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Icelandia

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ABSTRACT

We propose a new, sunken continent beneath the North Atlantic Ocean that we name Icelandia. It may comprise blocks of full-thickness continental lithosphere or extended, magma-inflated continental layers that form hybrid continental-oceanic lithosphere. It underlies the Greenland-Iceland-Faroe Ridge and the Jan Mayen microplate complex, covering an area of ~600,000 km^2. It is contiguous with the Faroe Plateau and known parts of the submarine continental rifted margin offshore Britain. If these are included in a "Greater Icelandia," the entire area is ~1,000,000 km^2 in size. The existence of Icelandia needs to be tested. Candidate approaches include magnetotelluric surveying in Iceland; ultralong, full-crust-penetrating reflection profiling along the length of the Greenland-Iceland-Faroe Ridge; dating zircons collected in Iceland; deep drilling; and reappraisal of the geology of Iceland. Some of these methods could be applied to other candidate sunken continents that are common in the oceans.

INTRODUCTION

Research papers, reputable textbooks, and teaching material typically present a simplistic, bimodal picture of the crust beneath landmasses and the oceans. It is taught, and widely assumed, that thick, lithologically complex continental crust underlies continents; thin, basaltic oceanic crust underlies oceans; and there is a clear, narrow, sharp boundary or a transition zone (e.g., a zone of exhumed serpentinized mantle) between the two types of crust at the edges of continental shelves (e.g., Boillot and Froitzheim, 2001; Eagles et al., 2015).

Although typically ignored as a minor issue not requiring any modification of fundamental plate-tectonic theory, it is accepted that some submerged continental crust also exists in the oceans as slivers, microcontinents, crustal fragments, or larger "sunken" continents. The Jan Mayen microplate complex in the NE Atlantic Ocean is one example of which scientists were aware as early as the 1980s (e.g., Nunns, 1983). Recently, the term "Zealandia" was proposed for a 4,900,000 km^2 expanse of continental crust of which 268,000 km^2 New Zealand is the only subaerial part (Mortimer et al., 2017). The term "Mauritia" was coined for an ~408,000 km^2 swath of submerged continental crust in the Indian Ocean that underlies Mauritius, the Seychelles, the adjacent Mascarene Plateau, and the Chagos-Maldive-Laccadive Ridge (Fig. 1; Torsvik et al., 2013).

Numerous other shallow bathymetric features isolated in the oceans are candidates for sunken continents of various sizes. In the Atlantic Ocean, on the basis of bathymetry and local bathymetric gradients, one might reasonably propose Meteoria (Meteor Rise), Walvia (Walvis Ridge), Rio Grandia (Rio Grande

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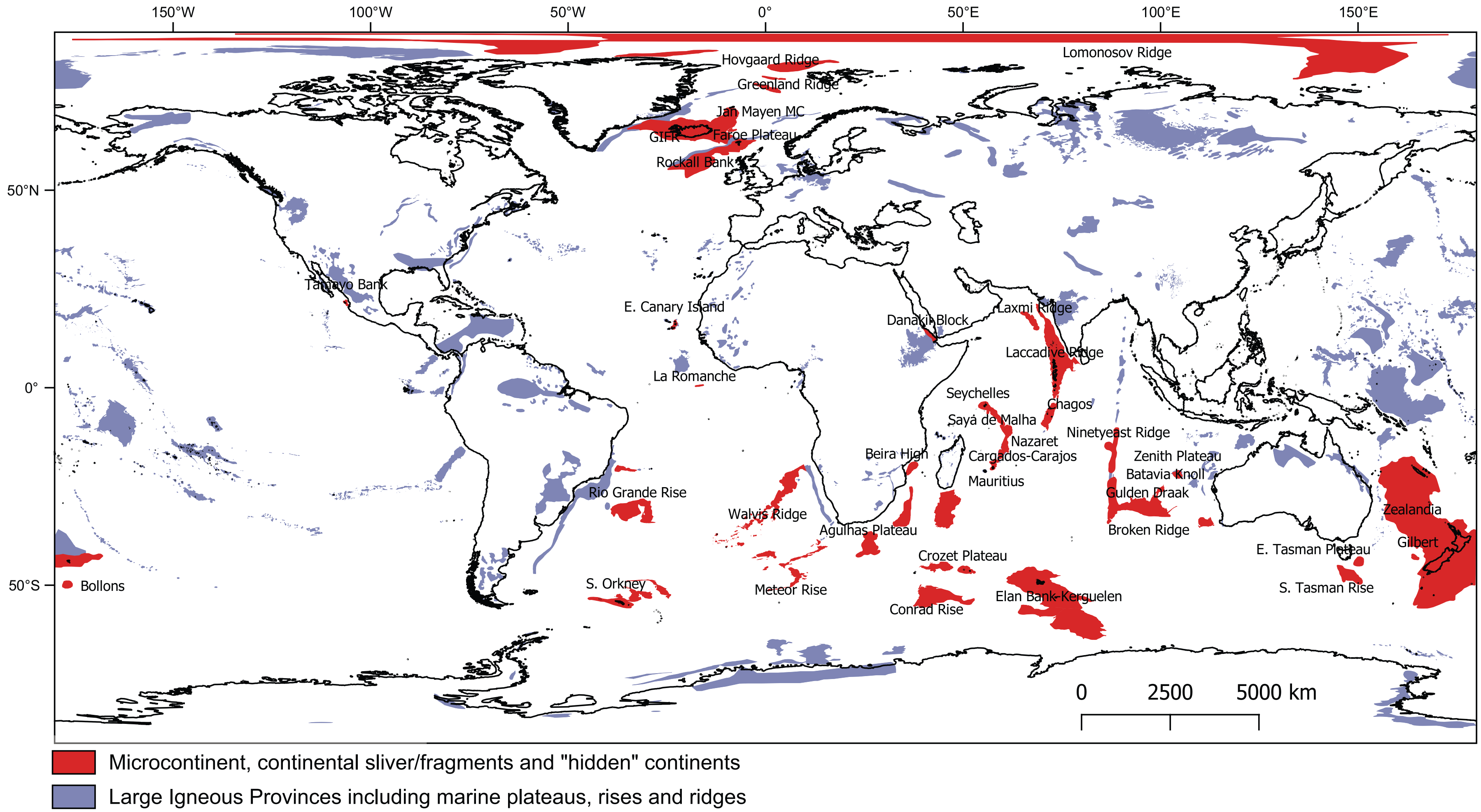

