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A new paradigm for the North Atlantic Realm

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The North Atlantic Realm, defined as the region of Pangaea breakup north of the Charlie-Gibbs Fracture Zone, is the type example locality for the Wilson Cycle. It is the first place where Wegener's continental drift hypothesis was tested using geodetic surveying and the source of some of the data most influential to development of the plate tectonic hypothesis. The region nevertheless, in many respects, stubbornly refused to fit neatly into the very hypotheses in whose birth it was so influential.

In recent decades a vast amount of new data has been collected there, swelling the huge legacy of work done over the previous half-century and earlier. These include land and marine seismic, magnetic, gravity, thermal, petrological and geochemical data and geodetic, bathymetric and satellite potential field measurements. They underpin major advances in understanding the structure and evolution of the region.

By 2016, what seemed to be lacking was full integration of the knowledge base into a holistic model that could shed light on the many vexed questions which remained, almost 50 years into the plate-tectonic era, stubbornly intransigent. These questions related to the trans-oceanic Greenland-Iceland-Faroe Ridge (GIFR), the composition of the 30–40 km thick Icelandic-type crust under it, the high-velocity lower crust beneath seaward-dipping reflectors (SDRs) at the ocean margins and the contrasting tectonic histories of the oceans north and south of the GIFR. Other puzzles related to the diachronous ridges of thickened crust that flank the Reykjanes Ridge, the curious petrology and geochemistry of Icelandic lavas, the origin of the Davis Strait picrites, their relationship to disintegration elsewhere in the Pangaean supercontinent, and the tectonic instability of the Faroe-Shetland basin which has exhibited persistent differential vertical motions since the Early Cretaceous.

In order to address these questions a series of four, 2–3-day interdisciplinary workshops were held at St. Chad's College, Durham

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University, Durham, UK, September 2016, April and November 2017, and September 2018 (http://www.mantleplumes.org/NAWorkshop/NAWorkshop4.html). A total of 25 scientists from Canada, Denmark, the Faroe Islands, France, Germany, Iceland, Norway, the UK and the USA participated in one or more of these workshops. Because of the diverse specialties of the attendees the workshops were structured to maximize cross-disciplinary learning rather than to provide a platform for formal presentations, and 80% of the time was dedicated to discussion. The main results that emerged from these workshops are as follows.

By the time Pangean breakup formed the North Atlantic Realm, episodic rifting and tectonic unrest in the region had already been longstanding, dating as far back as the Late Palaeozoic [Peace et al., 2019]. The continental disintegration that formed the North Atlantic Ocean and the seas west of Greenland was thus the culmination of already ongoing processes. When it occurred, breakup did not proceed, as often assumed, in a simple manner orthogonal to ridge crests. Instead it was complex, depth-dependent in the case of many processes [Schiffer et al., 2019] and accompanied by widespread magmatism [Clarke and Beutel, 2019; Hole and Natland, 2019]. It was guided by structural inheritance and major strike-slip faults, but nevertheless the Wilson Cycle is an imperfect model for the region.

Breakup commenced west of present-day Greenland in the Late Paleocene but by the Late Oligocene or Early Miocene it was entirely focused on the Northeast Atlantic. North of the GIFR breakup was magmatic and diachronous. It began with isolated, segmented spreading centres and propagating rifts that became extinct, migrated and reorganized [Gernigon et al., 2019]. This behavior was accompanied by major changes in kinematics. The transfer of breakup from the axis west of Greenland [Clarke and Beutel, 2019] to the Northeast Atlantic, and dislocation of the Jan Mayen Microplate Complex from Greenland in the Late Oligocene and Early Miocene, may be viewed as large- and medium-scale examples of this behavior.

