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A sub-crustal piercing point for North Atlantic reconstructions and tectonic implications

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ABSTRACT

Plate tectonic reconstructions are usually constrained by the correlation of lineaments of surface geology and crustal structures. This procedure is, however, largely dependent on and complicated by assumptions on crustal structure and thinning and the identification of the continent-ocean transition. We identify two geophysically and geometrically similar upper mantle structures in the North Atlantic and suggest that these represent remnants of the same Caledonian collision event. The identification of this structural lineament provides a sub-crustal piercing point and hence a novel opportunity to tie plate tectonic reconstructions. Further, this structure coincides with the location of some major tectonic events of the North Atlantic post-orogenic evolution such as the occurrence of the Iceland Melt Anomaly and the separation of the Jan Mayen microcontinent. We suggest that this inherited orogenic structure played a major role in the control of North Atlantic tectonic processes.

INTRODUCTION

The reconstruction of geometries and structural trends expressed in the exposed geology of conjugate continental margins is one of the principles of continental drift and a precursor to modern concepts of plate tectonics. Fitting conjugate continental margins together is dependent on interpretations of the width of conjugate continental shelves and of crustal and lithospheric structure and thinning, and on the choice of location of the continent-ocean transition (COT) (e.g., Skogseid et al., 2000). The recognition that exhumed upper mantle may occur within the COT (Boillot et al., 1988), and may even be characterized by magnetic striping (Sibuet et al., 2007), adds to this complexity. Further, magmatic edifices previously thought to be underlain by oceanic lithosphere may actually lie on thinned segments of continental lithosphere (Foulger, 2006; Lundin and Doré, 2011). Accordingly, these have to be incorporated into any plate tectonic reconstruction. It commonly remains uncertain whether these segments are separated from the continents by oceanic crust, hyperextended continental crust, or exhumed upper mantle. These issues pertain to reconstructing the conjugate margins of the North Atlantic Ocean (Gernigon et al., 2015) (Fig. 1).

A large number of studies demonstrate that the continental mantle lithosphere is characterized by significant heterogeneity (e.g., Balling, 2000; Thybo and Anderson, 2006). Here we propose correlation of upper mantle structures imaged by seismological techniques on the conjugate margins of the North Atlantic and discuss its implications for plate reconstructions and geodynamic processes.

THE CENTRAL FJORD AND FLANNAN MANTLE STRUCTURES

A seismological array deployed across the Central Fjord system (CF) in East Greenland (Fig. 1, 0 Ma) has revealed an east-dipping high-velocity structure (Vp > 8.3 km/s) (Fig. 2, left). It is interpreted to be the image of a fossil subduction zone comprising eclogitized subducted crust emplaced during early Paleozoic closure of the Iapetus Ocean (Schiffer et al., 2014). On the other side of the North Atlantic, the Flan-