Figure 1. Map showing place names mentioned in the text and locations of possible continental fragments in the Atlantic and Indian Oceans. Some are conventionally assumed to be volcanic constructs. Large igneous provinces are modified after Coffin and Eldholm (1994) and Johansson et al. (2018). GIFR—Greenland-Iceland-Faroe Ridge; MC—microplate complex.

Rise), and Lomonosovia (Lomonsov Ridge). In the Indian Ocean, Kerguelia (Elan Bank–Kerguelen Plateau), Broken Ridgia (Broken Ridge), Madagascia (Madagascar, including the Madagascar Plateau), Mozambiquia (Mozambique and Agulhas Plateaus), Crozetia (Crozet Plateau), and Conradia (Conrad Rise) are worthy of consideration (Fig. 1). Evidence has also been presented that the Pacific Ocean contained a considerable amount of continental crust in the past (Nur and Ben-Avraham, 1977). At some of these, evidence for continental crust or lithosphere is already available. Others remain little explored.

In this paper, we build on a recent study by Foulger et al. (2020) that reinterpreted the crust beneath Iceland and its adjacent aseismic ridges as being largely continental in lithology and not oceanic as generally assumed. We draw a logical conclusion from that work—that there exists in the NE Atlantic Ocean a substantial sunken continent that we call "Icelandia" (Fig. 2). Its core is an ~450,000 km^2 swath of shallow bathymetry that extends from the east coast of Greenland, through Iceland, and to the continental Faroe Plateau (the Greenland-Iceland-Faroe Ridge; Fig. 2; Foulger et al., 2020). The deepest parts of this swath are ~600 m below sea level (mbsl) west of Iceland and ~500 mbsl east of Iceland. This contrasts with the neighboring ocean basins, which are >2000 m deep. We include the Jan Mayen microplate complex. This ~150,000 km^2 region is largely continental and likely continuous with the thick crust of the Greenland-Iceland-Faroe Ridge via the ~15,000 km^2 Iceland Plateau, seaward of the NE continental shelf of Iceland (Blischke et al., 2016). The entire region thus covers ~600,000 km^2. This hypothesis implies that North America and Eurasia are joined by a continuous swath of continental crust spanning the Atlantic Ocean at ~65°N.

Icelandia is continuous with the submarine continental structures of the Faroe Plateau, the Wyville-Thompson and Fugløy Ridges, the Hatton, Rockall, George Bligh, Lousy, Bill Bailey's, and Faroe Banks, and the Rockall Plateau. These features formed during destabilization of the continental crust shortly before full opening of the ocean. They have long been recognized as containing a large percentage of continental crustal material, and the largest and most coherent blocks are considered to be continental ribbons embedded in thinned continental crust (Péron-Pinvidic and Manatschal, 2010; Geoffroy et al., 2020). They have a combined area of ~400,000 km^2. They formed earlier than Icelandia (e.g., Guan et al., 2019), but if they are included to make up a "Greater Icelandia," then the total area of sunken continental crust amounts to ~1,000,000 km^2.

The Icelandia hypothesis is in need of testing. Like most sunken continental fragments or proposed microcontinents, most