The breakup axis north of the GIFR was oblique to the earlier rift systems that developed in the Carboniferous to Jurassic. From the Cretaceous, the rift systems systematically localized towards the later line of breakup in a manner that suggests different inherited fabrics were reactivated at different times under evolving kinematic regimes. Prior to rifting, the brittle upper crust north of the GIFR comprised discrete fabrics in the form of Caledonian thrust faults. In contrast, the lower crust and mantle retained a pervasive fabric oblique to the shallow Caledonian trends as a result of reworking by late-Caledonian shear deformation. Initial reactivations of structures in the brittle upper crust could not penetrate the whole thickness of the lithosphere against the grain of the oblique, deep-seated, pervasive fabric. Continental breakup was only achieved after the stress field rotated to an orientation more favorable with respect to the deeper fabric [Schiffer et al., 2019].

South of the GIFR, in contrast, initial Reykjanes Ridge formation did not reactivate any known older structures. Instead, rifting, which initially formed the Cretaceous Hatton-Rockall basins, migrated west and finally broke intact cratonic lithosphere. A possible explanation for this behavior is a kinematic need for the rift to minimize its length in the context of adjacent developing ridges [Schiffer et al., 2019]. It may have been achieved via mechanical weakening by initial strike-slip faulting, thermal weakening due to preserved thick crust or the proximity of a rift-rift-rift triple junction south of Greenland.

The direction of plate motion about the Reykjanes Ridge varied subsequent to its formation. Cessation of spreading in the Labrador Sea was accompanied by reconfiguration of the Reykjanes Ridge from a linear ridge to a ridge-transform array in the Late Eocene. Later diachronous return to a linear, but obliquely spreading ridge was accomplished by southerly propagating rifts that migrated the spreading axis east. Diachronous ridges of thickened oceanic crust formed at the ridge tips, possibly produced by accompanying axially propagating magmatic instabilities [Martinez et al., 2019]. This return to an earlier configuration may have been encouraged by inherited mantle structure [Martinez et al., 2019].

A consequence of the rift migrations north and south of the GIFR is that a considerable amount of continental material is now dispersed in the ocean. The extent of this continental material has likely been underestimated. In addition to the well-documented Jan Mayen Microplate Complex and the crust beneath the Inner SDRs, continental crust is also likely present beneath the GIFR, Iceland itself, the Davis Strait, Baffin Bay, the Rockall Plateau, and elsewhere.

The complex, unstable and evolving tectonics that has characterized both continental and oceanic lithosphere in the North Atlantic Realm in the past, and is ongoing to the present day, manifests itself to a particularly extreme degree on the GIFR. This bathymetrically shallow, trans-oceanic ridge decouples the oceanic regions to the north and south. It enables them to behave independently and display different characteristics with the GIFR accommodating differential movements between them.

Initially, separate spreading ridges formed to the north and south and propagated towards each other. The amount of breakup-related magmatism and style of structural inheritance was entirely different north and south of the GIFR. Propagation both to the south and north stalled at the confluence of the Nagssugtoqidian and Caledonian orogens when the rift tips were still separated by ~150 km and ~400 km in the transverse and along-strike directions respectively.

Following this, the continental region between the stalled rift tips—the Iceland Microcontinent—along with flanking continental regions to the west and east, extended in a diffuse, unstable style along multiple, migrating axes with shearing taking up deformation between them [Foulger et al., 2019]. Erupted MORB-like lavas, contaminated with continental signatures, blanketed the surface. Such deformation and volcanism continue in Iceland to the present day.

This model has important implications. It suggests that Icelandic-type lower crust beneath the GIFR is not gabbroic as often assumed but instead comprises magma-inflated, hyper-extended, ductile mid- and lower continental crust, whereas the upper crust comprises a cap of basaltic lavas and intrusions. The GIFR may thus have a similar structure and composition to the Inner-SDRs on the Norwegian margin and may be likened to a chain of such SDRs spanning the ocean. Formation of two pairs of conjugate margins, one pair to the west and one pair to the east of the Iceland Microcontinent, may account for the exceptionally large, 1200-km width of the GIFR.

