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Seismological evidence for a fossil subduction zone in the East Greenland Caledonides

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ABSTRACT

The postorogenic collapse of the early Paleozoic Caledonian orogeny is well documented; however, several different plate tectonic models exist for the convergent phase involving closure of the Iapetus Ocean and the collision of Laurentia and Baltica. Receiver function analysis of 11 broadband seismometers along a 270 km transect in the East Greenland Caledonides reveals the existence of an east-dipping high velocity slab. Numerical modeling demonstrates that relict subducted and eclogitized crust is a plausible explanation. Thus, eastward subduction preceded subsequent west-dipping subduction during the formation of the East Greenland and Scandinavian Caledonides. This is a key constraint for understanding the Caledonian and continental margin evolution in the North Atlantic realm.

INTRODUCTION

The long-term geological evolution of the North Atlantic and its surrounding passive margins includes convergence and collision of Laurentia, Baltica, and Avalonia (Fig. 1) and the closure of the Iapetus Ocean, leading to the early Paleozoic Caledonian orogeny (Roberts, 2003; Gee et al., 2008). This was followed by Jurassic–Paleogene extension and multistage rifting, culminating in continental breakup and seafloor spreading from ca. 54 Ma (Skogseid et al., 2000).

Processes forming continental crust and lithosphere, such as subduction and collision processes, leave structural and compositional relicts that may be preserved over long geological time and today imaged at depth by geophysical methods, including a number within the Caledonian orogenic belt (e.g., Flack and Warner, 1990; Hall et al., 1990; Blundell et al., 1991; MONA LISA Working Group, 1997) (see Fig. 1B). Other examples come from cratonic areas (e.g., BABEL Working Group, 1993; Eaton and Cassidy, 1996). Near-vertical seismic reflection profiling (e.g., Balling, 2000; van der Velden and Cook, 2005) provides the majority of these images, sometimes in combination with other seismological methods such as wide-angle seismic refraction (e.g., Clowes et al., 2010) or teleseismic receiver functions (e.g., Bostock, 1998).

Wide-angle seismic investigations (e.g., Schlindwein and Jokat, 1999; Voss and Jokat, 2007, 2009) have provided information on crustal thickness and P-wave velocity (Vp) distribution in the Central Fjord (CF) region of East Greenland. However, the lack of complementary geophysical methods and thin data coverage mean that structural relationships between the surface geology and deeper features are unresolved. Here we consider the crust and uppermost mantle in this area by means of a teleseismic experiment carried out from 2009 through 2011. A total of 11 broadband seismometer sites formed an ~270-km-long profile (the CF system array) from the Greenland Ice Sheet to the Atlantic coast across the East Greenland Caledonides at ~73°N (Fig. 2).

GEOLOGICAL SETTING

The dominant tectonic feature in central East Greenland is the Caledonian orogen, part of the 6000-km-long Caledonian-Appalachian orogenic belt, the original width of which is estimated to have been 700–800 km in the North Atlantic region.

Clear tectonic signatures of the collisional history of this Himalayan-type orogeny (Gee et al., 2008) are preserved in East Greenland and Scandinavia. The final Scandian orogenic phase with westward subduction of