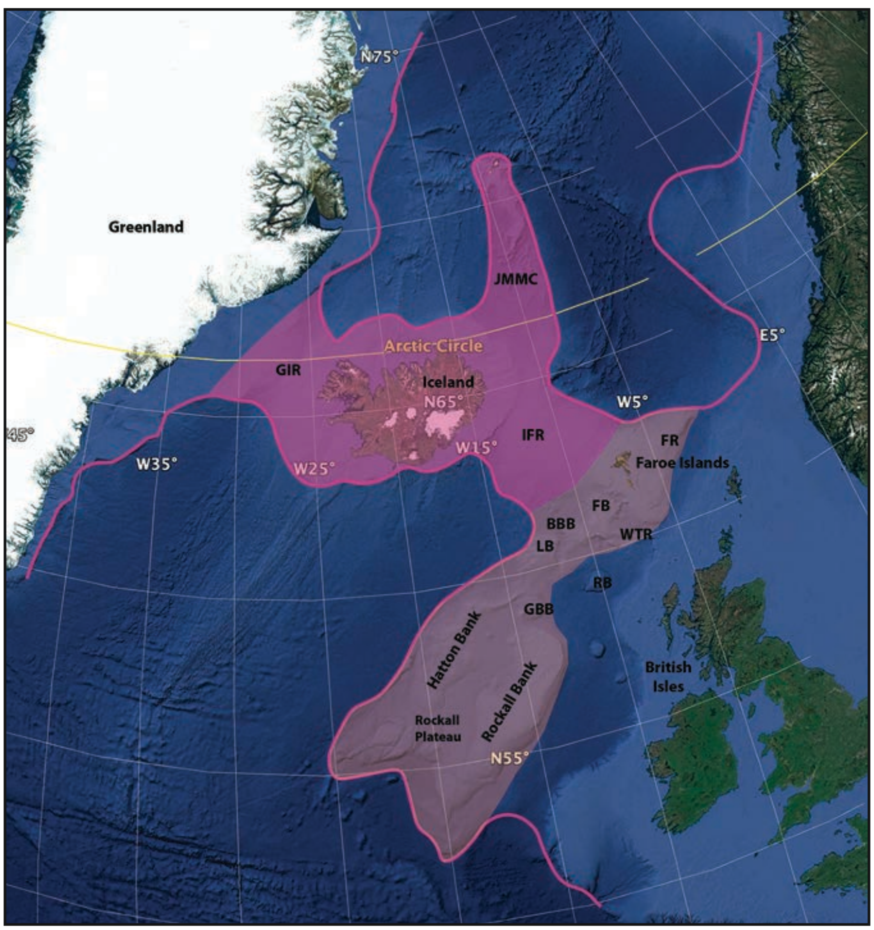

Figure 2. Bathymetric map of the NE Atlantic Ocean. Magenta line—boundary of continental crust; magenta—Icelandia; magenta + beige—Greater Icelandia; GIR—Greenland-Iceland Ridge; IFR—Iceland-Faroe Ridge; JMMC—Jan Mayen microplate complex; WTR—Wyville-Thompson Ridge; FR—Fugløy Ridge; GBB—George Bligh Bank; LB—Lousy Bank; BBB—Bill Bailey's Bank; FB—Faroe Bank; RB—Rosemary Bank. Base map: Google Earth.

of the rocks cannot yet be directly sampled, or evidence comes from very small zircon samples and/or ambiguous interpretations of geophysical data. The lower crust beneath Icelandia is proposed to be magma-inflated continental crust. This is blanketed by thick, stacked lava flows that form most of the upper crust (Foulger et al., 2020). Some 35% of Icelandia is exposed above sea level as the island of Iceland, but no exposures or xenoliths of continental crust have yet been found.

ICELANDIA

The Greenland-Iceland-Faroe Ridge, Jan Mayen microplate complex, and surrounding continental and oceanic regions have been studied intensively by earth scientists for close to a century because of the scientific, strategic, and economic importance of the region. Some of these observations made major contributions to early development of the plate-tectonic hypothesis (e.g., Wegener, 1924; Niemczyk, 1943; Vine and Matthews, 1963; Bott, 1974; Björnsson et al., 1977). Despite this, many observations have defied self-consistent explanation in the simplistic schema of plate tectonics and bimodal crustal affinities. Auxiliary hypotheses (Lakatos, 1970) applied uniquely to the Greenland-Iceland-Faroe Ridge have been invoked, e.g., ultrathick oceanic crust built by a high-productivity mantle plume. A special name for this "atypical" crust was proposed, i.e., "Icelandic type" crust (Bott, 1974; Foulger et al., 2003).

In recent years, as ever more detailed data have become available, the difficulties in explaining the complexities of the NE Atlantic region have expanded. The addition of a postulated mantle plume does little to explain these complexities, as is shown by the many auxiliary hypotheses that have been found necessary, e.g., the concepts of plume pulses and plume ridge-capture (White and Lovell, 1997; Gibson et al., 2015). Plate tectonics is a useful first-order description of general global lithosphere kinematics, but to adequately explain modern data from complex regions, a richer or revised version of the hypothesis is needed. That version must recognize that the fundamental processes of plate tectonics operate in a complex, inhomogeneous, and nonrigid Earth. As a result, the structures and materials produced are also complex and inhomogeneous.

Preexisting Structure and Its Consequences

The root cause for the structural complexities of the NE Atlantic region, and the existence of Icelandia, is that continental breakup occurred piecemeal in an environment of structural complexity (Schiffer et al., 2019). The high and atypical aspect ratio of the Greenland-Iceland-Faroe Ridge is likely inherited from the continental structure from which it originated—the western frontal thrust of the (Ordovician–Devonian) Caledonian suture and adjacent, collinear (1.86–1.84 Ga) Nagssugtoqidian orogen to the south (Fig. 3; Schiffer et al., 2019). The northerly strike of the Jan Mayen microplate complex contrasts with that of the Greenland-Iceland-Faroe Ridge, likely reflecting the longitudinal trend of the Caledonian suture, along which breakup ran north of the Greenland-Iceland-Faroe Ridge. The strike of the Faroe-Rockall swath, south of the Greenland-Iceland-Faroe Ridge, is northeasterly. Breakup there occurred along a fresh split in the North American craton. Greater Icelandia thus includes disrupted continental crust of at least three distinct types, and it would be of interest to study how this influenced the final structures.

A review of the relationship between preexisting orogenic belts and development of the Mid-Atlantic Ridge as a whole has been discussed by Lundin and Doré (2005) and was the subject of a recent reexamination of the integrity of the Wilson hypothesis (e.g., Wilson et al., 2019). Prior to breakup, Pangea was an amalgamation of lithospheric blocks with different strengths and structures that included both cratons and mobile belts. Prior to the onset of seafloor spreading in the Labrador Sea in the late Paleocene, phases of tectonic unrest had occurred in the future-breakup region since the late Paleozoic. The lithosphere was thus both structurally and mechanically inhomogeneous at the time when far-field forces finally required full breakup. As a consequence, spreading ridges formed in disconnected sections, with tips propagating along preexisting zones of weakness and stalling where they were blocked by strong, crosscutting structural barriers. The two most influential of these barriers each comprised the confluence of a pair of orogenic belts.

Chronology of Breakup

The chronology of the continental breakup that formed the NE Atlantic Ocean has been described in many papers. Our preferred, detailed reconstruction was described and illustrated by Foulger et al. (2020, their fig. 14). We give a short summary here. Place names are shown in Figure 3. At ca. 58–57 Ma, the segmented proto–Mid-Atlantic Ridge propagated north of what is now the Charlie-Gibbs Fracture Zone and split the North Atlantic craton to open the Labrador Sea west of Greenland (Gaina et al., 2009; Chauvet et al., 2019; Gernigon et al., 2019). Its onward progress was blocked at the junction of the N-S–trending (1.88 Ga) Rinkian fold belt and the E-W–trending Nagssugtoqidian orogen. There, a burst of intense volcanism occurred, and lithospheric extension was taken up on transtensional zones arrayed in a right-stepping, E-W–trending array. This formed the Davis Strait leaky transverse shear zone. Extension, and likely a small amount of seafloor spreading, occurred north of this to form Baffin Bay (Welford et al., 2018; Chauvet et al., 2019), but the axis of breakup west of Greenland did not last. At 36 Ma, it became extinct, and all spreading relocated to the Mid-Atlantic Ridge east of Greenland.

