridge was, in contrast, linked to Atlantic tectonics (Nikishin et al., 2021a). Formation of the NE Atlantic Ocean was linked to events farther south.

Both the Arctic and the NE Atlantic Oceans contain extensive regions of submerged continental crust, some of it blanketed by flood basalts or SDRs (Fig. 12). In the Arctic, the ~1500-km-wide Russian shelf, including the vast archipelago extending from Svalbard to Wrangel Island (Fig. 1) is underlain by continental crust. The Lomonosov Ridge comprises a ribbon microcontinent that split off the continental edge of the Barents Sea. The sub-parallel Alpha-Mendeleev Rise comprises, to a first order, a ~ 1400 km-long horst draped on both sides by SDR sequences (Fig. 6 and Fig. 10). Oceanic crust in the Arctic Ocean is likely limited to the central Canada Basin and the flanks of the Gakkel Ridge and in total as much as 80% of the deep-water part of the Arctic Ocean may be underlain by continental- or hybrid crust (Nikishin et al., 2024; Nikishin et al., 2021a; Nikishin et al., 2021b; Nikishin et al., 2021c; Nikishin et al., 2023).

The NE Atlantic exhibits similar features. Full-thickness continental crust likely underlies the Rockall-Hatton Plateau, the Faroe Bank, Faroe Plateau, and the ~60,000 km^2 JMMC (*e.g.*, Blischke et al., 2022; Schiffer et al., 2019). Additionally, wide swathes of Greenlandic and Norwegian seaboard are built of SDR-blanketed, hyper-extended continental crust. It has additionally been suggested that the GIFR comprises lava-capped, hyper-extended, magmatized continental crust (*e.g.*, Foulger et al., 2020a; Geoffroy et al., 2022a). If this is correct then the total amount of the NE Atlantic Ocean floored by classical oceanic crust may be as little as ~50% (Fig. 12).

In both oceans, breakup was not abrupt but the culmination of long periods of precursory regional unrest (Peace et al., 2020). In the Arctic Ocean, major, widespread tectonic destabilization began as activity in the Canada Basin ceased. Extreme extension was taken up along multiple rift zones. The Alpha-Mendeleev Rise formed *via* a pair of quasi-parallel extensional axes (Nikishin et al., 2021a). The crust beneath them underwent magma-inflation and fault-controlled extension but did not progress to full seafloor spreading (Figs. 6 and 10). In the NE Atlantic, precursory deformation and initial breakup followed a similar pattern and built similar structures. Breakup began on a pair of parallel ridges, initially west and east of Greenland, and finally retreated to a single ridge. Similar to the Lomonosov Ridge and the Alpha-Mendeleev Rise, continental blocks (*e.g.*, the JMMC) and heavily deformed continental material were distributed in the NE Atlantic Ocean.

Breakup in both oceans was highly magmatic. Igneous activity was prolonged and dispersed, and culminated in LIP formation. Extensive regions in both oceans feature SDR sequences, flood basalt/trap flows, and intrusions. In the Arctic, these are found throughout the archipelagos on the Russian and Canadian shelves and in seismic data they are seen draping both sides of the Alpha-Mendeleev Rise and its flanking

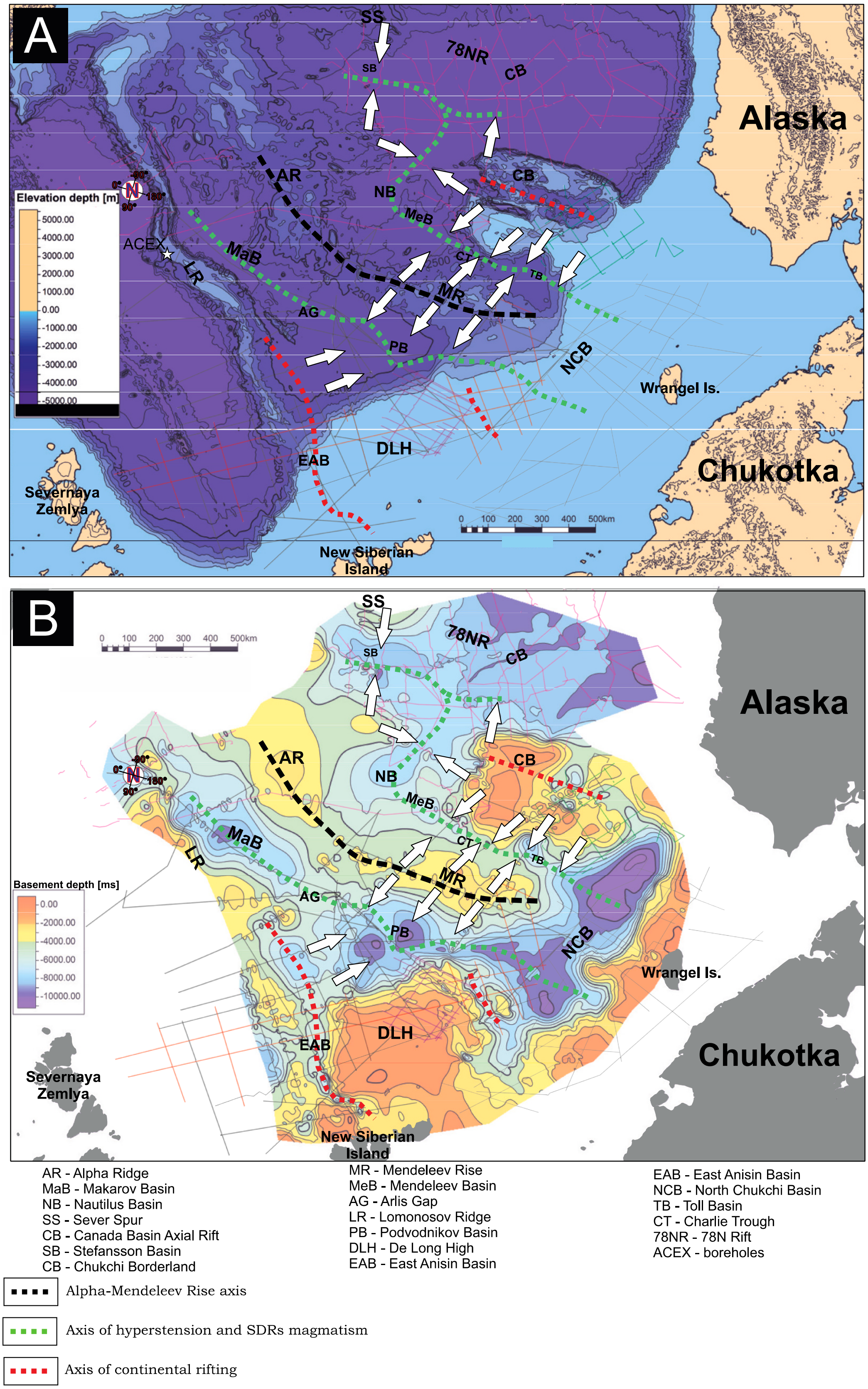

Fig. 11. Map of the Amerasia Basin showing major tectonic elements. Top panel shows bathymetry. Dashed black line: axis of Alpha-Mendeleev Rise, dashed green lines: axes of flanking deep basins, dashed red lines: axes of continental rifts. White arrows show dip directions of SDRs based on 2D seismic lines (adapted from Nikishin et al., 2023). Fine lines are 2D seismic profiles. Lower panel: same as upper panel but showing depth to basement (data from Nikishin et al., 2023). Bathymetric map is from Jakobsson et al. (2020). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

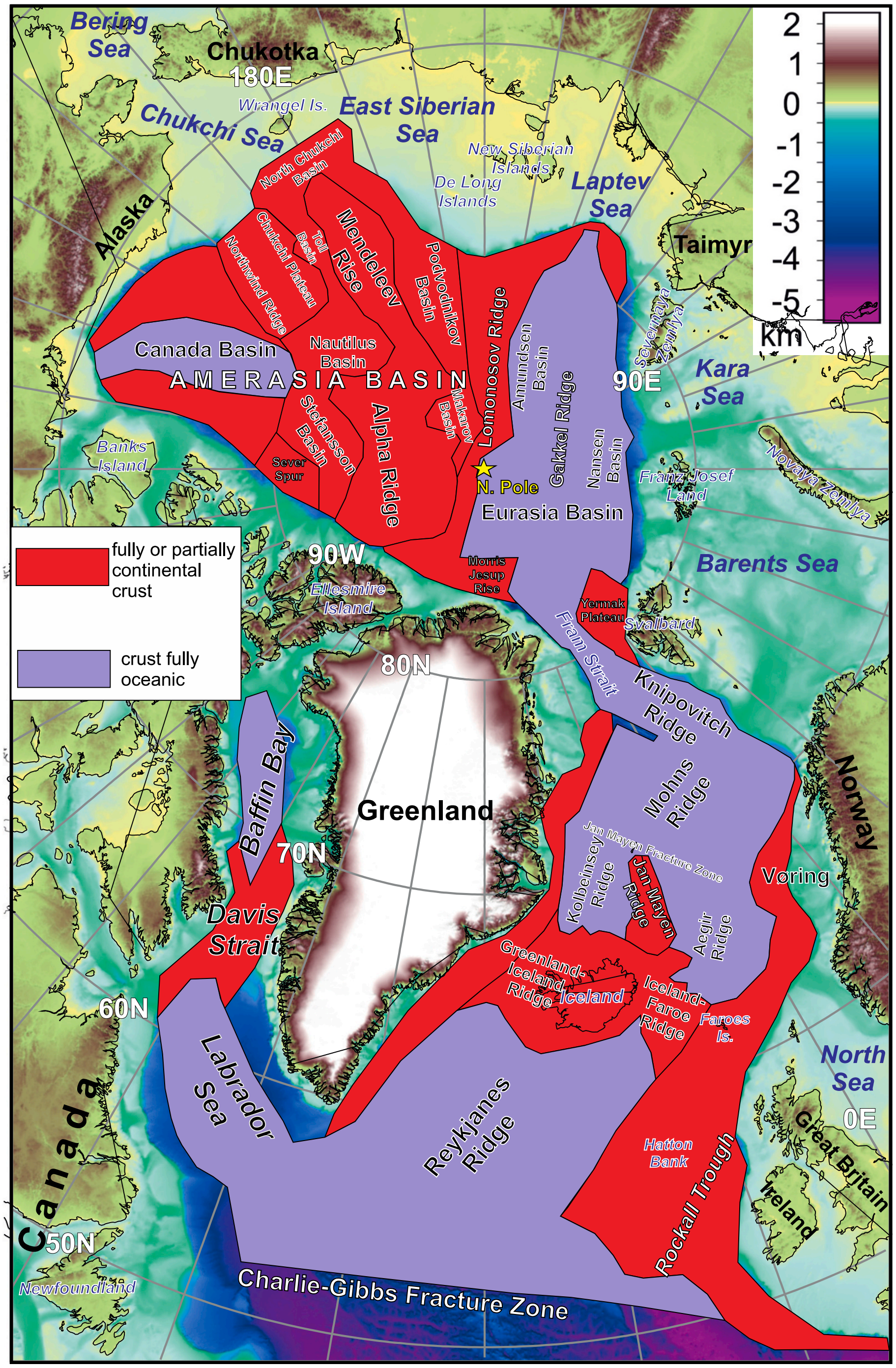

Fig. 12. Map of the NE Atlantic/Arctic region showing the proposed extent of continental/hybrid crust and classical oceanic crust.

deep-water basins. The Alpha-Mendeleev Rise, apparently a double-sided passive margin, has exactly the structure that was deduced independently for the GIFR (Foulger et al., 2020a). Magmatism accompanying breakup in the NE Atlantic was similar to that of the Arctic Ocean. First the Labrador Sea/Baffin Bay axis opened, and later the NE Atlantic, accompanied by LIP magmatism emplacing a similar suite of magmatic rocks. Ongoing volcanism contributing to this suite continues to the present day on land in Iceland.