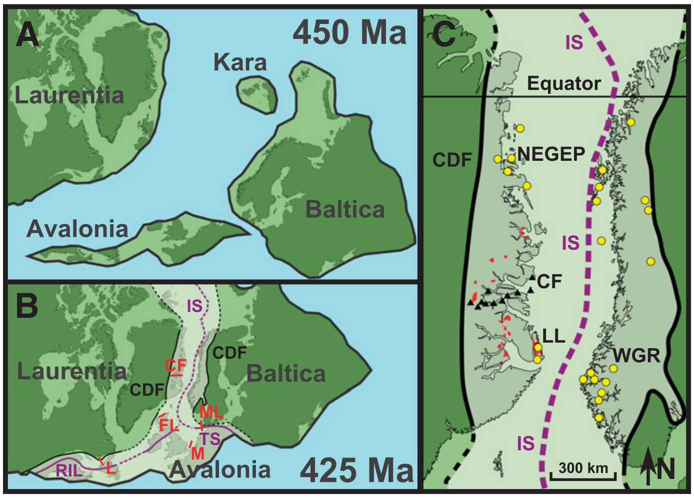

Figure 1. Paleogeography of Laurentia, Baltica, and Avalonia (from Cocks and Torsvik, 2005, 2011). A: At 450 Ma. B: At 425 Ma. Thick black line is Caledonian deformation front (CDF; Gee et al., 2008). Purple line shows Iapetus suture (IS; Cocks and Torsvik, 2005), Red Indian line (RIL; van Staal et al., 2009), and Thor suture (TS; Pharaoh, 1999). Red is geophysical observations of upper mantle structures in the Caledonian belt. CF—Central Fjord system array (this study), FL—Flannan (Flack and Warner, 1990), L—Lithoprobe 86.3 (Hall et al., 1990), M—MOBIL 6A and 7 (Blundell et al., 1991), ML—MONA LISA 1 and 2 (MONA LISA Working Group, 1997). C: Detail at 425 Ma. Thick black and purple line same as in B. Black triangles show station positions of the CF system array. Yellow circles show occurrence of eclogites (Fossen, 2010). Red is late to postkinematic granites (Henriksen, 1999). NEGEP—North-East Greenland eclogite province, LL—Liverpool Land eclogite terrane, WGR—Western Gneiss region.

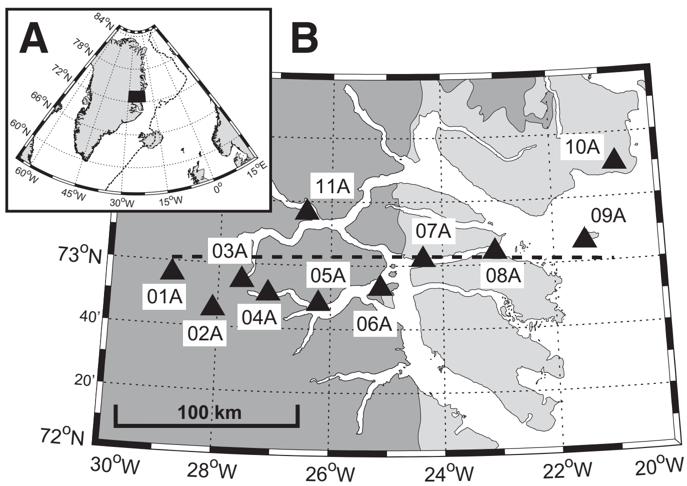

Figure 2. Location map. A: Regional setting; black box outlines study area. Stippled line shows the Mid-Atlantic Ridge. B: Study area. Geological map modified after Henriksen (1999). Dark gray shows Caledonian rocks. Light gray represents post-Devonian rocks. Triangles show station positions. Stippled black line is vertical projection plane of receiver function migration.

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the Iapetus Ocean below Laurentia has been established mainly from the occurrence of late Silurian–Early Devonian high-pressure rocks, such as eclogites, locally with coesite and microdiamonds (Dobrzhinetskaya et al., 1995), in the Western Gneiss region (Fig. 1C). This model is supported by the metamorphic age of the Liverpool Land eclogite terrane (~71°N; Fig. 1C) and its Baltic affinity (e.g., Augland et al., 2010). Pronounced thrust systems, generally west vergent in Greenland and east vergent in Scandinavia, as well as inferred island arc terranes in Scandinavia, are also strong indicators for continent-continent collision.

The Appalachians and European Caledonides are closely related (Fig. 1). A pre-Scandian convergent phase of southeast-directed subduction and arc accretion has been identified at the Laurentian margin (Taconian in North America and Grampian in the British Isles) (e.g., van Staal et al., 1998). Subduction termination was followed by the underthrusting of Baltica and Avalonia beneath Laurentia with a flipped subduction polarity, causing severe deformation of the Laurentian margin down to the underlying upper mantle (Leslie et al., 2008; van Staal et al., 2009).