The NE Atlantic Ocean basin also opened in a piecemeal way, but there, embryonic spreading ridges to the north and south of the Nagssugtoqidian orogen propagated in opposite directions (Franke et al., 2019; Gernigon et al., 2019). At ca. 54 Ma, the proto–Reykjanes Ridge propagated north from the Charlie-Gibbs Fracture Zone but stalled at the junction of the crosscutting Nagssugtoqidian orogen and the western Caledonian frontal

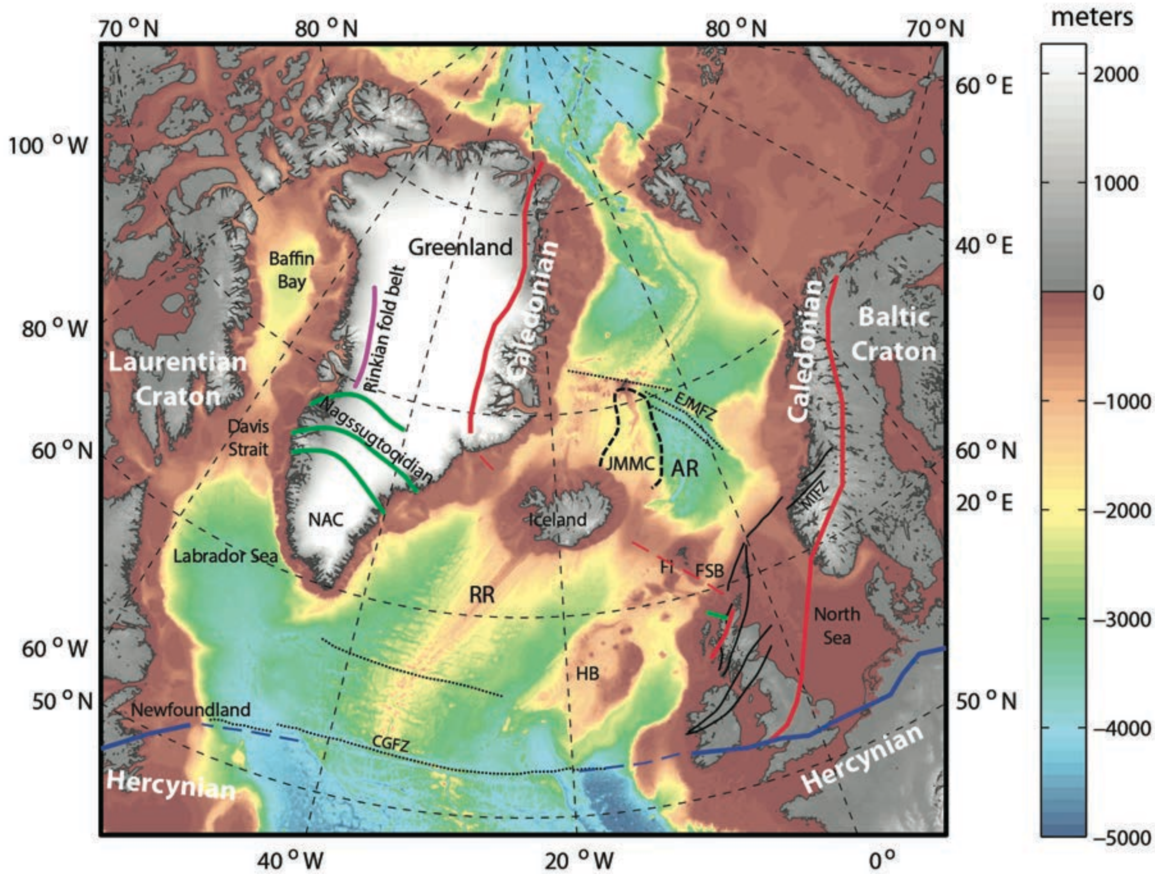

Figure 3. Structural and tectonic features in the NE Atlantic realm on a bathymetric map. CGFZ—Charlie-Gibbs Fracture Zone; NAC—North Atlantic craton; AR—Aegir Ridge; HB—Hatton Bank; EJMFZ—East Jan Mayen Fracture Zone; RR—Reykjanes Ridge; FI—Faroe Islands; FSB—Faroe-Shetland Basin; JMMC—Jan Mayen microplate complex. Red lines—fronts of Caledonian suture; green lines—sutures and the southern front of the Nagssugtoqidian suture; blue lines—Hercynian front (from Foulger et al., 2020); black lines—major faults within the Caledonian orogen.

thrust. At the same time, to the north of the future Greenland-Iceland-Faroe Ridge, the new Aegir Ridge propagated south over a period of ~2 m.y. from the location where the East Jan Mayen Fracture Zone now lies. It also stalled at the Caledonian-Nagssugtoqidian barrier. The two new ridges halted when still ~300 km apart along their strike and offset by 50–150 km laterally, in a right-stepping configuration.

These events set the scene for a subsequent style of deformation and volcanism that is rare but not unique. As Greenland and Eurasia separated, the motion was taken up by seafloor spreading about the Aegir and Reykjanes Ridges, but these ridges never connected. An ~45,000 km^2 block of continental crust was trapped between their stalled tips—the Iceland microcontinent (Foulger et al., 2020). This block stretched in a viscous manner and was widened by intrusions along multiple, parallel, northerly striking, simultaneously active axes of extension (Foulger et al., 2020). These axes migrated and jumped laterally (Foulger and Anderson, 2005; Hjartarson et al., 2017), behavior that is still ongoing in Iceland today.