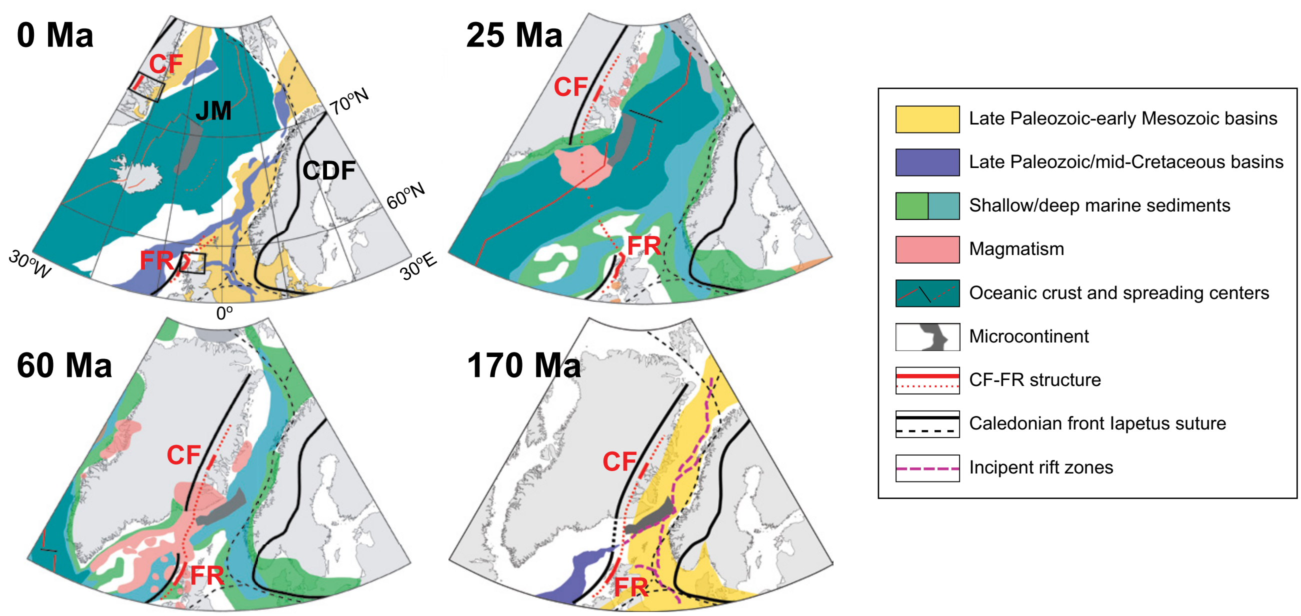

Figure 1. Present-day North Atlantic (after Skogseid et al., 2000) and paleogeographic reconstructions at 25 Ma, 60 Ma (after Torsvik et al., 2002), and 170 Ma (after Skogseid et al., 2000). CF—Central Fjord system; FR—Flannan reflector; JM—Jan Mayen microcontinent; CDF—Caledonian deformation front (from Gee et al., 2008). Black boxes at 0 Ma outline study areas around CF array and FR. Red lines are where these structures intersect the Moho (Schiffer et al., 2014; Chadwick and Pharaoh, 1998); stippling indicates where less constrained or inferred.

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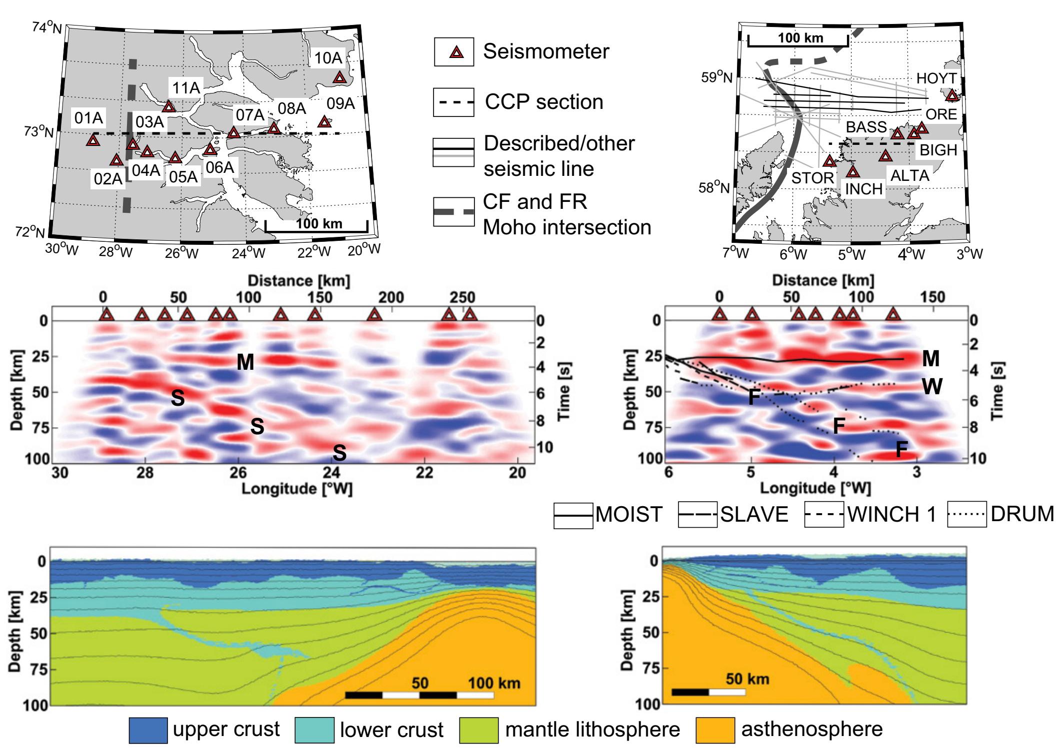