Tectonic scenarios including pre-Scandian subduction systems along the Laurentian margin of the East Greenland–Scandinavian Caledonides have also been proposed. Magmatic arcs in the uppermost thrust sheets in Scandinavia showing Laurentian affinity and ages predating the Scandian phase have been interpreted as evidence for an early eastward subduction (e.g., Yoshinobu et al., 2002) along the eastern margin of Laurentia (Roberts, 2003; Gee et al., 2008).

I-type granitic intrusions in East Greenland evidence active magmatism from 455 to 420 Ma and a varied geochemical composition, similar to arc-related terranes in the European Caledonides (Kalsbeek et al., 2008; Rehnström, 2010; Augland et al., 2012). Markedly different short-lived homogeneous S-type leucogranitic magmatics are thought to have formed in relation to Silurian orogenic thickening (Kalsbeek et al., 2008).

The eclogites in the North-East Greenland eclogite province (~77°–78°N; Fig. 1C) show Devonian postcollisional ages and a Laurentian affinity, interpreted as evidence of an eastward, intracontinental underthrusting within the previously collided Laurentian continent (Gilotti and McClelland, 2007).

Below thrust sheets emplaced during the Caledonian orogeny, East Greenland has a crust of Archean to Paleoproterozoic age, overlain by Mesoproterozoic metasediments and sediments of Neoproterozoic to early Paleozoic age (e.g., Henriksen, 1999). Intrusive granites formed in relation to the Neoproterozoic Valhalla orogeny (Cawood et al., 2010) are also found in the region.

RECEIVER FUNCTION ANALYSIS

Receiver functions (RFs) were computed from the CF system array teleseismic waveforms in order to isolate conversions of the incident P- to S-waves at strong velocity discontinuities, such as the Moho (Ammon, 1991). This was done by rotating the recorded vertical, north, and east teleseismic components with regard to back azimuth and the incidence angle of the arriving P-wave (Vinnik, 1977). Further iterative deconvolution (Ligorría and Ammon, 1999) removed the incoming P-waveform from the converted S-waveform, focusing each conversion as isolated impulses. We processed 105 events of epicentral distances from 30° to 100° and magnitudes >5.0, 30–50 of which were selected for most of the stations (for detailed information, see Tables DR1 and DR2 and Figs. DR1–DR3 in the GSA Data Repository[1]).

A common conversion point migration was applied, projecting each RF waveform in time along its teleseismic ray to the corresponding conversion position (e.g., Svenningsen et al., 2007). The three-dimensional (3-D) Vp model for the ray tracing was derived from wide-angle seismic crustal models (Schlindwein and Jokat, 1999; Voss and Jokat, 2007) and extended into the mantle according to the global IASP91 model (Kennett and Engdahl, 1991). Migrated RF profiles were produced by Fresnel zone–based 3-D averaging and 2-D projection on vertical sections.

The RFs (Fig. 3A) show a clear positive-polarity (red) Moho conversion almost throughout the section. Furthermore, a clear sub-Moho conversion lineament can be observed, dipping from ~45 km depth in the west to 100 km or more in the eastern end of the section. Its positive polarity (red) implies a velocity increase with depth and is followed by a negative conversion (blue) directly underneath, indicating a high-velocity layer. This conversion pair is generally linear with some irregularity, which could reflect real features, such as structural or compositional heterogeneity. To the west, near 28°W (40 km), this structure intersects with the Moho conversion at 41 km depth. The Moho shallows to ~30 km depth in the central part and to ~25 km from 23° to 21°W (200–250 km). The apparent increase to ~30 km depth at the eastern end may be explained by the large projection distance of station 10A (Fig. 2). In the eastern part the RFs show strong multiples at 2–4 s, indicating a sedimentary basin. This is in accordance with the wide-angle model as well as surface observations (Henriksen, 1999). At ~27°–26°W (50–100 km), the Moho conversion (~30 km depth) appears weaker than the dipping convertor underneath. This could be explained by a region of intermediate velocities (see following) between crust and the dipping structure.