Mechanism of Crustal Extension

We propose that the deeper parts of the continental crust extended by viscous flow of preexisting continental material, encouraged by mafic intrusions from below (Foulger et al., 2020). Such a tectonic process has been tested and confirmed to be feasible by numerical simulations (Petersen et al., 2018). Flowing and progressive exhumation of the ductile lower crust explains the space overlaps and mass deficit problems of traditional, rigid plate reconstructions of the NE Atlantic region (Foulger et al., 2020). We propose that, simultaneously, volcanism blanketed the surface with an igneous layer several kilometers thick. In the upper few kilometers beneath the surface lava flows, extension in the igneous layer was taken up by localized intrusions, forming central volcanoes, and diking in northerly striking fissure swarms. This style of volcanic continental extension is analogous to the nearby volcanic margins of Greenland and Scandinavia (Geoffroy et al., 2020). There, seaward-dipping reflectors overlie subsided, magma-inflated continental crust in sequences up to ~10 km thick

(Eldholm et al., 1989). It is possible that, in Iceland, the building of the seaward-dipping reflector–draped continental crust that forms volcanic passive margins is occurring at the present day. In other words, the region in and around Iceland is still experiencing the pre-complete-continental-breakup tectonic phase.

The extending ~45,000 km^2 Iceland microcontinent, supplemented by ductile flow of continental material from the flanking Greenland and Faroe margins, built the substratum of the Greenland-Iceland-Faroe Ridge. Buoyed by continental crust in its roots, this ridge remained above sea level until ca. 15–10 Ma. It permitted the exchange of fauna, alongside flora with dischory dispersal modes, between Scandinavia and Britain up until the time it was broken by foundering in the Faroe-Shetland Basin (Stoker et al., 2005; Denk et al., 2011; Ellis and Stoker, 2014). Today, active volcanism is confined to a region ~400 km wide in the center of the Atlantic Ocean. Because of this, regions where volcanism is extinct have cooled and subsided below sea level. Only Iceland remains above sea level to allow close scrutiny of the processes that built Icelandia.

Oceanic crust formed north and south of the Greenland-Iceland-Faroe Ridge, but these two regions were tectonically decoupled and behaved independently. This suggests that the Greenland-Iceland-Faroe Ridge comprises a new and unusual type of plate boundary running through the middle of Greater Icelandia. It decouples, tectonically, the oceanic regions to the north and south while deforming diffusely itself.

Explanatory Power of the New Model

The model described here contrasts with the earlier assumption that the Greenland-Iceland-Faroe Ridge crust is oceanic, and its volume has been boosted by a hot mantle plume. That assumption cannot account for many fundamental, reliable, well-tested observations, which include the following:

1. the distributed style of deformation in Iceland, with rifting and volcanism scattered over ~450 km in the direction of plate motion;
2. the long history of frequent ridge jumps, both easterly and westerly, that have left multiple, extinct, northerly striking rifts both in Iceland and on submarine parts of the Greenland-Iceland-Faroe Ridge;
3. the >40-km-thick crust beneath Iceland, which extends down well into the depth range normally expected to be the melt-source region of spreading ridges (Darbyshire et al., 2000; Foulger et al., 2003);
4. the high density of the Icelandic lower crust, ~3150 kg/m^3, which cannot be explained with a gabbroic petrology (Menke, 1999; Gudmundsson, 2003);
5. the impossibility of explaining production of a 30–40 km thickness of melt at realistic source temperatures (Hole and Natland, 2019);
6. the petrology of Icelandic lavas, which are 10% acid and intermediate;
7. the persistent tectonic unrest of the adjacent rifted margins, in particular, the Faroe-Shetland Basin (Stoker et al., 2005, 2018);
8. the tectonic instability on the Reykjanes Ridge, indicated by its ongoing easterly migration via southerly migrating rift propagators, which systematically transfer Eurasian oceanic crust to the North American plate and leave swaths of diachronous, slightly thickened crust in their wakes (Martinez et al., 2019); and
9. the independent and different tectonic histories of the oceans north and south of the Greenland-Iceland-Faroe Ridge.

These observations can, however, be naturally explained by a model of a largely continental Icelandia (Foulger et al., 2020).

TESTING ICELANDIA

A posteriori success in explaining existing observations is not a test of the correctness of any new theory. New observations that fulfil the predictions are required. How can this be applied to our new model of Icelandia?

Of all postulated largely submerged continents, the subaerial part of Icelandia is the best studied. A huge body of diverse observational data is available from marine-, land-, and space-based measurements. Despite this, almost all the data currently available have previously been individually interpreted by scientists under the assumption of anomalously thick oceanic crust, and not continental crust. This is notwithstanding the fact that some early experimentalists did suggest the Greenland-Iceland-Faroe Ridge was continental (Zverev et al., 1977). New data types and new approaches are thus needed to move forward. Some possible approaches are described below.

Magnetotelluric Surveying

Magnetotelluric surveying conducted on land in Iceland has yielded data suggestive of continental crust. Measurements have been made there since the 1960s, some to explore the electrical structure of the entire crust and others to prospect for shallow geothermal resources. A high-conductivity layer underlies much of the country at depths of 15–25 km; it is shallower beneath the active rift zones and deeper under older, peripheral regions (for a summary, see Björnsson et al., 2005). This structural trend is the opposite of that shown by seismic measurements, which find the thickest crust beneath the active rift areas of central Iceland and the thinnest crust beneath the coasts. This mismatch between the seismic and electrical structures is currently unexplained and suggests that the seismic measurements alone in Iceland are insufficient for a full understanding of geodynamics there.