Figure 2. Comparison of results in case of East Greenland at ~73°N (left) and northern Scotland at ~58°N (right). Note that these are not conjugate margin pairs. Upper panel: Location of seismic stations. Thick dark gray line is interpreted Moho intersection of Central Fjord system (CF) structure and Flannan reflector (FR) (Chadwick and Pharaoh, 1998). Thin black and gray lines are deep seismic reflection lines (Flack and Warner, 1990). Middle panel: Common conversion point (CCP) receiver function images of CF array and of seven Scottish stations. Red and blue indicate positive and negative conversions, respectively. Superimposed black lines are sub-Moho reflections from seismic lines (see text). M—Moho; S—CF structure; F—Flannan reflector; W—W reflector. Lower panel: Structural images of numerical modeling at 60 m.y. (left) and 80 m.y. (right) after onset of extension (see Figs. DR1–DR3 [see footnote 1] for details).

nan reflector (FR), offshore northwest Scotland, exhibits similar characteristics imaged by deep seismic profiling (e.g., Smythe et al., 1982).

The geometry of the CF structure is similar to that of the FR and, in both cases, high mantle velocities and densities are suggested as the cause of the seismic signature (Warner et al., 1996; Morgan et al., 2000; Schiffer et al., 2015). Interpretations on the origin of the FR range from a sub-crustal shear zone (e.g., Flack et al., 1990), mafic intrusions, and mantle hydration (e.g., Warner and McGeary, 1987) to fossil subduction of pre-Caledonian age (Morgan et al., 1994) or Caledonian age (Snyder and Flack, 1990).

In order to corroborate a similar origin of the CF and FR structures, we test the similarity of their seismological signature by analyzing receiver functions (RFs) of seven stations in northern Scotland using the same technique as for the CF array in East Greenland (Schiffer et al., 2015, and references therein).

A total of 105 teleseismic events with epicentral distances of 30° to 100° and magnitudes >5.0 were processed for the CF array. Depending on noise level and period of active measurements, seven to 62 RFs were selected at each station (see Tables DR1 and DR2 in the GSA Data Repository[1] for details). The Scottish data were available from Orfeus (Observatories and Research Facilities for European Seismology; www.orfeus-eu.org). Five stations (STOR, INCH, BASS, ALTA, and HOYT) were part of the RUSH (Reflections Under the Scottish Highlands) experiment (Bastow et al., 2007) and two (BIGH and ORE) are permanent stations of the British Geological Survey. No combined RF analysis of these stations has been published, but single-station RF analysis has been conducted (Asencio et al., 2003; Tomlinson et al., 2006). Magnitudes >5.8 were processed with 13–34 selected events at each station (Tables DR1 and DR3).

Common conversion point stacking (CCP) (e.g., Svenningsen et al., 2007) was applied to the RFs, projecting each waveform along the theoretical teleseismic ray path in three dimensions. The signals were averaged and projected onto a vertical two-dimensional (2-D) section. The velocity models for the ray tracing were based on crustal velocity models (Barton, 1992; Schlindwein and Jokat, 1999) and extrapolated into the upper mantle.

The sub-Moho reflections from four seismic profiles—MOIST (Smythe et al., 1982), SLAVE (Snyder and Flack, 1990), WINCH 1 (Brewer et al., 1983), and DRUM (McGeary and Warner, 1985)—closest to the Scottish stations were superimposed on the FR CCP image, as well as the Moho reflection of the MOIST profile (Fig. 2, middle panel, right). Each profile is shifted to the same FR-Moho intersection point.