The robustness of this 2-D section and especially the dipping lineament was tested by migration onto vertical sections with azimuths

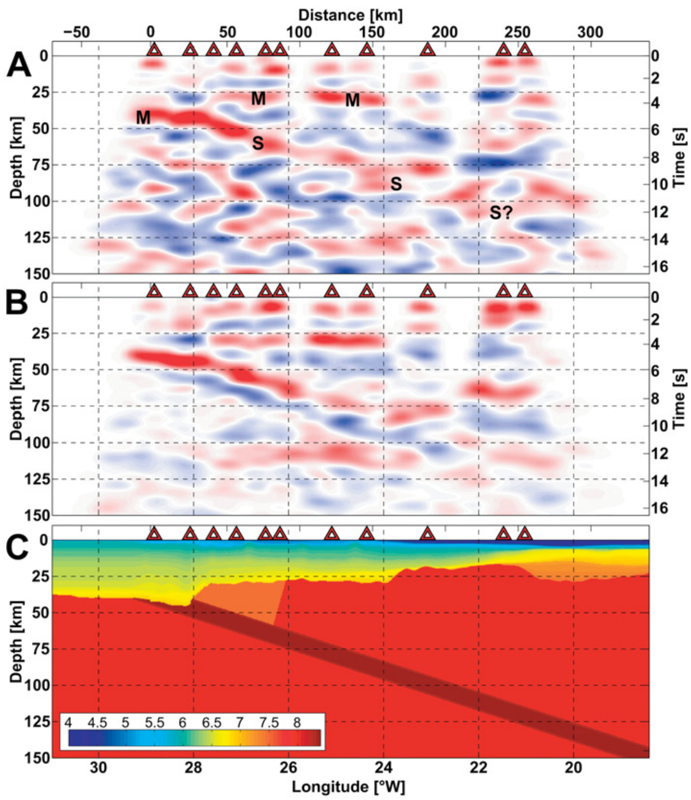

Figure 3. A: Final migrated receiver function (RF) profile. Triangles show station positions. Red represents positive conversions. Blue represents negative conversions. M—Moho conversion, S—sub-Moho conversion. B: Same as A, with migrated synthetic RFs and realistic noise, using P-wave velocity model illustrated in C (noise-free images in Figs. DR5 and DR6; see footnote 1). C: West-east section through three-dimensional model of P-wave velocity model used for RF simulation in B at 73°N. Color bar is in km/s. Aspect ratio is 1:1.

[1]GSA Data Repository item 2014116, additional array and station information, event information, map of piercing points, comparison of the used velocity models, and additional images of recorded and synthetic receiver functions, is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

between 70° and 110° (north at 0°). The migration at 90° azimuth (west-east section) gave the best coherence of the dipping structure.

SYNTHETIC MODEL AND INTERPRETATION

Adaptive 2-D finite difference wavefield modeling (Levander, 1988) simulates the effects of the 3-D crustal model on conversions from each specific P-wave. For each event and each station a vertical section in a 3-D model is cut in the direction toward the earthquake. The 3-D Vp model is adjusted from the velocity model used for the ray tracing; the eastward-dipping high-velocity slab, rooted under a zone with a Vp of 7.4 km/s, is added. The RF data require lower velocities in the uppermost crust as well as some local adjustments of Moho depths. A section through 73°N is shown in Figure 3C (for a comparison with the initial model, see Fig. DR2).

Densities are calculated after Christensen and Mooney (1995) and Vs values were determined on the basis of Poisson's ratios between 0.25 and 0.3 for various lithologies (Christensen, 1996). To obtain realistic synthetic waveforms, each computed waveform is convolved with the observed vertical component. The real ambient noise measured 100–5 s before P-wave arrival was superimposed on the synthetic waveforms.