The Alpha-Mendeleev Rise and the GIFR are close analogs. Both likely contain a horst-like core of continental crust with extensional axes on either side (c.f. Fig. 9 and 10). Both are underlain by thick crust with ambiguous seismic wave-speeds and density but which is likely magma-inflated continental crust blanketed with SDRs (Geoffroy et al., 2022b; Geoffroy et al., 2020). Both structures initially formed accompanied by flood basalt volcanism (LIP eruptions). Both extended along parallel-pair axes and, in the continental model, neither (have yet) progressed to full breakup and the onset of seafloor spreading. They differ in that the GIFR is ~1200 km wide in the extension direction and ~ 400 km long perpendicular to this, whereas the Alpha-Mendeleev Rise has the inverse aspect ratio. It is ~500 km wide in the extension direction and ~ 1400 km long perpendicular to this. In contrast to the Alpha-Mendeleev Rise, the GIFR is still actively building at the present day.

Tectonic events in the Arctic and the NE Atlantic ultimately became coordinated. A change in plate motion in the NE Atlantic in the late Eocene (38–36 Ma) (Gaina et al., 2017) coincided with cessation of spreading in the Labrador Sea, reorganization of the Reykjanes Ridge and slowing of spreading on the Gakkel Ridge. It may be that, as breakup in the NE Atlantic progressed, spreading along the entire axis became more coherent and early, multiple local Euler poles coalesced to approximate more nearly a single pole governing large-scale North American-Eurasian plate motion.

Asymmetric spreading (*i.e.* slow lateral ridge migration) occurs in both oceans. The Gakkel ridge is migrating north, thus gradually increasing its strike-normal distance from the Mohns Ridge (Nikishin et al., 2018). The Reykjanes Ridge is migrating east as a consequence of periodic ridge propagators that migrate south from Iceland in co-ordination with tectonic reorganizations on land there (Martinez and Hey, 2022; Martinez et al., 2020). Similar, less-pronounced but related behavior is observed on the Kolbeinsey Ridge (Jones et al., 2002).

6.2. Processes

Regional relaxation of compressional stress – cessation of adjacent orogenic compression – has been suggested to have permitted the extension that opened both oceans. In the Arctic, this comprised cessation of the eastern Russia Verkhoyansk-Chukotka orogenic collision (Nikishin et al., 2024). In the NE Atlantic a temporary, ~10 Myr, pause in African-Eurasian convergence in the mid-Paleocene (~60 Ma) is indicated by plate kinematic reconstructions (Rosenbaum et al., 2002), large-scale flexural relaxation of sedimentary inversion structures, and fault-analysis in western Europe (Nielsen et al., 2007; Stephenson et al., 2020). This would have relaxed compressional stresses throughout Eurasia and in the North American-Greenland continent. Although breakup was oblique to the direction of compressional-stress reduction in the Eurasian hinterland, models predict that old orogenies, in this case the Caledonian suture, will guide the axes of new breakup (Corti et al., 2003).

LIPs have been suggested to trigger continental breakup (*e.g.*, Døssing et al., 2013b; Saunders et al., 1997). However, the Arctic did not break up at the time and place of HALIP emplacement (Nikishin et al., 2021a; Nikishin et al., 2021c) and in the case of the NE Atlantic there is no evidence for radial propagation of rift tips away from the NAIP (Franke et al., 2019; Gernigon et al., 2020). On the contrary, rifts have been demonstrated to propagate toward LIPs (Peace et al., 2020). The question thus arises regarding the role of magmatism in breakup. Although some ridges developed by rift-tip propagation (*e.g.*, the Reykjanes Ridge) in both oceans, some magma-assisted extensional axes developed in isolation. These include the Mohns Ridge (~54 Ma), the Aegir Ridge (~54 Ma) and the Gakkel Ridge (~56 Ma) (Gernigon et al., 2020).

In both oceans, significant control was exerted by pre-existing structure. Orogenic belts were particularly influential. The Gakkel, Mohns and Aegir Ridges formed piecemeal and obliquely within the Caledonian suture (Schiffer et al., 2020). Old shear zones may also reactivate and guide breakup (Lundin et al., 2022). There is persuasive evidence for this from the Labrador Sea/Baffin Bay axis and the NE Atlantic. A major influential shear zone in the Arctic region may comprise the Canadian Arctic Transform System (CATS), a 4500-km-long lineament running along the north coast of Canada and into northern Norway (McClelland et al., 2021). Conjugate shear zones have also been proposed to run parallel with the Alpha-Mendeleev Rise and the Lomonosov Ridge. The Yenisey-Khatanga lineament between the Eurasia Basin and the Laptev Sea shelf (Fig. 2) has been proposed to be a large-scale transform fault (*e.g.*, Pease et al., 2014). It is a challenge for the future to test these hypotheses for the Arctic region. Commencement in shear is not ruled out for the Eurasia Basin and the Amerasia Basin, but recent seismic data find no evidence for such faults (Nikishin et al., 2018; Nikishin et al., 2021b; Nikishin et al., 2021c).

The proposal that the Alpha-Mendeleev Rise and the GIFR, parts of which are distant from passive margins, are underlain by hybrid crust requires further scrutiny. In particular, the extreme extension-parallel width of the GIFR – 1200 km – requires explanation. Regional breakup was initially engineered by oppositely propagating, laterally offset, ridges to the north and the south that did not connect across the frontal thrust of the Caledonian suture where the GIFR later developed (Section 4). As a result, continental crust was trapped in the newly forming ocean between the rift tips. Extension on the GIFR thereafter chronically proceeded along two or more rifts, allowing two pairs of passive margins to form and creating twice the normal width of hyper-extended volcanic margin.

Breakup across an orogenic front with thick crust has been modelled numerically using realistic physical parameters (Petersen et al., 2018). This modelling shows that, under reasonable assumptions, the process proposed is feasible. As a result of delamination of thick, orogenic, eclogitized lower crust, and mantle lithosphere, enhanced convection is stimulated in the upper mantle. This juxtaposes asthenosphere against the remaining crust, warming it, enhancing ductile flow, and prolonging stretching.

The dimensions of the Alpha-Mendeleev Rise, with its more modest ~500-km width, are within the normal range for a pair of passive margins. Numerical simulations of pre-breakup continental stretching demonstrate that passive margins as wide as 250 km can be built over a period of ~25 Myr. This requires low coupling between the crust and mantle lithosphere so the latter can extend without immediately rupturing the crust (Fig. 13) (Huismans and Beaumont, 2008; Lu and Huismans, 2021).

7. Discussion

It is inevitable that tectonic events in one region influence adjacent regions. At the time the NE Atlantic began to open *via* northward propagation of the mid-Atlantic Ridge, the Arctic region was already in a tectonically compliant state for breakup as a result of regional reduction in compression at the end of Verkhoyansk-Chukotka orogenic collision. Continental breakup occurs most easily *via* rift propagation (Franke et al., 2010; Franke et al., 2007) but where continental extension is extreme it may begin as disconnected segments. Those segments may, initially, be unable to connect up in a simple way. Currently, the mid-ocean plate boundary is continuous from the Gakkel Ridge south to the Reykjanes Ridge and beyond, albiet comprising several distinct sections. The plate rate increases from the Euler pole in northern Russia to ~2 cm/a at the Charlie-Gibbs Fracture Zone. As the spreading rate increases, so does the amount of classical oceanic crust and magma volumes (Lundin et al., 2018).

LIPs are envisaged to be short-lived, high-volume magmatic events and have been suggested to trigger continental breakup (Bryan and Ernst, 2008; Coffin and Eldholm, 1994; Sheth, 2007). However, neither the HALIP nor the NAIP fit easily into this model (Peace et al., 2020). The duration of the HALIP was ~45 Myr and that of the NAIP ~65 Myr or longer depending on the choice of start and end time. The volume rates followed, to a first order, the severity of extension. Full lithosphere rupture did not occur along with HALIP magmatism.

Crustal heating and weakening, as a result of magmatism, without doubt accompanies and facilitates deformation, hyper-extension and rupture of the continental lithosphere (*e.g.*, Buck, 2007). However, it does not appear to be a driver of it. Instead, it is a predicted consequence of lithosphere rupture. Full breakup of lithosphere 100 km or more thick allows asthenosphere from corresponding depths to upwell, triggering vigorous convection in the upper mantle. Finite-element modelling of this process and subsequent transition to steady state seafloor spreading that takes into account evolving temperature, pressure and spatial fields has been conducted. This modelling predicts large, initial volcanic-margin-building magmatic volumes followed by the smaller steady-state melt production that characterizes seafloor spreading (~6 km igneous crust equivalent) (Allken et al., 2012; Huismans and Beaumont, 2011; Huismans and Beaumont, 2008; Huismans and Beaumont, 2014; Simon et al., 2009; van Wijk et al., 2001) (Fig. 13). Depth-dependent extension resulting, for example, from rheological contrasts between

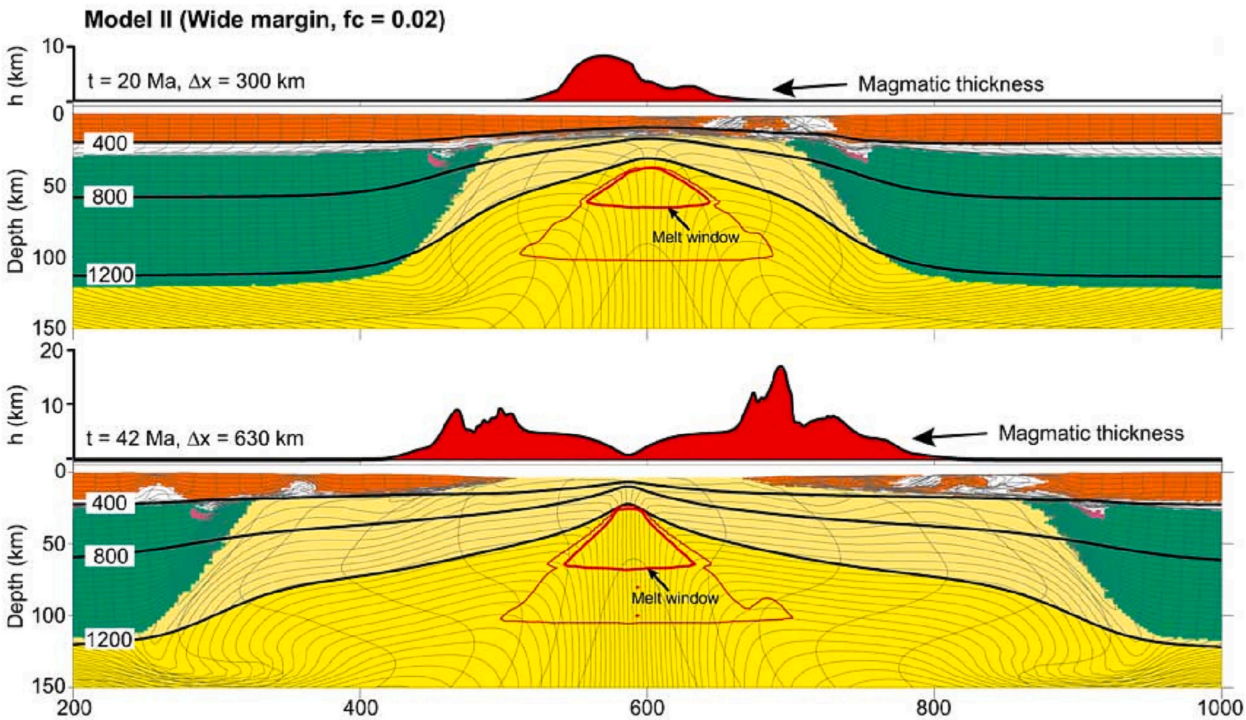

Fig. 13. Numerical model of melt production for breakup with a weak crust. Top part of each panel shows predicted magmatic thickness. t, time since the onset of extension, Δx, extension at a full speed of 1.5 cm/year. Bottom part of each panel shows composition overlain onto isotherms (black lines) in °C and incremental melt fraction (red lines). Thick red line: region of major decompression melting. Orange, upper crust; white, lower crust; green, continental mantle lithosphere; yellow: asthenosphere; pale yellow: oceanic lithosphere (from Lu and Huismans, 2021). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

upper and lower crust, can affect the apparent timing of volcanism relative to full breakup (Huismans and Beaumont, 2014; Lu and Huismans, 2021). Induction of LIP magmatism by continental breakup, which is in turn itself induced by far-field stress changes, should thus be the primary working hypothesis.