High-conductivity layers are common beneath continents, where they have been interpreted as lower crust containing interconnected saline pore fluids, minor amounts of graphite, or alternating pyroxene-rich and plagioclase-rich layers (e.g., Hyndman et al., 1993; Yang, 2011). Revisiting and extending the earlier, deep magnetotelluric work in Iceland could provide new data with which to test the continental versus thick-oceanic crustal models. New surveying should augment earlier work by (1) correctly accounting for static shifts, which may require collocated transient electromagnetic (TEM) measurements (Árnason, 2015), (2) extending the measurements to cover the whole country at regular intervals, (3) completing full three-dimensional interpretation, and (4) developing methods to jointly interpret the magnetotelluric and seismic data.

Ultralong, Full-Crust-Penetrating Reflection Profiling

Acquisition of deep seismic reflection data that penetrate the full crust along the entire length of the Greenland-Iceland-Faroe Ridge, including on land in Iceland, is now technically possible. Such surveys have been conducted in the South Atlantic and Arctic Oceans, where thousands of kilometers of profiles have been obtained.

Suggestive data have been gathered on the eastern Iceland-Faroe Ridge. McBride et al. (2004) investigated the reflectivity and velocity structure of thick crust underneath the Iceland-Faroe Ridge in order to constrain models of underplating and the origins of lower-crustal layering in an environment assumed to be dominated by young igneous processes. Bohnhoff and Makris (2004) concluded that the southeastern part of the Iceland-Faroe Ridge comprises stretched continental crust and is part of paleo-Europe, and therefore it is not thick oceanic crust. Seaward-dipping reflectors have been imaged along the whole Greenland-Iceland-Faroe Ridge by seismic reflection (Hjartarson et al., 2017).

In the South Atlantic Ocean, ultralong, deep, seismic reflection profiles have revealed the structures of the continental margins. These include seaward-dipping reflector–draped continental crust and its transition to true oceanic crust (e.g., Geoffroy et al., 2015).

Zircons

Collecting and dating zircons is a rapidly developing new method of probing the age and provenance of the strata underlying young and active volcanic areas (e.g., Torsvik et al., 2013). Paleoproterozoic and Neoproterozoic zircons from beach sands on the island of Mauritius in the Indian Ocean were pivotal in concluding that the volcanism there occurs over continental crust (Torsvik et al., 2013). Similar work has been reported for the Solomon island arc (Tapster et al., 2014) and the northern Arabian-Nubian Shield, Egypt (Li et al., 2018).

Archean and Jurassic zircons have been reported from Iceland (Schaltegger et al., 2002; Paquette et al., 2006; Torsvik et al., 2015). However, whereas similar zircon results were readily accepted as evidence for underlying continental crust elsewhere, this has not happened for Iceland, despite supporting evidence in the form of elevated $^{87}Sr/^{86}Sr$ and Pb isotope ratios (Prestvik et al., 2001).

Inexplicably, the process of expanding and bringing to fruition the work of collecting and dating zircons in Iceland has not yet been pursued to completion despite a lapse of over 15 yr since the first report. This work is urgently needed. An initial project would collect material from several tens or even hundreds of sites covering all parts of Iceland and preferably also offshore parts of the Greenland-Iceland-Faroe Ridge.

Deep Drilling

Deep drilling in Iceland is predicted to encounter rocks in the lower crust that are either continental or mafic material intruded in continental rocks. Geothermal boreholes in Iceland, which typically are not cored, are up to ~3000 m deep.

The deepest penetration to date has been 4659 m in well IDDP-2 at Reykjanes, at the extreme SW tip of Iceland. This well was drilled for geothermal research purposes. Drill cutting samples were retrieved from 3000–3200 m depth, along with 27.3 m of core, including from the very bottom of the well. The core has not been exhaustively studied but was reported to contain evolved rocks (i.e., rocks that have undergone fractional crystallization) in its lowest levels (Weisenberger et al., 2019). The top of the lower crust, estimated from extrapolated seismic and gravity data, is ~5–7 km deep at the drill site, and so it has not yet been reached (Darbyshire et al., 2000; Foulger et al., 2003). In order to test the hypothesis that the Icelandic lower crust is largely continental, drilling considerably deeper than has been conducted to date is thus needed.

The extreme SW of Iceland, close to the Reykjanes Ridge, may be peripheral to the main continental domain. Nevertheless, it is conceivable that lower-crustal xenocrysts or material with a continental signature might be found in the deepest material retrieved. Further study of this material is warranted. Testing the Icelandia hypothesis is an important additional goal of continued deep drilling.

Reappraisal of the Geology

Although it does not amount to an independent test, reappraisal of the geology of Iceland in the context of the Icelandia hypothesis is needed. The question to be answered is whether existing geological knowledge can rule out the hypothesis that Iceland comprises an assemblage of seaward-dipping reflector–draped blocks of magma-inflated continental crust.

Deep erosion in the fjords of Tertiary eastern Iceland has exposed up to ~1000 m of continual vertical thickness of subaerial lavas (Fig. 4; Fridleifsson, 1982) that dip at gentle angles (up to ~10°) to the west. The 8.5 km of noncontinuous succession there includes ~700 lava flows.

The oldest exposed rocks are ca. 13 Ma in east Iceland and ca. 16 Ma at a location 450 km to the west, in the Northwest Fjords region. That distance corresponds to 22.5 m.y. of crustal extension at the regional plate rate. This proves that crust older than that yet found on the surface must exist at depth beneath Iceland