The CF RFs (Fig. 2, middle panel, left) show a positive conversion (red, downward impedance increase), starting at ~40 km depth (5 s delay time) in the west of the section and dipping east with 20° to at least 100 km depth (11 s). This positive conversion is followed by a 10–15 km, deeper negative conversion (blue, downward impedance decrease). The Moho is identified at ~40 km (5 s) in the east and at 25–30 km (3.5 s) in the west with an abrupt offset at ~50 km distance.

The Moho of the FR RFs (Fig. 2, middle panel, right) appears horizontal at 25–30 km depth (3.5 s) and coincides with the Moho of the MOIST profile. Below the Moho, a second horizontal positive conversion can be seen at 45–50 km depth (~5 s), but only in the east, which coincides with reflections from the SLAVE and DRUM profiles; the so-called W reflector. A third positive conversion dips from ~35 km depth (4 s) in the west to 75–80 km (8–9 s) in the east, followed by a 10–15 km deeper negative conversion. As for the CF array, this is the signature of a high-velocity zone. Both positive and negative conversions coincide with seismic reflections.

Conversions of globally observed active and fossil subduction zones are commonly related to anisotropy of the present materials and fabrics (e.g., Bostock, 2013), which may also be the case here.

Snyder and Flack (1990) suggested that the FR and other dipping sub-Moho structures were genetically linked as orogenic remnants, at least 400 m.y. old and several hundreds of kilometers long. Chadwick and Pharaoh (1998) agreed but proposed that these structures are of pre-Caledonian age. The CF and FR structures align in trend

[1]GSA Data Repository item 2015363, detailed information, additional figures, and tables on the receiver function and numerical modeling, is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

and dip on pre-rift paleogeographic reconstructions (Fig. 1) and are both explicable by a fossil subduction zone. Given that they follow Caledonian structural trends (e.g., Caledonian deformation front, Fig. 1), it is likely that initial formation occurred during the Caledonian orogeny.

RESPONSE OF A FROZEN-IN SLAB TO RIFTING

If the CF-FR structures form a coherent lithospheric element existing before North Atlantic breakup, then that element survived rifting and breaching of its host lithosphere. Rifting developed on the down-dip side (east) of the CF and on the up-dip side (west) of the FR (Fig. 1, 170 Ma). The post-rift survival of a contiguous sub-Moho structure requires an explanation, and here we analyze a representative scenario using 2-D geodynamic modeling (Petersen et al., 2010, 2015).

The modeling considers a 20 m.y. phase of continent-continent convergence at a rate of 2 cm/yr followed by extension at a rate of either 2.5 or 0.5 cm/yr, representing rates reported for the North Atlantic (Mosar et al., 2002). This scenario epitomizes the Paleozoic closure of the Iapetus Ocean followed by Mesozoic–Cenozoic extension and opening of the North Atlantic. A description of the methods, parametric details, and figures are given in Table DR4 and Figures DR1–DR3 in the Data Repository.

The results (Fig. 2, bottom panel) indicate that (1) a slab of lower continental crust is preserved in the lithospheric mantle during phases of either fast or slow extension, and (2) the locus of the continental breakup can occur on either side—up-dip or down-dip—of the inherited structure. The position of breakup relative to the slab depends on the extension rate, with the down-dip away from breakup (FR) being produced by a higher extension rate and vice versa, in agreement with estimated rifting rates (1–2 cm/yr at Reykjanes Ridge; 0.5–1.5 cm/yr at Mohns Ridge; Mosar et al., 2002).

Even though the strength contrast between the fossil slab and the mantle lithosphere might imply that the slab could act as a detachment upon extension, the models show that crustal flow associated with gravitational collapse of thickened, orogenic crust (Buck, 1991) imposes a first-order control on the locus of breakup. Even in the case of thinner crust, crustal flow can lead to protracted breakup and hyperextension, depending on extension rate (Brune et al., 2014). Extension rate controls the efficiency of crustal flow relative to localizing effects (Buck, 1991) and the degree of localized deformation. The latter also depends on the rate of advective heating due to thinning relative to conductive cooling, which is also a function of extension rate (England, 1983).