The LIP concept tends to assume that large-volume magmas result from the sudden arrival of a coherent package of source material with a definable center, and that emplacement has a clearly defined beginning, end, and geographic area (Campbell, 2006; Coffin and Eldholm, 1992). Neither the HALIP or the NAIP fit easily into this model. HALIP magmatism was widespread and prolonged. NAIP volcanism was the high-volume peak of long-term magmatism extending as far back as the Mesozoic and associated "failed breakup attempts" east of the Rockall-Hatton region and west of Greenland. The distribution of NAIP volcanics is not circular. They did not emanate from a single center, and breakup did not radiate away from them. It is furthermore unclear how extensive an area should be included (Peace et al., 2017; Peace et al., 2020).

Iceland is the only remaining subaerial section of the GIFR. Depending on whether the thick lower crust is igneous or continental, magmatic production there may be anomalously large (~0.06 km^3/a per 100-km-long ridge segment, if a spreading rate of 2 cm/a and a 30-km-thick melt layer is assumed) or only a typical mid-ocean-ridge volume rate (~0.01 km^3/a per 100-km-long ridge segment, if a 5-km-thick, typical oceanic crust is assumed). In the latter case, there would be little excess magma production rate needing to be explained (*e.g.*, by invoking high source temperatures) and contemporary volcanism in Iceland would comprise an essentially globally unique case of SDRs forming at the present day (Geoffroy et al., 2022b; Geoffroy et al., 2020). Estimated total volumes for the NAIP would also have to be downward revised by some 30% (Foulger et al., 2020a).

Why did extension evolve to full seafloor spreading in the NE Atlantic but not in the Arctic, even though both experienced continent-scale stress relaxation and passed through the stages of magmatic lithosphere destabilization? The answer is likely that whereas the Arctic Ocean was surrounded by continental regions and subduction zones, breakup was already ongoing immediately adjacent to the NE Atlantic. It is easier to form a new spreading ridge by propagation or enhancement of an already existing one, than it is to create a new one in isolation in the interior of an intact plate (*e.g.*, Franke et al., 2007). The NE Atlantic, and later the Eurasian Basin, were thus fundamentally continuations of continent-scale breakup more southerly in the Atlantic Ocean.

The processes and resulting structures in the Arctic-Atlantic region are not unique. The Davis Strait is, structurally, a close analog of the Alpha-Mendeleev Rise and the GIFR (Heron et al., 2019; Suckro et al., 2013). It formed where the north-propagating Labrador spreading axis met the transverse Nagssugtoqidian orogenic front and was unable to propagate through it. The Mozambique Channel, between Madagascar and Africa, developed as a result of detachment of the continental island of Madagascar from the African mainland between the end of the Jurassic and the Early Cretaceous (Dofal et al., 2021; Dofal et al., 2022). It separated from Africa in right-lateral transtension and the northern part of the channel – the Comoros Basin – may be underlain by stretched, sheared continental crust (Phethean et al., 2016). In the NW Indian Ocean, the north Laxmi Ridge/Pannikar Ridge crust is 17 km thick and likely continental (Geoffroy et al., 2020; Minshull et al., 2008). That region is likely an aborted continental extension system with conjugate volcanic passive margins which developed from extended continental crust (Collier et al., 2008; Guan et al., 2019). This process is similar to that proposed for the Alpha-Mendeleev Rise and the GIFR.

The South Atlantic Ocean provides further examples of wide, extended continental crust beneath its margins (*e.g.*, Tamara et al., 2020). The bathymetrically shallow region between the coast of Brazil and the Rio Grande Rise is ~500 km long and ~ 2000 km wide – considerably wider than the GIFR (see Foulger, 2018 for a summary). This zone is underlain by at least some continental crust though its quantity and distribution are unknown. It features anomalously thick crust and features a string of angular blocks, canyons, plateaus and circular edifices which may be volcanic. Blocks of continental crust are known to be distributed farther out in the South Atlantic. Granite has been dredged, and observed *in situ*, on the Rio Grande Rise itself (Santos et al., 2019). A little farther north, much of the Santos Basin-São Paulo Plateau region on the SE Brazilian margin, extensively explored for hydrocarbons, is thought to be underlain by stretched and thinned continental crust that extends out to several hundred kilometers from the shore, though the continuity of this is unsure (*e.g.*, Evain et al., 2015; Karner et al., 2021). These features developed where the north-propagating Atlantic spreading ridge stalled at a major pre-existing transverse structure comprising the junction between the Santos and Rio Plata blocks (Foulger, 2018; Franke et al., 2007; Kusznir et al., 2017; Peace et al., 2017). The spreading ridge in this area has also been chronically unstable and experienced at least four ridge jumps (Graça et al., 2019).

A terrestrial analog of these marine regions is the Basin and Range province in the western USA (Christiansen et al., 2002). This ~700-km-wide extensional region formed when subduction along the Californian coast ceased at ~17 Ma, reducing compression in the former back-arc hinterland (*e.g.*, Christiansen and McKee, 1978). LIP volcanism onset simultaneously, emplacing the Columbia River Basalts, and scattered, low-volume volcanism continues to be chronic throughout the region. Ongoing extension is focused on two dominant axes – a western and an eastern axis – separated by ~500 km (Christiansen et al., 2002; Foulger et al., 2015; Thatcher et al., 1999).

Bathymetry, the history and mechanics of continental breakup, and geological and geophysical observations suggest that many other regions in the oceans may be underlain by continental material. This may comprise partial sequences (*e.g.*, mid- and/or lower-continental crust only), possibly capped by lavas, or blocks of full-thickness continental crust. A $\sim 4.9 \times 10^6$ km^2 marine region around New Zealand that is floored by continental crust has been named 'Zealandia' (Mortimer et al., 2017). A $\sim 0.4 \times 10^6$ km^2 region in the Indian Ocean underlying Mauritius and the Seychelles, Mascarene Plateau, and Chagos-Maldive-Laccadive Ridge, has been suggested to contain continental material and named 'Mauritia' (Torsvik et al., 2013). The Tamayo Bank in the Gulf of California (Abera et al., 2015), Flemish Cap (Welford et al., 2012), Kerguelen Plateau (*e.g.*, Neuharth et al., 2021), Falkland Plateau and Exmouth Plateau are additional candidates.

8. Future work

The NE Atlantic and Arctic oceans have had contrasting histories of research. Research in the Arctic is predominantly ship-based. Research in the NE Atlantic away from shelf regions of interest for hydrocarbon production is typically done on a more modest scale and much is land-based in Iceland. The proposal that the GIFR has a continental substrate is based on very different data (isostasy, seismic attenuation, hypsometry, heat flow, petrology, magnetic, geological mapping and age-dating) from those used, independently, to reach a similar conclusion for the Alpha-Mendeleev Rise (mainly deep seismic reflection profiles). This naturally suggests future work that could be done in each ocean.

Specific targets for future research include:

- In the NE Atlantic, breakup was strongly influenced by pre-existing structure (see Schiffer et al., 2020 for a review). How did pre-existing structure influence the loci of extension in the Arctic, including possible inherited shear zones (Lundin et al., 2022)?
- The structure, timing and development of the Canada Basin is still unclear (Mosher and Hutchinson, 2019).
- In the NE Atlantic, Inner- and Outer-SDRs are distinguished (Geoffroy et al., 2020). Do the SDRs in the Arctic Ocean also follow this pattern?
- The total volumes of both NAIP and HALIP magmatism need to be recalculated (Dockman et al., 2018; Eldholm and Grue, 1994).
- In the NE Atlantic NAIP magmatism was followed by full lithosphere rupture with the possible exception of the GIFR. In contrast, in the Arctic Ocean, HALIP SDRs blanket regions that did not progress to seafloor spreading. What stage of lithosphere extension is intrinsic to LIP/SDR formation? How does this relate to the processes that induce intraplate LIP eruptions elsewhere including those associated both with and without later breakup (*e.g.*, the Deccan Traps and the Karoo flood basalt)?
- Site-specific numerical simulations to test the viability of the continental-crustal-flow model for formation of the GIFR.
- Extensive ultra-deep seismic reflection profiling such as imaged the deep structure of Alpha-Mendeleev Rise, if conducted on the GIFR, could settle once and for all the question of the composition of the deep crust of the GIFR. This, in turn, would inform the need or otherwise of invoking a mantle plume to explain the existence of Iceland (Foulger et al., 2020a).

Finally, advances could be made using petrological and geochemical approaches. Where mantle melts erupt through basalt-capped continental crust, OIB- and *E*-MORB geochemical signatures are expected (Lustrino and Anderson, 2015). This suggests that the common assumption that such geochemical signatures arise from geochemical reservoirs in the deep mantle (*e.g.*, Stracke et al., 2005) could be revisited.

9. Conclusions

1. Recent advances in understanding the NE Atlantic and Arctic Oceans, made using complementary approaches, make a comparison timely, informative, and point to key future research directions in both regions.
2. There is a systematic gradation from south to north in structure, tectonics and magmatic rates and volumes.
3. Extension and breakup in both oceans was permitted by relaxations of adjacent orogenic compressions.
4. Breakup in both oceans followed long histories of tectonic unrest. It was complex and piecemeal, with multiple axes extending simultaneously and frequent rift migrations. This style of magmatic extension continues in Iceland today.
5. The style of breakup was influenced by the nature of adjacent plate boundaries, pre-existing orogenic structures, and the proximity of propagating rifts.
6. The Alpha-Mendeleev Rise is underlain by hyper-extended continental crust draped with SDRs, a close analog of the GIFR. Much of the Arctic Ocean resembles the NE Atlantic at an early stage in the breakup process.
7. The two oceans are structurally similar. Both contain extensive continental crust. Seaward of the continental shelves as much as ~50% of the NE Atlantic Ocean is underlain by crust that is wholly or partly continental, and as much as ~80% of the Arctic Ocean.
8. Both oceans host LIPs that are consequences of crustal hyper-extension, not drivers of it. The HALIP did not precede breakup and the NAIP was not the centre from which breakup emanated. Magmatism may be most abundant where propagating rifts encounter barriers that stall progress.
9. Understanding LIP magmatism in the Arctic and NE Atlantic Oceans could inform the processes that produce intraplate LIPs.
10. Analogous regions elsewhere are the Mozambique Channel, NW Indian Ocean, South Atlantic and the Basin and Range province in the western USA.

CRediT authorship contribution statement

Gillian R. Foulger: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Conceptualization. **Anatoly M. Nikishin:** Writing – review & editing, Writing – original draft, Funding acquisition, Data curation, Conceptualization. **Ksenia F. Aleshina:** Writing – review & editing. **Elizaveta A. Rodina:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The work of A. Nikishin, E. Rodina and K. Aleshina was supported by Russian Science Foundation Grant 22-27-00160. The authors thank Editor G. Rosenbaum for his careful handling of the manuscript and constructive reviews, and two helpful anonymous reviewers.

References

Abdelmalak, M.M., Meyer, R., Planke, S., Faleide, J.I., Gernigon, L., Frieling, J., Sluijs, A., Reichart, G.J., Zastrozhnov, D., Theissen-Krah, S., Said, A., Myklebust, R., 2016. Pre-breakup magmatism on the Vøring margin: insight from new sub-basalt imaging and results from Ocean Drilling Program Hole 642E. Tectonophysics 675, 258–274.

Abdelmalak, M.M., Planke, S., Polteau, S., Hartz, E.H., Faleide, J.I., Tegner, C., Jerram, D.A., Millett, J.M., Myklebust, R., 2019. Breakup volcanism and plate tectonics in the NW Atlantic. Tectonophysics 760, 267–296.