A slab of 10 km thickness and a Vp of 8.4 km/s with an eastward dip of 18° gave the best fitting RF image (Fig. 3B). The multiples, noise, and additional convolution in the synthetic test add substantial complexity to the image, especially that of the dipping structure (noise-free synthetic RFs are shown in Figs. DR5 and DR6). The synthetic test demonstrates that an eastward-dipping high-velocity slab is an excellent explanation for the features observed in the RFs.

The revealed sub-Moho conversion pair is interpreted as a fossil eastward-dipping subduction zone. The Vp of the modeled slab, 8.4 km/s, is typical of eclogitized oceanic crust, but might also originate from mafic continental lower crust. Similar seismic properties have been proposed for the upper mantle Flannan reflector off northwest Scotland (Morgan et al., 2000) and from seismic studies of remnant collision zones in the North Sea and Baltic Sea (Hansen and Balling, 2004). The linearity and geometry of the observed feature and its apparent homogeneous thickness of 10 km indicate transformed oceanic crust. Furthermore, a Moho offset of 11 km, from 40 km depth west to 29 km east of the slab attachment, is observed, similar to several cases discussed by Balling (2000). The Moho offset may be linked to a body of intermediate velocities (7.4 km/s) in the corner of the subducted slab, interpreted as a serpentinized mantle wedge, similar to that invoked for active subduction zones (e.g., Bostock et al., 2002).

DISCUSSION

A wealth of published data constrains the closure of the Iapetus Ocean and the main Scandian collision of the Caledonian orogeny in East Greenland and Scandinavia. Models have been developed in the context of surface geological evidence, such as geochronological data of subduction-related metamorphic units and intrusions and emplaced thrust sheets. While the overall picture is not debated, the details of the collisional development are ambiguous, given a lack of deep geophysical constraints. Our RF results, however, reveal a well-preserved, eastward-dipping fossil subduction zone with eclogitized crust, featuring a serpentinized mantle wedge beneath the East Greenland Caledonides. Although an origin related to the Neoproterozoic Valhalla orogeny (Cawood et al., 2010) cannot be fully excluded, the published information suggests an early Caledonian phase of eastward subduction predating the major Scandian collision and its westward subduction. This is corroborated by the geographical position of the structure at the edge of the Caledonian orogen, the presence of I-type granitic intrusions in the study area, magmatism in the uppermost thrust sheets in northwestern Norway, and observations in the Appalachians and the British Isles, where early phases of eastward subduction together with the accretion of volcanic arcs have been inferred (Taconian and Grampian phases) (e.g., van Staal et al., 1998). Furthermore, the proposed fossil subduction zone and therefore the uppermost mantle appear undisturbed by later tectonic events of the region, such as the major Scandian westward underthrusting of Baltica. Terranes accreted during this eastward-directed subduction might have prevented the subsequent Scandian deformation from penetrating toward the west.

The detailed evolution of the Caledonides clearly has to be revised, combining our new lithosphere-scale evidence with geological observations in East Greenland and Scandinavia. The existence of an old, eclogitized subducted slab also has implications for our understanding of mechanisms connected to the long-term preservation and stability of such structures.

CONCLUSIONS

The RF analysis and the synthetic modeling presented herein are interpreted as evidence of an eastward-dipping fossil subduction zone of eclogitized crustal material, in part underlying a serpentinized mantle wedge. These findings are key evidence for unraveling the complex tectonic evolution, including the closure of the Iapetus Ocean and the convergence and collision of Laurentia and Baltica, not only in East Greenland but for the entire Caledonian orogeny. The subduction event is interpreted to be of early Caledonian age, earlier than the major Scandian phase. This scenario provides the simplest explanation of a succession of Caledonian events of similar style along the entire Laurentian margin, comprising an early phase of eastward subduction, followed by a main collisional phase of westward subduction. Furthermore, this allows establishing and promoting the idea of possible long-term deep preservation of fossil subduction zones and the existence of associated deep (upper mantle) geological features. These insights are of general importance to the understanding of the geodynamics and lithospheric mechanisms of continent-continent collisions and the observable relicts that they preserve.

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