The feasibility of this model is confirmed by numerical modeling [Foulger et al., 2019]. Both crust and lithospheric mantle from the Caledonian and Nagssugtoqidian orogenies may underlie the GIFR, and through this MORB melts rise, melting continental wall rocks and thereby augmenting their volume and acquiring characteristic geochemical and isotopic signatures.

This model can account for petrological data that show no reasonable source temperature or composition could generate the full, maximum ~40-km thickness of Icelandic-type crust measured seismically [Hole and Natland, 2019]. Mantle potential temperatures for the sources of igneous rocks in North Atlantic Realm have been widely overestimated in the past because problems such as the presence of accumulated olivine in samples and magma mixing have been neglected. Source temperatures for picrites from West Greenland suggest a maximum T_P of ~1500 °C and for Icelandic basaltic glass a maximum T_P of ~1450 °C, no more than ~100 °C hotter than MORB source. If the sources are wet, as observations suggest, these temperature estimates may be lowered by ~50 °C [Hole and Natland, 2019]. Likewise, the Davis Strait picrites are also postulated to be unrelated to elevated mantle temperatures [Clarke and Beutel, 2019]. Instead they are proposed to be related to rifting at the thickened lithosphere where the Paleoproterozoic Rinkian and Nagssugtoqidian Fold Belts intersect. The area underwent less thinning and extension than proximal regions, producing pull-apart basins and pathways for picritic melts to reach the surface. This model is purely tectonic and accounts for the Paleocene picrites of Davis Strait without appealing to an exceptionally high temperature source [Clarke and Beutel, 2019].

Such a model, that takes account of pre-existing structure in the fragmenting supercontinent, can also explain holistically petrological, radiogenic isotope and trace-element features of basalts from Iceland and other parts of the North Atlantic Realm which require the source of the magmas to be lithologically and chemically heterogeneous. Petrological data suggest it is most likely hybrid pyroxenite-peridotite with the more fusible pyroxenite component arising from old subducted slabs trapped in the underlying orogenic continental crust. These have been imaged seismically [Schiffer et al., 2014], and may be the source of the high ^{3}He/^{4}He signatures reported for some basalts. Such a model can account for previously enigmatic gravity and seismic observations on the GIFR and has the radical implication that the volume of melt produced in Iceland may, in truth, be little different from that on the Reykjanes and Kolbeinsey Ridges—only the source lithologies differ. If stretched continental crust is continuous beneath much or all of the GIFR then Pangaea breakup is, to date, incomplete at this latitude.

This model stands the test of predictive potential for oceanic regions elsewhere. In addition to the North Atlantic Ocean and the seas west of Greenland, the Central and South Atlantic Oceans, the Indian Ocean and the South China Sea are examples of regions that show many of the characteristics described above [Peace et al., 2019]. Rifts form by propagation, they migrate laterally, dispersing continental material in the oceans, and scattered off-ridge volcanism attests to distributed extension. Flood basalt provinces form distal to propagator tips, typically at sites of major, lithosphere-scale shear structures, and aborted rifts or microcontinents are rafted into the oceanic domain [Peace et al., 2019].

Overall, it is apparent that the dynamics of the North Atlantic Realm are far more complex and diffuse than commonly assumed. Instead of there being a strict divide between rigid continental material and oceanic crust newly formed at mid-ocean ridges, there are both lateral and vertical continuums of lithospheric affinity. Continent-ocean-transitions are diffuse and the non-rigid behaviour of plates is likely underestimated.

In addition to the findings summarized above, which are reported in detail in this Special Issue, the Durham North Atlantic Workshops highlighted fundamental issues that continue to offer challenges. These include the mechanics of breakup initiation, in particular the roles of strike-slip motion and rift propagation, and the context of associated intraplate deformation and magmatism, both for tholeiitic flood basalts and small-volume igneous rocks. The North Atlantic Realm still guards many secrets and will continue to offer challenges and puzzles to researchers for many years to come.

Workshop attendees and current affiliations

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