Abera, R., Wijk, J., Axen, G.A., 2015. Formation of continental fragments: the Tamayo Bank, Gulf of California, Mexico. Geology 44, 595–598.

Akinin, V.V., et al., 2020. Episodicity and the dance of late Mesozoic magmatism and deformation along the northern circum-Pacific margin: North-Eastern Russia to the Cordillera. Earth Sci. Rev. 208, 103272.

Allken, V., Huismans, R.S., Thieulot, C., 2012. Factors controlling the mode of rift interaction in brittle-ductile coupled systems: a 3D numerical study. Geochem. Geophys. Geosyst. 13.

Alvey, A., Gaina, C., Kusznir, N.J., Torsvik, T.H., 2008. Integrated crustal thickness mapping and plate reconstructions for the high Arctic. Earth Planet. Sci. Lett. 274, 310–321.

Amundsen, H.E.F., Schaltegger, U., Jamtveit, B., Griffin, W.L., Podladchikov, Y.Y., Torsvik, T., Gronvold, K., 2002. Reading the LIPs of Iceland and Mauritius. In: Jamtveit, B., Amundsen, H.E.F. (Eds.), 15th Kongsberg Seminar, Kongsberg, Norway.

Angenheister, G., Gebrande, H., Miller, H., Goldflam, P., Weigel, W., Jacoby, W.R., Palmason, G., Bjornsson, S., Einarsson, P., Pavlenkova, N.I., Zverev, S.M., Litvinenko, I.V., Loncarevic, B., Solomon, S.C., 1980. Reykjanes ridge Iceland seismic experiment (RRISP 77). J. Geophys. 47, 228–238.

Backman, J., Moran, K., McInroy, D., the, I.E.S, 2005. IODP Expedition 302, Arctic Coring Expedition (ACEX): a first look at the Cenozoic Paleoceanography of the Central Arctic Ocean. Sci. Drill. 1, 12–17.

Barnett-Moore, N., Müller, D.R., Williams, S., Skogseid, J., Seton, M., 2018. A reconstruction of the North Atlantic since the earliest Jurassic. Basin Res. 30, 160–185.

Bédard, J., Troll, V., Deegan, F., Tegner, C., Saumur, B., Evenchick, C., Grasby, S., Dewing, K., 2021. High Arctic large Igneous Province Alkaline Rocks in Canada: evidence for multiple mantle components. J. Pet. 62.

Berglar, K., Franke, D., Lutz, R., Schreckenberger, B., Damm, V., 2016. Initial opening of the Eurasian Basin, Arctic Ocean. Front. Earth Sci. 4.

Bjarnason, I.T., Schmeling, H., 2009. The lithosphere and asthenosphere of the Iceland hotspot from surface waves. Geophys. J. Int. 178, 394–418.

Bjarnason, I.T., Menke, W., Flovenz, O.G., Caress, D., 1993. Tomographic image of the mid-Atlantic plate boundary in South-Western Iceland. J. Geophys. Res. 98, 6607–6622.

Blischke, A., Gaina, C., Hopper, J.R., Péron-Pinvidic, G., Brandsdóttir, B., Guarnieri, P., Erlendsson, Ö., Gunnarsson, K., 2017. The Jan Mayen microcontinent: an update of its architecture, structural development and role during the transition from the Ægir Ridge to the mid-oceanic Kolbeinsey Ridge. Geol. Soc. Lond. Spec. Publ. 447, 299.

Blischke, A., Brandsdóttir, B., Stoker, M.S., Gaina, C., Erlendsson, Ö., Tegner, C., Halldórsson, S.A., Helgadóttir, H.M., Gautason, B., Planke, S., Koppers, A.A.P., Hopper, J.R., 2022. Seismic volcanostratigraphy: the key to resolving the Jan Mayen Microcontinent and Iceland Plateau Rift evolution. Geochem. Geophys. Geosyst. 23 e2021GC009948.

Bohnhoff, M., Makris, J., 2004. Crustal structure of the southeastern Iceland-Faeroe Ridge (IFR) from wide aperture seismic data. J. Geodyn. 37, 233–252.

Borchardt, J.S., Lee, C.-T., 2022. Hot or Fertile Origin for continental break-up flood basalts: insights from olivine systematics. Lithosphere 2022, 7161484.

Bott, M.H.P., 1974. Deep structure, evolution and origin of the Icelandic transverse ridge. In: Kristjansson, L. (Ed.), Geodynamics of Iceland and the North Atlantic Area. D. Reidel Publishing Company, Dordrecht, pp. 33–48.

Bott, M.H.P., 1985. Plate tectonic evolution of the Icelandic transverse ridge and adjacent regions. J. Geophys. Res. 90, 9953–9960.

Bott, M.H.P., Gunnarsson, K., 1980. Crustal structure of the Iceland-Faeroe ridge. J. Geophys. 47, 221–227.

Brandsdóttir, B., Hooft, E.E.E., Mjelde, R., Murai, Y., 2015. Origin and evolution of the Kolbeinsey Ridge and Iceland Plateau, N-Atlantic. Geochem. Geophys. Geosyst. 16, 612–634.

Brotzer, A., Funck, T., Geissler, W.H., Piepjohn, K., Heyde, I., Berglar, K., 2022. Geophysical insights on the crustal structure of Greenland's northern continental margin towards the Morris Jesup Spur. Tectonophysics 843, 229588.

Bruvoll, V., Kristoffersen, Y., Coakley, B., Hopper, J., 2010. Hemipelagic deposits on the Mendeleev and northwestern Alpha submarine Ridges in the Arctic Ocean: acoustic stratigraphy, depositional environment and an inter-ridge correlation calibrated by the ACEX results. Mar. Geophys. Res. 31, 149–171.

Bruvoll, V., Kristoffersen, Y., Coakley, B., Hopper, J., Planke, S., Kandilarov, A., 2012. The nature of the acoustic basement on Mendeleev and northwestern Alpha ridges, Arctic Ocean. Tectonophysics 514-517, 123–145.

Bryan, S.E., Ernst, R.E., 2008. Revised definition of Large Igneous Province (LIP). Earth Sci. Rev. 86, 175–202.

Buchan, K., Ernst, R., 2018. A giant circumferential dyke swarm associated with the High Arctic large Igneous Province (HALIP). Gondwana Res. 58, 39–57.

Buck, W.R., 2007. 6.08 - Dynamic processes in extensional and compressional settings: the dynamics of continental breakup and extension. In: Schubert, G. (Ed.), Treatise on Geophysics. Elsevier, Amsterdam, pp. 335–376.

Campbell, I.H., 2006. Large Igneous Provinces and the mantle plume hypothesis. Elements 1, 265–269.

Chalmers, J.A., 2012. Labrador Sea, Davis Strait, and Baffin Bay. In: Roberts, D.G., Bally, A.W. (Eds.), Regional Geology and Tectonics: Phanerozoic Passive Margins, Cratonic Basins and Global Tectonic Maps. Elsevier, Boston, pp. 384–435.

Chauvet, F., Geoffroy, L., Guillou, H., Maury, R., Le Gall, B., Agranier, A., Viana, A., 2019. Eocene continental breakup in Baffin Bay. Tectonophysics 757, 170–186.

Chian, D., Jackson, H., Hutchinson, D.R., Shimeld, J.W., Oakey, G.N., Lebedeva-Ivanova, N., Li, Q., Saltus, R., Mosher, D.C., 2016. Distribution of crustal types in Canada Basin, Arctic Ocean. Tectonophysics 691, 8–30.

Christiansen, R.L., McKee, E.H., 1978. Late Cenozoic volcanic and tectonic evolution of the Great Basin and Columbia Intermontane region. In: Smith, R.B., Eaton, G.P. (Eds.), Cenozoic Tectonics and Regional Geophysics of the Western Cordillera. Geological Society of America, pp. 283–312.

Christiansen, R.L., Foulger, G.R., Evans, J.R., 2002. Upper mantle origin of the Yellowstone hotspot. Bull. Geol. Soc. Am. 114, 1245–1256.

Clarke, D.B., Beutel, E.K., 2020. Davis Strait Paleocene picrites: products of a plume or plates? Earth Sci. Rev. 206, 102770.

Clift, P.D., 2005. Sedimentary evidence for moderate mantle temperature anomalies associated with hotspot volcanism. In: Foulger, G.R., Natland, J.H., Presnall, D.C., Anderson, D.L. (Eds.), Plates, Plumes, and Paradigms. Geological Society of America, pp. 279–288.

Coakley, B., Brumley, K., Lebedeva-Ivanova, N., Mosher, D., 2016. Exploring the geology of the Central Arctic Ocean; understanding the basin features in place and time. J. Geol. Soc. Lond. 173, 967–987.

Coffin, M.F., Eldholm, O., 1992. Volcanism and continental break-up: a global compilation of large igneous provinces. In: Storey, B.C., Alabaster, T., Pankhurst, R. J. (Eds.), Magmatism and the Causes of Continental Break-up, pp. 17–30.

Coffin, M.F., Eldholm, O., 1993. Scratching the surface: estimating dimensions of large igneous provinces. Geology 21, 515–518.

Coffin, M.F., Eldholm, O., 1994. Large igneous provinces: crustal structure, dimensions and external consequences. Rev. Geophys. 32, 1–36.

Cole, J.E., Peachey, J., 1999. Evidence for pre-cretaceous rifting in the Rockall Trough: an analysis using quantitative plate tectonic modelling. Geol. Soc. Lond. Petrol. Geol. Conf. Ser. 5, 359–370.

Collier, J.S., Sansom, V., Ishizuka, O., Taylor, R.N., Minshull, T.A., Whitmarsh, R.B., 2008. Age of Seychelles–India break-up. Earth Planet. Sci. Lett. 272, 264–277.

Corfu, F., Polteau, S., Planke, S., Faleide, J.I., Svensen, H., Zayoncheck, A., Stolbov, N., 2013. U–Pb geochronology of Cretaceous magmatism on Svalbard and Franz Josef Land, Barents Sea Large Igneous Province. Geol. Mag. 150, 1127–1135.

Corti, G., Van Wijk, J., Bonini, M., Sokoutis, D., Cloetingh, S., Innocenti, F., Manetti, P., 2003. Transition from continental break-up to punctiform seafloor spreading: how fast, symmetric and magmatic. Geophys. Res. Lett. 30.

Darbyshire, F.A., Bjarnason, I.T., White, R.S., Flovenz, O.G., 1998. Crustal structure above the Iceland mantle plume imaged by the ICEMELT refraction profile. Geophys. J. Int. 135, 1131–1149.

Deegan, F.M., Pease, V., Nobre Silva, I.G., Bédard, J.H., Morris, G., 2023. Age and geochemistry of high Arctic large Igneous Province Tholeiitic Magmatism in NW Axel Heiberg Island, Canada. Geochem. Geophys. Geosyst. 24 e2023GC011083.

Denk, T., Grímsson, F., Zetter, R., Símonarson, L.A., 2011. The Biogeographic History of Iceland – The North Atlantic Land Bridge Revisited, Late Cainozoic Floras of Iceland. Springer Science, pp. 647–668.

Detrick, R.S., Sclater, J.G., Thiede, J., 1977. The subsidence of aseismic ridges. Earth Planet. Sci. Lett. 34, 185–196.

Dockman, D.M., Pearson, D.G., Heaman, L.M., Gibson, S.A., Sarkar, C., 2018. Timing and origin of magmatism in the Sverdrup Basin, Northern Canada—implications for lithospheric evolution in the High Arctic Large Igneous Province (HALIP). Tectonophysics 742-743, 50–65.

Dofal, A., Fontaine, F.R., Michon, L., Barruol, G., Tkalčić, H., 2021. Nature of the crust beneath the islands of the Mozambique Channel: constraints from receiver functions. J. Afr. Earth Sci. 184, 104379.

Dofal, A., Michon, L., Fontaine, F.R., Rindraharisaona, E., Barruol, G., Tkalčić, H., 2022. Imaging the lithospheric structure and plumbing system below the Mayotte volcanic zone. C. R. Géosci. 354, 47–64.