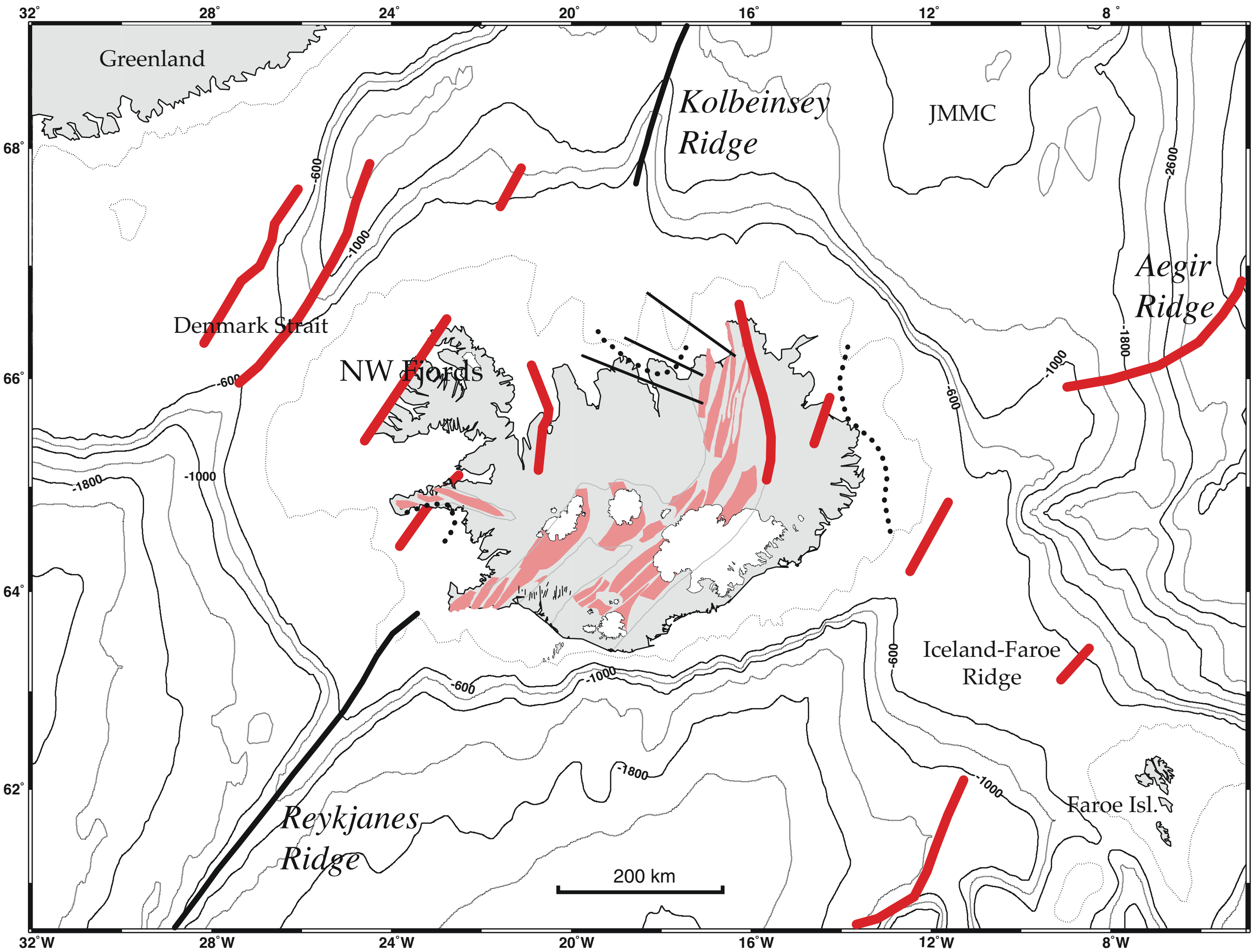

Figure 4. The Greenland-Iceland-Faroe Ridge region showing bathymetry in m b.s.l. and tectonic features. JMMC—Jan Mayen microplate complex. Thick black lines—axes of currently active oceanic Reykjanes and Kolbeinsey Ridges; thin gray lines on land—outlines of spreading zones; pink—currently active extensional volcanic systems; thin black lines—individual faults of the complex transform zones in south and north Iceland; dotted lines—unconformities; white—glaciers; thick red lines—extinct rift zones from Hjartarson et al. (2017).

(Foulger, 2006). In north-central Iceland, there is a major unconformity where a steeply SE-dipping (up to ~35°) lava pile aged ca. 13–9.5 Ma is unconformably overlain by lavas aged 7–6 Ma, emplaced by the currently active Northeast volcanic zone (Jancin et al., 1985). The younger lavas are commonly attributed to an eastward jump of the main spreading axis. However, the underlying older lavas show that volcanism was active in the east prior to such a jump. This provides conclusive geological evidence for the long-term existence of multiple parallel volcanic zones in Iceland. Other unconformities are found in west and east Iceland (Fig. 4).

Structure in the Icelandic lava pile is generally interpreted in terms of the "Palmason model" (Palmason, 1973, 1980). This model suggests lava flows are originally emplaced horizontally, but subsequently sag under the weight of later flows that are progressively piled on top. These are thickest closest to the source rift, and thus this axis subsides most rapidly. Material simultaneously migrates away from the rift as crustal widening occurs. The assumption that Iceland and the Greenland-Iceland-Faroe Ridge most commonly formed about a single, through-going axis of spreading, operating according to the Palmason model, cannot account for the complexity of the geological structure in Iceland. A reappraisal is required, in particular, examining evidence for possible crustal-scale faults that control the growth of Icelandic seaward-dipping reflectors.

APPLICATION TO OTHER CANDIDATE SUBMERGED CONTINENTAL BLOCKS

Icelandia is the best and most easily studied of all postulated submerged continents because of the proximity of large landmasses and the exposure of 35% of its area above sea level in the island of Iceland. This provides subaerial exposure broad enough to study the spatial and temporal volcanic processes on a regional and multiphase scale.

Most other candidate continental blocks in the deep oceans expose little more than small volcanic islands. They are thus challenging to study, and only limited data can be acquired as a practical matter. Currently, the only way of investigating such regions is using petrology and geochemistry coupled with satellite gravity, magnetic, and bathymetric data. A combination of these techniques, including the finding of old zircon xenocrysts, was used by Torsvik et al. (2013) to conclude that continental crust underlies the Seychelles-Mauritius Plateau and the Chagos-Laccadive Ridge. They proposed that these regions comprise ribbons of lava-blanketed continental lithosphere sliced off the coast of Madagascar and India by spreading-ridge jumps at 83.5–61 Ma.