Although falling short of the full complexity of the tectonic evolution of the North Atlantic margins, these models illustrate that mantle structures formed during continental collision can survive the process of orogenic collapse and continental breakup.

DISCUSSION

RF imaging, geometry, and relation to large-scale geological trends suggest that two sub-crustal, eastward-dipping structures in East Greenland (73°N) and northern Scotland (58°N) are segments of the same pre-breakup structure. RFs and previous seismic and gravity studies imply high velocities and densities suggestive of eclogite. Numerical modeling of orogenesis and subsequent extension shows that previously subducted crustal material is able to survive rifting on both conjugate passive margins. A fossil subduction zone of pre- to early Caledonian age is therefore a plausible interpretation.

Moreover, the inferred sub-Moho structure appears to play a fundamental role in controlling the tectonic evolution of the North Atlantic region. Post-Caledonian formation of extensional sedimentary basins is dominantly within the Caledonian orogen, which lies entirely east of the CF-FR structure (Fig. 1, 170 Ma). Continental breakup in this area was driven by global extrinsic tectonic forces propagating to the north (Nielsen et al., 2007).

Later (Fig. 1, 60 Ma), the southwest-northeast–trending intracratonic rift system crossed the CF-FR structure, and this was accompanied by a short period of magmatism, which quickly dissipated after a major outburst (Storey et al., 2007). The reconstructions tie the intersection of the rift axis and the CF-FR structure to the occurrence of the early Cenozoic magmatic center and the later manifestation of Iceland. Magmatism at this time occurred predominantly west of the CF-FR structure, with only minor activity observed to the east. After the bulk of magmatic products had erupted, "normal" rifting and seafloor spreading continued to the north near the Iapetus suture.

By 25 Ma, new oceanic lithosphere had been accreted (Fig. 1) and seafloor spreading terminated at the Aegir Ridge and focused at the Kolbeinsey Ridge west of the Jan Mayen microcontinent (e.g., Gernigon et al., 2015). This rift axis coincides with location and strike of the CF-FR structure, and we speculate that this might be connected to a second melting event of the inherited crustal material. Elevated rifting rates have been estimated for this period (Mosar et al., 2002). This event might be coeval with what was argued to be a Miocene magmatic event, possibly related to the formation of so-called "Iceland Insular Margin" (Doré et al., 2008).

Lithospheric crustal contamination and fertilization, higher temperatures, or water in the asthenosphere could have enhanced melting, forming the North Atlantic igneous province (Jamtveit et al., 2001; Korenaga, 2004; Foulger et al., 2005, Brown and Lesher, 2014). The here-proposed CF-FR sub-Moho structure might represent one example of inherited crustal material.

We note that there is a distinct sinistral offset of the two portions of the CF-FR structure (Fig. 1, 170 Ma). This may imply that East Greenland and mid-Norway lay closer together. Lining up the structures would remove Mesozoic extension, creating a close-fit pre-Mesozoic reconstruction as discussed for the South Atlantic by Macdonald et al. (2003), with the effect of removing extension from the Rockall Trough. Our study demonstrates the potential value of a sub-crustal piercing point not only to illuminate tectonic processes in the North Atlantic, but also to motivate modifications to North Atlantic plate reconstructions.

CONCLUSION

Sub-crustal structures inferred from seismological data in northern Scotland and East Greenland are conjugate remnants of the same pre-rift mantle heterogeneity, possibly an early Caledonian fossilized subduction zone. We believe it may represent the first example of a sub-crustal piercing point for the plate tectonic reconstruction of conjugate continental margins. Further, given the geometric correlation of the inferred structure with the post-Caledonian tectonics of the North Atlantic, we suggest that it is a causative agent for plate tectonic mechanisms and rearrangements in the area, such as the occurrence of early Cenozoic magmatism and the formation of the North Atlantic igneous province and possibly the deviation of the spreading axis and the separation of the Jan Mayen microcontinent from East Greenland. Our results support models that argue that plate tectonic processes may have played an important role in the formation of principal magmatic and tectonic features of the North Atlantic.

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Notes