Døssing, A., Hopper, J., Olesen, A., Rasmussen, T., Halpenny, J., 2013a. New aero-gravity results from the Arctic: linking the latest Cretaceous-early Cenozoic plate kinematics of the North Atlantic and Arctic Ocean: new aero-gravity results, Arctic Ocean. Geochem. Geophys. Geosyst. 14, 4044–4065.

Døssing, A., Jackson, H., Matzka, J., Einarsson, I., Rasmussen, T., Olesen, A.V., Brozena, J., 2013b. On the origin of the Amerasia Basin and the High Arctic large Igneous Province—results of new aeromagnetic data. Earth Planet. Sci. Lett. 363, 219–230.

Døssing, A., Gaina, C., Jackson, H.R., Andersen, O.B., 2020. Cretaceous ocean formation in the High Arctic. Earth Planet. Sci. Lett. 551, 116552.

Dove, D., Coakley, B., Hopper, J., Kristoffersen, Y., 2010. Bathymetry, controlled source seismic and gravity observations of the Mendeleev ridge; implications for ridge structure, origin, and regional tectonics. Geophys. J. Int. 183, 481–502.

Drachev, S., Saunders, A.D., 2006. The early cretaceous Arctic LIP: its geodynamic setting and implications for Canada Basin opening. In: Scott, R.A., Thurston, D.K. (Eds.), Proceedings of the Fourth International Conference on Arctic Margins. US Department of the Interior MMS, Dartmouth, Nova Scotia, Canada, pp. 216–223.

Ehlers, B.-M., Jokat, W., 2013. Paleo-bathymetry of the northern North Atlantic and consequences for the opening of the Fram Strait. Mar. Geophys. Res. 34, 25–43.

Einarsson, P., 1988. The South Iceland Seismic Zone. Episodes 11, 34–35.

Einarsson, P., 1991. Earthquakes and present-day tectonism in Iceland. Tectonophysics 189, 261–279.

Eldholm, O., Grue, K., 1994. North Atlantic volcanic margins: dimensions and production rates. J. Geophys. Res. 99, 2955–2968.

Ellis, D., Stoker, M.S., 2014. The Faroe–Shetland Basin: a regional perspective from the Paleocene to the present day and its relationship to the opening of the North Atlantic Ocean. In: Cannon, S.J.C., Ellis, D. (Eds.), Hydrocarbon Exploration to Exploitation West of Shetlands. Geological Society, London, London, pp. 11–31.

Evain, M., Afilhado, A., Rigoti, C., Loureiro, A., Alves, D., Klingelhoefer, F., Schnurle, P., Feld, A., Fuck, R., Soares, J., de Lima, M.V., Corela, C., Matias, L., Benabdellouahed, M., Baltzer, A., Rabineau, M., Viana, A., Moulin, M., Aslanian, D., 2015. Deep structure of the Santos Basin-São Paulo Plateau System, SE Brazil. J. Geophys. Res. Solid Earth 120, 5401–5431.

Evangelatos, J., Funck, T., Mosher, D., 2016. The sedimentary and crustal velocity structure of Makarov Basin and adjacent Alpha Ridge. Tectonophysics 696, 99–114.

Evenchick, C., Davis, W., Bédard, J., Hayward, N., Friedman, R., 2015. Evidence for protracted High Arctic large igneous province magmatism in the Central Sverdrup Basin from stratigraphy, geochronology, and paleodepths of saucer-shaped sills. Geol. Soc. Am. Bull. 127, 1366–1390.

Foulger, G.R., 2006. Older crust underlies Iceland. Geophys. J. Int. 165, 672–676.

Foulger, G.R., 2018. Origin of the South Atlantic igneous province. J. Volcanol. Geotherm. Res. 355, 2–20.

Foulger, G.R., Du, Z., Julian, B.R., 2003. Icelandic-type crust. Geophys. J. Int. 155, 567–590.

Foulger, G.R., Christiansen, R.L., Anderson, D.L., 2015. The Yellowstone "hot spot" track results from migrating basin-range extension. In: Foulger, G.R., Lustrino, M., King, S. D. (Eds.), The Interdisciplinary Earth: A Volume in Honor of Don L. Anderson. Geological Society of America, Boulder, CO, pp. 215–238.

Foulger, G.R., Doré, T., Emeleus, C.H., Franke, D., Geoffroy, L., Gernigon, L., Hey, R., Holdsworth, R.E., Hole, M., Höskuldsson, Á., Julian, B., Kusznir, N., Martinez, F., McCaffrey, K.J.W., Natland, J.H., Peace, A.L., Petersen, K., Schiffer, C., Stephenson, R., Stoker, M., 2020a. The Iceland Microcontinent and a continental Greenland-Iceland-Faroe Ridge. Earth Sci. Rev. 206, 102926.

Foulger, G.R., Schiffer, C., Peace, A.L., 2020b. A new paradigm for the North Atlantic Realm. Earth Sci. Rev. 206, 103038.

Foulger, G.R., Gernigon, L., Geoffroy, L., 2022. Icelandia. In: Foulger, G.R., Hamilton, L. C., Jurdy, D.M., Stein, C.A., Howard, K.A., Stein, S. (Eds.), In the Footsteps of Warren B. Hamilton: New Ideas in Earth Science. The Geological Society of America, Boulder, CO.

Franke, D., Neben, S., Ladage, S., Schreckenberger, B., Hinz, K., 2007. Margin segmentation and volcano-tectonic architecture along the volcanic margin off Argentina/Uruguay, South Atlantic. Mar. Geol. 244, 46–67.

Franke, D., Ladage, S., Schnabel, M., Schreckenberger, B., Reichert, C., Hinz, K., Paterlini, M., Abelleyra, J.d., Siciliano, M., 2010. Birth of a volcanic margin off Argentina, South Atlantic. Geochem. Geophys. Geosyst. 11.

Franke, D., Klitzke, P., Barckhausen, U., Berglar, K., Berndt, C., Damm, V., Dannowski, A., Ehrhardt, A., Engels, M., Funck, T., Geissler, W., Schnabel, M., Thorwart, M., Trinhammer, P., 2019. Polyphase magmatism during the formation of the Northern East Greenland Continental margin. Tectonics 38, 2961–2982.

Funck, T., Shimeld, J., 2023. Crustal structure and magmatism of the Marvin Spur and northern Alpha Ridge, Arctic Ocean. Geophys. J. Int. 233, 740–768.

Funck, T., Erlendsson, Ö., Geissler, W.H., Gradmann, S., Kimbell, G.S., McDermott, K., Petersen, U.K., 2017. A review of the NE Atlantic conjugate margins based on seismic refraction data. Geol. Soc. Lond. Spec. Publ. 447, 171–205.

Funck, T., Shimeld, J., Salisbury, M., 2022. Magmatic and rifting-related features of the Lomonosov Ridge, and relationships to the continent-ocean transition zone in the Amundsen Basin, Arctic Ocean. Geophys. J. Int. 229, 1309–1337.

Gac, S., Minakov, A., Shephard, G.E., Faleide, J.I., Planke, S., 2020. Deformation analysis in the Barents Sea in relation to Paleogene transpression along the Greenland-Eurasia Plate Boundary. Tectonics 39 e2020TC006172.

Gaina, C., Gernigon, L., Ball, P., 2009. Palaeocene–Recent plate boundaries in the NE Atlantic and the formation of the Jan Mayen microcontinent. J. Geol. Soc. Lond. 166, 1–16.

Gaina, C., Werner, S., Saltus, R., Maus, S., Aaro, S., Damaske, D., Forsberg, R., Glebovsky, V., Johnson, K., Jonberger, J., Koren, T., Korhonen, J., Litvinova, T., Oakey, G., Olesen, O., Petrov, O., Pilkington, M., Rasmussen, T., Schreckenberger, B., Smelror, M., 2011. Chapter 3: Circum-Arctic mapping project: new magnetic and gravity anomaly maps of the Arctic, Vol. 35. Geological Society Memoir, pp. 39–48.

Gaina, C., Nikishin, A.M., Petrov, E.I., 2015. Ultraslow spreading, ridge relocation and compressional events in the East Arctic region: a link to the Eurekan orogeny? arktos 1, 16.

Gaina, C., Nasuti, A., Kimbell, G.S., Blischke, A., 2017. Break-up and seafloor spreading domains in the NE Atlantic. Geol. Soc. Lond. Spec. Publ. 447, 393–417.

Gallahue, M.M., Stein, S., Stein, C.A., Jurdy, D., Barklage, M., Rooney, T.O., 2020. A compilation of igneous rock volumes at volcanic passive continental margins from interpreted seismic profiles. Mar. Pet. Geol. 122, 104635.

Galloway, B.J., Dewing, K., Beauchamp, B., 2018. Upper Paleozoic hydrocarbon systems in the Sverdrup Basin, Canadian Arctic Islands. Mar. Pet. Geol. 92, 809–821.

Geoffroy, L., 2005. Volcanic passive margins. Compt. Rendus Geosci. 337, 1395–1408.

Geoffroy, L., Burov, E.B., Werner, P., 2015. Volcanic passive margins: another way to break up continents. Sci. Rep. 5, 14828.

Geoffroy, L., Guan, H., Gernigon, L., Foulger, G.R., Werner, P., 2020. The extent of continental material in oceans: C-Blocks and the Laxmi Basin example. Geophys. J. Int. 222, 1471–1479.

Geoffroy, L., Chauvet, F., Ringenbach, J.-C., 2022a. Middle-lower continental crust exhumed at the distal edges of volcanic passive margins. Commun. Earth Environ. 3, 95.

Geoffroy, L., Gernigon, L., Foulger, G.R., 2022b. Linear magnetic anomalies and the limits of oceanic crust in oceans. In: Foulger, G.R., Jurdy, D.M., Stein, C.A., Hamilton, L.C., Howard, K., Stein, S. (Eds.), In the Footsteps of Warren B. Hamilton: New Ideas in Earth Science. Geological Society of America, Boulder, CO.

Gernigon, L., Ringenbach, J.C., Planke, S., Gall, B.L., Jonquet-Kolsto, H., 2003. Extension, crustal structure and magmatism at the outer Vøring Basin, Norwegian margin. J. Geol. Soc. Lond. 160, 197–208.

Gernigon, L., Gaina, C., Olesen, O., Ball, P.J., Péron-Pinvidic, G., Yamasaki, T., 2012. The Norway Basin revisited: from continental breakup to spreading ridge extinction. Mar. Pet. Geol. 35, 1–19.

Gernigon, L., Blischke, A., Nasuti, A., Sand, M., 2015. Conjugate volcanic rifted margins, seafloor spreading, and microcontinent: insights from new high-resolution aeromagnetic surveys in the Norway Basin. Tectonics 34, 907–933.

Gernigon, L., Franke, D., Geoffroy, L., Schiffer, C., Foulger, G.R., Stoker, M., 2020. Crustal fragmentation, magmatism, and the diachronous opening of the Norwegian-Greenland Sea. Earth Sci. Rev. 206, 102839.

Gernigon, L., Zastrozhnov, D., Planke, S., Manton, B., Abdelmalak, M.M., Olesen, O., Maharjan, D., Faleide, J.I., Myklebust, R., 2021. A digital compilation of structural and magmatic elements of the Mid-Norwegian continental margin (version 1.0). Nor. J. Geol. 101, 202112.

Glebovsky, V.Y., Zaionchek, A., Kaminsky, V., Maschenkov, S., 2002. Digital data bases and maps of potential fields of the Arctic Ocean. In: The Russian Arctic: Geological History, Mineragenesis, Environmental Geology, pp. 134–141.

Glebovsky, V.Y., Kaminsky, V.D., Minakov, A.N., Merkur'ev, S.A., Childers, V.A., Brozena, J.M., 2006. Formation of the Eurasia Basin in the Arctic Ocean as inferred from geohistorical analysis of the anomalous magnetic field. Geotectonics 40, 263–281.