Many of the submerged crustal blocks proposed in the introduction here and illustrated in Figure 1 have features in common (Table 1):

1. a ribbon-like shape, which may be inherited from linear features such as fault zones or propagating ridges slicing off strips of coastal continental material (e.g., this process is occurring at the present day at Baja California);
2. the appearance of a tilted block with one steep side and one gently dipping side (e.g., the Walvis Ridge slopes gently to the NW but its SE side is steep);
3. association with unstable spreading ridges, as shown by nearby ridge jumps;
4. recent volcanism, often low in volume, occasionally with some time progression as the volcanism apparently propagated, for example, along the ribbon of continental crust (e.g., on the Chagos-Laccadive Ridge); and
5. an origin popularly attributed to a mantle plume.

The SW Indian Ridge presents another example of continental lithosphere in the ocean. The eastern 2000 km of this ridge—the Marion Rise—is bathymetrically shallow. A thermal explanation for its high stand would require high mantle temperatures and a thick crust. However, the crust is thin, peridotite is exposed extensively on the seafloor, volcanic features are minor, and the isotopic geochemistry of the basalts contrasts with that of the adjacent ridge that lacks the anomalous elevation. These observations suggest that the high stand of the Marion Rise is supported by buoyant mantle delaminated from beneath African cratonic lithosphere during Gondwana breakup (Zhou and Dick, 2013; Dick et al., 2014; Dick and Zhou, 2015). Independent evidence for such a process is provided by seismology, which detects interfaces that are continuous beneath both the African cratonic regions and adjacent ocean basins (Wang et al., 2017). That study suggests that continental lithosphere can extend far from the coasts, out into the oceans, as we propose for Icelandia.

A structurally inhomogeneous supercontinent can disintegrate in a piecemeal and complex way, with breakup axes growing by propagation, jumping laterally, and possibly also activating major continental faults or other linear structures in shear. Under these circumstances, the disintegrating region will involve multiple blocks and microplates, each with its own migrating local Euler pole, and breakup will be piecemeal and complex. Lateral rift migrations may slice off ribbons of continental crust that are transported into new oceans by the formation of oceanic crust on their landward sides, as is happening at present-day Baja California. If extension becomes established along the East African Rift in the future, an elongate continental block and one or more

TABLE 1. FEATURES OBSERVED AT SOME POSSIBLE INTRA-OCEANIC CONTINENTAL BLOCKS

Postulated submerged continent	R = ribbon shape	T = tilted block morphology	UR = unstable ridges	V = recently volcanic	P = mantle plume has been proposed	Area (km^2)	References
Broken Ridgia	R	T			P	572,000	Mahoney et al. (1995)
Conradia	R	T		V	P	331,000	Cross et al. (2011)
Crozetia	R	T		V	P	188,000	Cross et al. (2011)
Icelandia	R	T	UR	V	P	600,000	
Greater Icelandia	R	T	UR	V	P	1,000,000	
Kerguelia	R	T		V	P	1,360,000	Mahoney et al. (1995); Ponthus et al. (2020)
Lomonosovia	R	T				359,000	Artyushkov (2010)
Madagascia	R		UR		P	1,225,000	Cross et al. (2011)
Mauritia	R	T	UR	V	P	408,000	Torsvik et al. (2013)
Meteoria	R	T	UR	V	P	120,000	
Mozambiquia		T				850,000	Doucouré and Bergh (1992)
Rio Grandia			UR	V	P	459,000	Graça et al. (2019)
Walvia	R	T	UR	V	P	740,000	Graça et al. (2019)
Zealandia						4,900,000	Morton et al. (1995)

continental microplates may become separated from East Africa by a new ocean.

Microcontinents that formed in this way at volcanic margins become capped by surface lavas and densified from below by mafic intrusions into the lower crust. This creates hybrid crust that founders below sea level, introducing bathymetric, compositional, structural, and strength inhomogeneities into the crust that floors the ocean. A spectrum of structures may form, with varying proportions of continental crust and lithosphere incorporated into oceanic crust and upper mantle at different scales. The existence of such crust challenges the simplistic view that there is a clear bimodal division of all crust into continental and oceanic types and that the oceans are floored by simple oceanic igneous crust with the occasional simple, well-defined continental block. The inhomogeneities introduced by continental material create weak zones where intraplate deformations are preferentially taken up. Where this is extensional, pathways for rejuvenated volcanism are provided.

The extent of continental crust and lithosphere in the oceans is undoubtedly presently underestimated, as is its potential for explaining enigmatic observations. We recommend this model as a candidate working hypothesis to interpret data from ocean rises and plateaus.

CONCLUSIONS

We propose that an ~450,000 km^2 swath of crust, comprising stretched, magma-inflated continental crust capped with lavas, links Greenland to Eurasia at ~65°N. It is contiguous with the ~150,000 km^2 Faroe Platform, and we name this sunken continent Icelandia. It is also contiguous with the passive continental rifted margin offshore Britain, and if that is included in a "Greater Icelandia," then the entire, largely sunken continent has an area of ~1,000,000 km^2. The crust forming Icelandia is hybrid continental-oceanic material, possibly consisting of >75% continental material (Foulger et al., 2020), and it may be considered to comprise a third kind of crust.

Approximately 100,000 km^2 is exposed as the island of Iceland, making Icelandia a convenient example to test these hypotheses because techniques can be used that are much easier to apply on a large landmass than at sea. These include magnetotelluric surveying; ultralong, full-crust-penetrating reflection profiling; dating of collected zircons; deep drilling; and reappraisal of structural geology. Some of these methods could also be applied to other candidate or proven sunken continents or continental fragments, including the Walvis, Lomonsov, and Broken Ridges, the Rio Grande, Meteor, and Conrad Rises, and the Elan Bank–Kerguelen, Madagascar, Mozambique, Agulhas, and Crozet Plateaus.

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