Graça, M.C., Kusznir, N., Gomes Stanton, N.S., 2019. Crustal thickness mapping of the central South Atlantic and the geodynamic development of the Rio Grande Rise and Walvis Ridge. Mar. Pet. Geol. 101, 230–242.

Guan, H., Geoffroy, L., Gernigon, L., Chauvet, F., Grigné, C., Werner, P., 2019. Magmatic Ocean-continent transitions. Mar. Pet. Geol. 104, 438–450.

Gudmundsson, O., 2003. The dense root of the Iceland crust. Earth Planet. Sci. Lett. 206, 427–440.

Hegewald, A., Jokat, W., 2013. Tectonic and sedimentary structures in the Northern Chukchi Region, Arctic Ocean. J. Geophys. Res. 118, 3285–3296.

Helgason, J., 1984. Frequent shifts of the volcanic zone in Iceland. Geology 12, 212–216.

Heron, P.J., Peace, A.L., McCaffrey, K.J.W., Welford, J.K., Wilson, R., van Hunen, J., Pysklywec, R.N., 2019. Segmentation of rifts through structural inheritance: creation of the Davis Strait. Tectonics 38, 2411–2430.

Hey, R., Martinez, F., Höskuldsson, A., Benediktsdóttir, A., 2010. Propagating rift model for the V-shaped ridges south of Iceland. Geochem. Geophys. Geosyst. 11.

Hitchen, K., Ritchie, J.D., 1987. Geological review of the West Shetland area. In: Brooks, J.G.K. (Ed.), Petroleum Geology of North West Europe. Graham & Trotman, London, pp. 737–749.

Hjartarson, Á., Erlendsson, Ö., Blischke, A., 2017. The Greenland–Iceland–Faroe Ridge complex. Geol. Soc. Lond. Spec. Publ. 447, 127.

Hole, M.J., Natland, J.H., 2020. Magmatism in the North Atlantic Igneous Province; mantle temperatures, rifting and geodynamics. Earth Sci. Rev. 206, 102794.

Huismans, R.S., Beaumont, C., 2008. Complex rifted continental margins explained by dynamical models of depth-dependent lithospheric extension. Geology 36, 163–166.

Huismans, R., Beaumont, C., 2011. Depth-dependent extension, two-stage breakup and cratonic underplating at rifted margins. Nature 473, 74.
Huismans, R.S., Beaumont, C., 2014. Rifted continental margins: the case for depth-dependent extension. Earth Planet. Sci. Lett. 407, 148–162.
Hutchinson, D.R., Jackson, H., Houseknecht, D., Li, Q., Shimeld, J.W., Mosher, D.C., Chian, D., Saltus, R., Oakey, G.N., 2017. Significance of northeast-trending features in Canada Basin, Arctic Ocean. Geochem. Geophys. Geosyst. 18.
Ilhan, I., Coakley, B., Houseknecht, D., 2018. Meso–Cenozoic evolution of the Chukchi Shelf and North Chukchi Basin, Arctic Ocean. Mar. Pet. Geol. 95, 100–109.
Jakobsson, M., Mayer, L.A., Bringensparr, C., Castro, C.F., Mohammad, R., Johnson, P., Ketter, T., Accettella, D., Amblas, D., An, L., Arndt, J.E., Canals, M., Casamor, J.L., Chauché, N., Coakley, B., Danielson, S., Demarte, M., Dickson, M.-L., Dorschel, B., Dowdeswell, J.A., Dreutter, S., Fremand, A.C., Gallant, D., Hall, J.K., Hehemann, L., Hodnesdal, H., Hong, J., Ivaldi, R., Kane, E., Klaucke, I., Krawczyk, D.W., Kristoffersen, Y., Kuipers, B.R., Millan, R., Masetti, G., Morlighem, M., Noormets, R., Prescott, M.M., Rebesco, M., Rignot, E., Semiletov, I., Tate, A.J., Travaglini, P., Velicogna, I., Weatherall, P., Weinrebe, W., Willis, J.K., Wood, M., Zarayskaya, Y., Zhang, T., Zimmermann, M., Zinglersen, K.B., 2020. The international bathymetric chart of the Arctic Ocean Version 4.0. Sci. Data 7, 176.
Japsen, P., Green, P.F., Chalmers, J.A., 2023. Synchronous exhumation episodes across Arctic Canada, North Greenland and Svalbard in relation to the Eurekan Orogeny. Gondwana Res. 117, 207–229.
Jokat, W., Ickrath, M., 2015. Structure of ridges and basins off East Siberia along 81°N, Arctic Ocean. Mar. Pet. Geol. 64, 222–232.
Jokat, W., Schmidt-Aursch, M.C., 2007. Geophysical characteristics of the ultraslow spreading Gakkel Ridge, Arctic Ocean. Geophys. J. Int. 168, 983–998.
Jokat, W., Ickrath, M., O'Connor, J., 2013. Seismic transect across the Lomonosov and Mendeleev Ridges: constraints on the geological evolution of the Amerasia Basin, Arctic Ocean. Geophys. Res. Lett. 40, 5047–5051.
Jokat, W., Lehmann, P., Damaske, D., Bradley Nelson, J., 2016. Magnetic signature of North-East Greenland, the Morris Jesup rise, the Yermak Plateau, the central Fram Strait: constraints for the rift/drift history between Greenland and Svalbard since the Eocene. Tectonophysics 691, 98–109.
Jokat, W., O'Connor, J., Hauff, F., Koppers, A., Miggins, D., 2019. Ultraslow spreading and volcanism at the eastern end of Gakkel Ridge, Arctic Ocean. Geochem. Geophys. Geosyst. 20.
Jones, S.M., White, N., Maclennan, J., 2002. V-shaped ridges around Iceland; implications for spatial and temporal patterns of mantle convection. Geochem. Geophys. Geosyst. 3, 2002GC000361.
Karner, G.D., Johnson, C., Shoffner, J., Lawson, M., Sullivan, M., Sitgreaves, J., McHarge, J., Stewart, J., Figueredo, P., 2021. Tectono-magmatic development of the santos and campos basins, offshore Brazil. In: Mello, M.R., Yilmaz, P.O., Katz, B.J. (Eds.), The Supergiant Lower Cretaceous Pre-Salt Petroleum Systems of the Santos Basin, Brazil. The American Association of Petroleum Geologists and Brazilpetrostudies, pp. 215–256.
Kashubin, S.N., Petrov, O.V., Artemieva, I.M., Morozov, A.F., Vyatkina, D.V., Golysheva, Y.S., Kashubina, T.V., Milshtein, E.D., Rybalka, A.V., Erinchek, Y.M., Sakulina, T.S., Krupnova, N.A., Shulgin, A.A., 2018. Crustal structure of the Mendeleev rise and the Chukchi Plateau (Arctic Ocean) along the Russian wide-angle and multichannel seismic reflection experiment "Arctic-2012". J. Geodyn. 119, 107–122.
Keen, C.E., Dickie, K., Dafoe, L.T., 2018. Structural evolution of the rifted margin off Northern Labrador: the role of hyperextension and magmatism. Tectonics 37, 1955–1972.
Kingsbury, C.G., Kamo, S.L., Ernst, R.E., Söderlund, U., Cousens, B.L., 2018. U-Pb geochronology of the plumbing system associated with the late cretaceous Strand Fiord Formation, Axel Heiberg Island, Canada: part of the 130-90 Ma High Arctic large igneous province. J. Geodyn. 118, 106–117.
Kristoffersen, Y., Hall, J.K., Nilsen, E.H., 2021. Morris Jesup Spur and Rise north of Greenland – exploring present seabed features, the history of sediment deposition, volcanism and tectonic deformation at a Late Cretaceous/early Cenozoic triple junction in the Arctic Ocean. Nor. J. Geol. 101.
Kusznir, N., Alvey, A., Graça, M.C., 2017. Intra-ocean Ridge Jumps, Oceanic Plateaus & Upper Mantle Inheritance, Proceedings of the William Smith Meeting 2017: Plate Tectonics at 50. The Geological Society, London, pp. 41–43.
Lu, G., Huismans, R.S., 2021. Melt volume at Atlantic volcanic rifted margins controlled by depth-dependent extension and mantle temperature. Nat. Commun. 12, 3894.
Lundin, E.R., Doré, A.G., 2019. Non-Wilsonian break-up predisposed by transforms: examples from the North Atlantic and Arctic. Geol. Soc. Lond. Spec. Publ. 470, 375.
Lundin, E.R., Doré, A.G., Redfield, T.F., 2018. Magmatism and extension rates at rifted margins. Pet. Geosci. 24, 379–392.
Lundin, E.R., Doré, A.G., Naliboff, J., Wijk, J.V., 2022. Utilization of continental transforms in break-up: observations, models, and a potential link to magmatism. Geol. Soc. Lond., Spec. Publ. 524.
Lustrino, M., Anderson, D.L., 2015. The mantle isotopic printer. Basic mantle plume geochemistry for seismologists and geodynamicists. In: Foulger, G.R., Lustrino, M., King, S.D. (Eds.), The Interdisciplinary Earth: A Volume in Honor of Don L. Anderson. Geological Society of America, Boulder, CO, pp. 257–279.
Lutz, R., Franke, D., Berglar, K., Heyde, I., Schreckenberger, B., Klitzke, P., Geissler, W., 2018. Evidence for mantle exhumation since the early evolution of the slow-spreading Gakkel Ridge, Arctic Ocean. J. Geodyn. 118, 154–165.
Martinez, F., Hey, R., 2022. Mantle melting, lithospheric strength and transform fault stability: insights from the North Atlantic. Earth Planet. Sci. Lett. 579, 117351.
Martinez, F., Hey, R., Höskuldsson, Á., 2020. Reykjanes Ridge evolution: effects of plate kinematics, small-scale upper mantle convection and a regional mantle gradient. Earth Sci. Rev. 206, 102956.
McClelland, W.C., Strauss, J.V., Colpron, M., Gilotti, J.A., Faehnrich, K., Malone, S.J., Gehrels, G.E., MacDonald, F.A., Oldow, J.S., 2021. Taters versus sliders; evidence for a long-lived history of strike-slip displacement along the Canadian Arctic transform system (CATS). GSA Today 31, 4–11.
Menke, W., 1999. Crustal isostasy indicates anomalous densities beneath Iceland. Geophys. Res. Lett. 26, 1215–1218.
Menke, W., Levin, V., 1994. Cold crust in a hot spot. Geophys. Res. Lett. 21, 1967–1970.
Menke, W., Levin, V., Sethi, R., 1995. Seismic attenuation in the crust at the mid-Atlantic plate boundary in south-west Iceland. Geophys. J. Int. 122, 175–182.
Menke, W., Brandsdottir, B., Einarsson, P., Bjarnason, I.T., 1996. Reinterpretation of the RRISP-77 Iceland shear-wave profiles. Geophys. J. Int. 126, 166–172.
Michael, P.J., Langmuir, C.H., Dick, H.J.B., Snow, J.E., Goldstein, S.L., Graham, D.W., Lehnert, K., Kurras, G., Jokat, W., Mühe, R., Edmonds, H.N., 2003. Magmatic and amagmatic seafloor generation at the ultraslow-spreading Gakkel ridge, Arctic Ocean. Nature 423, 956–961.
Midtkandal, I., Svensen, H.H., Planke, S., Corfu, F., Polteau, S., Torsvik, T.H., Faleide, J. I., Grundvåg, S.-A., Selnes, H., Kürschner, W., Olaussen, S., 2016. The Aptian (Early Cretaceous) oceanic anoxic event (OAE1a) in Svalbard, Barents Sea, and the absolute age of the Barremian-Aptian boundary. Palaeogeogr. Palaeoclimatol. Palaeoecol. 463, 126–135.
Minakov, A., Yarushina, V., Faleide Jan, I., Krupnova, N., Sakoulina, T., Dergunov, N., Glebovsky, V., 2018. Dyke emplacement and crustal structure within a continental large igneous province, northern Barents Sea. Geol. Soc. Lond. Spec. Publ. 460, 371–395.
Minshull, T.A., Lane, C.I., Collier, J.S., Whitmarsh, R.B., 2008. The relationship between rifting and magmatism in the northeastern Arabian Sea. Nat. Geosci. 1, 463–467.
Mortimer, N., Campbell, H.J., Tulloch, A.J., King, P.R., Stagpoole, V., Wood, R.A., Rattenbury, M.S., Sutherland, R., Adams, C.J., Collot, J., Seton, M., 2017. Zealandia: Earth's hidden continent. GSA Today 27, 27–35.
Mosher, D.C., Hutchinson, D.R., 2019. Canada Basin. In: Piskarev, A., Poselov, V., Kaminsky, V. (Eds.), Geologic Structures of the Arctic Basin. Springer International Publishing, Cham, pp. 295–325.
Mosher, D.C., Shimeld, J., Hutchinson, D., Chian, D., Lebedova-Ivanova, N., Jackson, R., 2012. Canada Basin revealed. In: Society of Petroleum Engineers – Arctic Technology Conference, pp. 805–815.
Mosher, D.C., Dickson, M.-L., Shimeld, J., Jackson, H.R., Oakey, G.N., Boggild, K., Campbell, D.C., Travaglini, P., Rainey, W.-A., Murphy, A., Dehler, S., Ells, J., 2023. Canada's maritime frontier: the science legacy of Canada's extended continental shelf mapping for UNCLOS. Can. J. Earth Sci. 60, 1–51.
Mudge, D.C., Rashid, B., 1987. The geology of the Faeroe Basin area. In: Brooks, J.G., K. (Eds.), Petroleum Geology of North West Europe. Graham & Trotman, London, pp. 751–763.
Mukasa, S.B., Andronikov, A., Brumley, K., Mayer, L.A., Armstrong, A., 2020. Basalts from the Chukchi Borderland: 40Ar/39Ar ages and geochemistry of submarine intraplate lavas dredged from the Western Arctic Ocean. J. Geophys. Res. 125 e2019JB017604.
Nasuti, A., Olesen, O., 2014. Magnetic data. In: Hopper, J.R., Funck, T., Stoker, T., Arting, U., Peron-Pinvidic, G., Doornebal, H., Gaina, C. (Eds.), Tectonostratigraphic Atlas of the North-East Atlantic Region. Geological Survey of Denmark and Greenland (GEUS), Copenhagen, Denmark, pp. 41–51.
Neuharth, D., Brune, S., Glerum, A., Heine, C., Welford, J.K., 2021. Formation of continental microplates through rift linkage: numerical modeling and its application to the Flemish Cap and Sao Paulo Plateau. Geochem. Geophys. Geosyst. 22 e2020GC009615.
Nielsen, S.B., Stephenson, R., Thomsen, E., 2007. Dynamics of Mid-Palaeocene North Atlantic rifting linked with European intra-plate deformations. Nature 450, 1071–1074.
Nikishin, A.M., Malyshev, N.A., Petrov, E.I., 2014. Geological Structure and History of the Arctic Ocean. EAGE Publications bv, Netherlands.
Nikishin, A.M., Gaina, C., Petrov, E.I., Malyshev, N.A., Freiman, S.I., 2018. Eurasia Basin and Gakkel Ridge, Arctic Ocean: crustal asymmetry, ultra-slow spreading and continental rifting revealed by new seismic data. Tectonophysics 746, 64–82.
Nikishin, A.M., Petrov, E.I., Cloetingh, S., Freiman, S.I., Malyshev, N.A., Morozov, A.F., Posamentier, H.W., Verzhbitsky, V.E., Zhukov, N.N., Startseva, K., 2021a. Arctic Ocean Mega Project: Paper 3 - Mesozoic to Cenozoic geological evolution. Earth Sci. Rev. 217, 103034.
Nikishin, A.M., Petrov, E.I., Cloetingh, S., Korniychuk, A.V., Morozov, A.F., Petrov, O.V., Poselov, V.A., Beziazykov, A.V., Skolotnev, S.G., Malyshev, N.A., Verzhbitsky, V.E., Posamentier, H.W., Freiman, S.I., Rodina, E.A., Startseva, K.F., Zhukov, N.N., 2021b. Arctic Ocean mega Project: Paper 1 - data collection. Earth Sci. Rev. 217, 103559.
Nikishin, A.M., Petrov, E.I., Cloetingh, S., Malyshev, N.A., Morozov, A.F., Posamentier, H.W., Verzhbitsky, V.E., Freiman, S.I., Rodina, E.A., Startseva, K.F., Zhukov, N.N., 2021c. Arctic Ocean mega Project: Paper 2 – Arctic stratigraphy and regional tectonic structure. Earth Sci. Rev. 217, 103581.
Nikishin, A.M., Petrov, E.I., Startseva, K.F., Rodina, E.A., Posamentier, H.W., Foulger, G. R., Glumov, I.F., Morozov, A.F., Verzhbitsky, V.E., Malyshev, N.A., Freiman, S.I., Afanasenkov, A.P., Beziazykov, A.V., Doronina, M.S., Nikishin, V.A., Skolotnev, S.G., Chernykh, A.A., 2022. Seismostratigraphy, paleogeography and paleotectonics of the Arctic deep-water basin and its Russian shelf. Transactions of the Geological Institute, Moscow, GIN RAS. https://doi.org/10.54896/00023272_2022_632_1, 156 pp.
Nikishin, A.M., Rodina, E.A., Startseva, K.F., Foulger, G.R., Posamentier, H.W., Afanasenkov, A.P., Beziazykov, A.V., Chernykh, A.A., Malyshev, N.A., Petrov, E.I., Skolotnev, S.G., Verzhbitsky, V.E., Yakovenko, I.V., 2023. Alpha-Mendeleev rise, Arctic Ocean: a double volcanic passive margin. Gondwana Res. 120, 85–110.

Nikishin, A.M., Foulger, G.R., Akinin, V.V., Rodina, E.A., Posamentier, H.W., Aleshina, K. F., 2024. Arctic cretaceous Tectonic and Igneous Mega-Province (TIMP): regional domains and geodynamics. J. Geodyn. 160, 102031.
Nirrengarten, M., Manatschal, G., Tugend, J., Kusznir, N., Sauter, D., 2018. Kinematic evolution of the Southern North Atlantic: implications for the formation of hyperextended rift systems. Tectonics 37, 89–118.
Oakey, G.N., Saltus, R.W., 2016. Geophysical analysis of the Alpha–Mendeleev ridge complex: characterization of the High Arctic Large Igneous Province. Tectonophysics 691, 65–84.
Paquette, J., Sigmarsson, O., Tiepolo, M., 2006. Continental Basement under Iceland Revealed by Old Zircons, American Geophysical Union, Fall Meeting. AGU, San Francisco.
Paton, D.A., Pindell, J., McDermott, K., Bellingham, P., Horn, B., 2017. Evolution of seaward-dipping reflectors at the onset of oceanic crust formation at volcanic passive margins: insights from the South Atlantic. Geology 45, 439–442.
Peace, A., McCaffrey, K., Imber, J., Phethean, J., Nowell, G., Gerdes, K., Dempsey, E., 2016. An evaluation of Mesozoic rift-related magmatism on the margins of the Labrador Sea: implications for rifting and passive margin asymmetry. Geosphere 12.
Peace, A.L., Foulger, G.R., Schiffer, C., McCaffrey, K.J.W., 2017. Evolution of Labrador Sea-Baffin Bay: plate or plume processes? Geosci. Can. 44, 91–102.
Peace, A., Dempsey, E., Schiffer, C., Welford, J., McCaffrey, K.J.W., Imber, J., Phethean, J., 2018a. Evidence for basement reactivation during the opening of the Labrador Sea from the Makkovik Province, Labrador, Canada: insights from field data and numerical models. Geosciences 8, 308.
Peace, A., McCaffrey, K., Imber, J., Hunen, J., Hobbs, R., Wilson, R., 2018b. The role of pre-existing structures during rifting, continental breakup and transform system development, offshore West Greenland. Basin Res. 30, 373–394.
Peace, A.L., Phethean, J.J.J., Franke, D., Foulger, G.R., Schiffer, C., Welford, J.K., McHone, G., Rocchi, S., Schnabel, M., Doré, A.G., 2020. A review of Pangaea dispersal and large Igneous Provinces – in search of a causative mechanism. Earth Sci. Rev. 206, 102902.
Peace, A.L., Phethean, J.J.J., Li, Y., Foulger, G.R., 2023. Iceland: mantle plume or microcontinent? A zircon study. In: EGU General Assembly 2023, Vienna, Austria, 23–28 April 2023.
Pease, V., Drachev, S., Stephenson, R., Zhang, X., 2014. Arctic lithosphere — a review. Tectonophysics 628, 1–25.
Petersen, K.D., Schiffer, C., Nagel, T., 2018. LIP formation and protracted lower mantle upwelling induced by rifting and delamination. Sci. Rep. 8, 16578.
Petrov, O.V., Smelror, M., 2021. Tectonics of the Arctic. In: Litvin, Y., Jiménez-Franco, A., Olegovna, C.T. (Eds.), Springer Geology, 1 ed. Springer Cham. pp. XIII, 208.
Petrov, O., Morozov, A., Shokalsky, S., Kashubin, S., Artemieva, I.M., Sobolev, N., Petrov, E., Ernst, R.E., Sergeev, S., Smelror, M., 2016. Crustal structure and tectonic model of the Arctic region. Earth Sci. Rev. 154, 29–71.
Phethean, J.J.J., Kalnins, L.M., van Hunen, J., Biffi, P.G., Davies, R.J., McCaffrey, K.J.W., 2016. Madagascar's escape from Africa: a high-resolution plate reconstruction for the Western Somali Basin and implications for supercontinent dispersal. Geochem. Geophys. Geosyst. 17, 5036–5055.
Piepjohn, K., von Gosen, W., Tessensohn, F., 2016. The Eurekan deformation in the Arctic: an outline. J. Geol. Soc. Lond. 173, 1007–1024.
Piskarev, A., Poselov, V., Kaminsky, V., 2019. Geologic Structures of the Arctic Basin, 1 Ed.
Planke, S., Symonds, P.A., Alvestad, E., Skogseid, J., 2000. Seismic volcanostratigraphy of large-volume basaltic extrusive complexes on rifted margins. J. Geophys. Res. Solid Earth 105, 19335–19351.
Polteau, S., Hendriks, B.W.H., Planke, S., Ganerød, M., Corfu, F., Faleide, J.I., Midtkandal, I., Svensen, H.S., Myklebust, R., 2016. The early cretaceous Barents Sea Sill complex: distribution, 40Ar/39Ar geochronology, and implications for carbon gas formation. Palaeogeogr. Palaeoclimatol. Palaeoecol. 441, 83–95.
Prestvik, T., Goldberg, S., Karlsson, H., Gronvold, K., 2001. Anomalous strontium and lead isotope signatures in the off-rift Oraefajokull central volcano in south-East Iceland. Evidence for enriched endmember(s) of the Iceland mantle plume? Earth Planet. Sci. Lett. 190, 211–220.
Ribe, N.M., Christensen, U.R., Theissing, J., 1995. The dynamics of plume-ridge interaction, 1: Ridge-centered plumes. Earth Planet. Sci. Lett. 134, 155–168.
Rosenbaum, G., Lister, G.S., Duboz, C., 2002. Relative motions of Africa, Iberia and Europe during Alpine orogeny. Tectonophysics 359, 117–129.
Saemundsson, K., 1979. Outline of the geology of Iceland. Jokull 29, 7–28.
Saltus, R.W., Miller, E.L., Gaina, C., Brown, P.J., 2011. Chapter 4 Regional magnetic domains of the Circum-Arctic: a framework for geodynamic interpretation. Geol. Soc. Lond. Mem. 35, 49–60.
Santos, R.V., Ganade, C.E., Lacasse, C.M., Costa, I.S.L., Pessanha, I., Frazão, E.P., Dantas, E.L., Cavalcante, J.A., 2019. Dating Gondwanan continental crust at the Rio Grande rise, South Atlantic. Terra Nova 31, 424–429.
Saunders, A.D., Fitton, J.G., Kerr, A.C., Norry, M.J., Kent, R.W., 1997. The North Atlantic Igneous Province. In: Mahoney, J., Coffin, M.F. (Eds.), Large Igneous Provinces. American Geophysical Union, pp. 45–93.
Sauter, D., Manatschal, G., Kusznir, N., Masquelet, C., Werner, P., Ulrich, M., Bellingham, P., Franke, D., Autin, J., 2023. Ignition of the southern Atlantic seafloor spreading machine without hot-mantle booster. Sci. Rep. 13, 1195.
Schaltegger, U., Amundsen, H.E.F., Jamtveit, B., Frank, M., Griffin, W.L., Gronvold, K., Tronnes, R.G., Torsvik, T., 2002. Contamination of OIB by underlying ancient continental lithosphere: U-Pb and Hf isotopes in zircons question EM1 and EM2 mantle components. Geochim. Cosmochim. Acta 66, A673.
Scharff, R.F., 1909. On the evidences of a former land-bridge between northern Europe and North America. Proc. R. Ir. Acad. 28 (1909/1910), 1–28.
Schiffer, C., Stephenson, R.A., Petersen, K.D., Nielsen, S.B., Jacobsen, B.H., Balling, N., Macdonald, D.I.M., 2015. A sub-crustal piercing point for North Atlantic reconstructions and tectonic implications. Geology 43, 1087–1090.
Schiffer, C., Peace, A., Phethean, J., Gernigon, L., McCaffrey, K., Petersen, K.D., Foulger, G., 2019. The Jan Mayen microplate complex and the Wilson cycle. In: Houseman, G. (Ed.), Tectonic Evolution: 50 Years of the Wilson Cycle Concept. Geological Society, London, Special Publications, London, pp. 393–414.
Schiffer, C., Doré, A.G., Foulger, G.R., Franke, D., Geoffroy, L., Gernigon, L., Holdsworth, B., Kusznir, N., Lundin, E., McCaffrey, K., Peace, A.L., Petersen, K.D., Phillips, T.B., Stephenson, R., Stoker, M.S., Welford, J.K., 2020. Structural inheritance in the North Atlantic. Earth Sci. Rev. 206, 102975.
Senger, K., Tveranger, J., Ogata, K., Braathen, A., Planke, S., 2014. Late Mesozoic magmatism in Svalbard: a review. Earth Sci. Rev. 139, 123–144.
Sheth, H.C., 2007. "Large Igneous Provinces (LIPs)": definition, recommended terminology, and a hierarchical classification. Earth Sci. Rev. 85, 117–124.
Shimeld, J., Boggild, K., Mosher, D.C., Jackson, H.R., 2021. Reprocessed Multi-Channel Seismic-Reflection Data Set from the Arctic Ocean, Collected Using Icebreakers between 2007–2011 and 2014–2016 for the Canadian Extended Continental Shelf Program. Geological Survey of Canada. Open File, p. 10.
Shipilov, E.V., 2016. Basaltic magmatism and strike-slip tectonics in the Arctic margin of Eurasia: evidence for the early stage of geodynamic evolution of the Amerasia Basin. Russ. Geol. Geophys. 57, 1668–1687.
Sigmundsson, F., Einarsson, P., Hjartardóttir, Á.R., Drouin, V., Jónsdóttir, K., Árnadóttir, T., Geirsson, H., Hreinsdóttir, S., Li, S., Ófeigsson, B.G., 2020. Geodynamics of Iceland and the signatures of plate spreading. J. Volcanol. Geotherm. Res. 391, 106436.
Simon, K., Huismans, R.S., Beaumont, C., 2009. Dynamical modelling of lithospheric extension and small-scale convection: implications for magmatism during the formation of volcanic rifted margins. Geophys. J. Int. 176, 327–350.
Skolotnev, S., Aleksandrova, G., Isakova, T.Y., Tolmacheva, T.Y., Kurilenko, A., Raevskaya, E., Rozhnov, S., Petrov, E., Korniychuk, A., 2019. Fossils from seabed bedrocks: implications for the nature of the acoustic basement of the Mendeleev rise (Arctic Ocean). Mar. Geol. 407, 148–163.
Skolotnev, S.G., Freiman, S.I., Khisamutdinova, A.I., Ermolaev, B.V., Okina, O.I., Skolotneva, T.S., 2022. Sedimentary Rocks in the Basement of the Alpha–Mendeleev Rise, Arctic Ocean. Lithol. Miner. Resour. 57, 121–142.
Skolotnev, S.G., Fedonkin, M.A., Korniychuk, A.V., 2023. New data on the age of magmatic rocks of the Alpha-Mendeleev rise (Arctic Ocean): results of isotopic u/pb dating of zircons. Dokl. Earth Sci. 513, 1104–1109.
Staples, R.K., White, R.S., Brandsdottir, B., Menke, W., Maguire, P.K.H., McBride, J.H., 1997. Faeroe-Iceland ridge experiment 1. Crustal structure of northeastern Iceland. JGR 102, 7849–7866.
Stephenson, R., Schiffer, C., Peace, A., Nielsen, S., Jess, S., 2020. Late Cretaceous-Cenozoic basin inversion and palaeostress fields in the North Atlantic-western Alpine-Tethys realm: implications for intraplate tectonics. Earth Sci 210, 103252.
Stoker, M.S., Praeg, D., Shannon, P.M., Hjelstuen, B.O., Laberg, J.S., Nielsen, T., van Weering, T.C.E., Sejrup, H.P., Evans, D., 2005. Neogene evolution of the Atlantic continental margin of NW Europe (Lofoten Islands to SW Ireland): anything but passive. In: Doré, A.G., Vining, B.A. (Eds.), Petroleum Geology: North-West Europe and Global Perspectives–Proceedings of the 6th Petroleum Geology Conference. Geological Society, London, pp. 1057–1076.
Stoker, M.S., Stewart, M.A., Shannon, P.M., Bjerager, M., Nielsen, T., Blischke, A., Hjelstuen, B.O., Gaina, C., McDermott, K., Ólavsdóttir, J., 2017. An overview of the Upper Palaeozoic-Mesozoic stratigraphy of the NE Atlantic margin. In: Péron-Pinvidic, G., Hopper, J.R., Stoker, M.S., Gaina, C., Doornenbal, J.C., Funck, T., Árting, U.E. (Eds.), The NE Atlantic Region: A Reappraisal of Crustal Structure, Tectonostratigraphy and Magmatic Evolution. Geological Society, London, Special Publications, pp. 11–68.
Stoker, M.S., Holford, S.P., Hillis, R.R., 2018. A rift-to-drift record of vertical crustal motions in the Faroe–Shetland Basin, NW European margin: establishing constraints on NE Atlantic evolution. J. Geol. Soc. Lond. 175, 263–274.
Stracke, A., Hofmann, A.W., Hart, S.R., 2005. FOZO, HIMU, and the rest of the mantle zoo. Geochem. Geophys. Geosyst. 6.
Suckro, S.K., Gohl, K., Funck, T., Heyde, I., Schreckenberger, B., Gerlings, J., Damm, V., 2013. The Davis Strait crust—a transform margin between two oceanic basins. Geophys. J. Int. 193, 78–97.
Tamara, J., McClay Ken, R., Hodgson, N., 2020. Crustal structure of the central sector of the NE Brazilian equatorial margin. Geol. Soc. Lond. Spec. Publ. 476, 163–191.
Tard, F., Masse, P., Walgenwitz, F., Gruneisen, P., 1991. The volcanic passive margin in the vicinity of Aden, Yemen. Bull. centr. Rech. Explor. Elf-Aquit. 15, 1–9.
Thatcher, W., Foulger, G.R., Julian, B.R., Svarc, J., Quilty, E., Bawden, G.W., 1999. Present-day deformation across the basin and range province, western United States. Science 283, 1714–1718.
Thórarinsson, S.B., Söderlund, U., Døssing, A., Holm Paul, M., Ernst Richard, E., Tegner, C., 2015. Rift magmatism on the Eurasia basin margin: U–Pb baddeleyite ages of alkaline dyke swarms in North Greenland. J. Geol. Soc. Lond. 172, 721–726.
Torsvik, T.H., Amundsen, H., Hartz, E.H., Corfu, F., Kusznir, N., Gaina, C., Doubrovine, P. V., Steinberger, B., Ashwal, L.D., Jamtveit, B., 2013. A Precambrian microcontinent in the Indian Ocean. Nat. Geosci. 6, 223–227.
Torsvik, T.H., Amundsen, H.E.F., Trønnes, R.G., Doubrovin, P.V., Gaina, C., Kusznir, N.J., Steinberger, B., Corfu, F., Ashwal, L.D., Griffin, W.L., Werner, S.C., Jamtveit, B., 2015. Continental crust beneath Southeast Iceland. Proc. Natl. Acad. Sci. 112, E1818–E1827.
Vamvaka, A., Pross, J., Monien, P., Piepjohn, K., Estrada, S., Lisker, F., Spiegel, C., 2019. Exhuming the top end of North America: episodic evolution of the Eurekan Belt and

its potential relationships to North Atlantic Plate Tectonics and Arctic climate change. Tectonics 38, 4207–4228.
van Wijk, J.W., Huismans, R.S., Ter Voorde, M., Cloetingh, S.A.P.L., 2001. Melt generation at volcanic continental margins: no need for a mantle plume? Geophys. Res. Lett. 28, 3995–3998.
Vogt, P.R., 1976. Plumes, sub-axial pipe flow, and topography along mid-oceanic ridges. Earth Planet. Sci. Lett. 29, 309–325.
Voss, M., Jokat, W., 2007. Continent-ocean transition and voluminous magmatic underplating derived from P-wave velocity modelling of the East Greenland continental margin. Geophys. J. Int. 170, 580–604.
Weigelt, E., Jokat, W., Franke, D., 2014. Seismostratigraphy of the Siberian Sector of the Arctic Ocean and adjacent Laptev Sea Shelf. J. Geophys. Res. 119, 5275–5289.
Welford, J.K., Shannon Patrick, M., O'Reilly Brian, M., Hall, J., 2012. Comparison of lithosphere structure across the Orphan Basin–Flemish Cap and Irish Atlantic conjugate continental margins from constrained 3D gravity inversions. J. Geol. Soc. Lond. 169, 405–420.
Welford, J.K., Peace, A.L., Geng, M., Dehler, S.A., Dickie, K., 2018. Crustal structure of Baffin Bay from constrained 3-D gravity inversion and deformable plate tectonic models. Geophys. J. Int. 214, 1281–1300.
Wilkinson, C.M., Ganerød, M., Hendriks, B.W.H., Eide, E.A., 2017. Compilation and appraisal of geochronological data from the North Atlantic Igneous Province (NAIP). Geol. Soc. Lond. Spec. Publ. 447, 69.
Yuan, X., Korenaga, J., Holbrook, W.S., Kelemen, P.B., 2020. Crustal structure of the Greenland-Iceland Ridge from joint refraction and reflection seismic tomography. J. Geophys. Res. Solid Earth 125 e2020JB019847.
Zastrozhnov, D., Gernigon, L., Gogin, I., Planke, S., Abdelmalak, M.M., Polteau, S., Faleide, J.I., Manton, B., Myklebust, R., 2020. Regional structure and polyphased Cretaceous-Paleocene rift and basin development of the mid-Norwegian volcanic passive margin. Mar. Pet. Geol. 115, 104269.
Zhang, T., Dyment, J., Gao, J., 2019. Age of the Canada Basin, Arctic Ocean: indications from high-resolution magnetic data. Geophys. Res. Lett. 46.
Zverev, S.M., Kosminskaya, I.P., Krasil'shchikova, G.A., Mikhota, G.G., 1977. Deep structure of Iceland and the Iceland-Faeroe-Shetland region based on seismic studies (NASP-72). Int. Geol. Rev. 19, 11–24.