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Geophysical-petrological modelling of the East Greenland Caledonides – Isostatic support from crust and upper mantle

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ABSTRACT

Teleseismic receiver function analysis imaged a complex upper mantle structure in the Central Fjord Region of East Greenland, including an east-dipping high velocity layer and a mantle wedge of high crustal or low mantle velocities. This was interpreted as a fossil Caledonian subduction complex, including a slab of eclogitised mafic crust and an overlying wedge of serpentinised mantle. In this paper, we use a multi-disciplinary geophysical and petrological modelling approach to test this proposed fossil subduction model.

The consistency of the obtained velocity model with the regional gravity field is tested by forward density modelling and isostatic calculations. The models show that the sub-crustal structure, given by the more buoyant mantle wedge and the dipping high velocity/density layer, yield in a markedly better fit as compared to a homogeneous mantle lithosphere.

Petrological-geophysical modelling is performed by testing different upper mantle compositions with regard to topography, gravity and seismic velocities using Litmod2D. This suggests that the observed lower crustal/uppermost mantle bodies could be a combination of mafic intrusions, serpentinised peridotite and metamorphosed mafic crust. The preferred composition for the dipping structure is eclogitised mafic crust, and hydrated peridotite filling the overlying mantle wedge. Models lacking an eclogite layer or a hydrated upper mantle composition show an inferior fit and, therefore, are not favoured representatives. This supports the interpretation as a fossil subduction zone complex. The spatial relations with Caledonian structures suggest an early Caledonian origin.

1. Introduction

The North Atlantic Realm (NAR) experienced a number of major tectonic events during the past 500 Ma which shaped the present-day topographic and crustal and upper mantle structure of the North Atlantic passive margins. While the general geodynamic evolution is known, various issues are still a matter of discussion. This applies to details of accretionary events associated with the Palaeozoic Caledonian orogeny, deep processes in the mantle related to the formation of the North Atlantic Igneous Province and the present-day state of isostasy of the high topography along the magma-rich passive margins of East Greenland and Scandinavia.

Recently, it has been suggested that remnants of an early Caledonian east-dipping subduction zone are entrained in the lithosphere of the Central Fjord (CF) region of East Greenland (Schiffer et al., 2014, 2015a). Teleseismic receiver functions of the CF array indicate eclogitised mafic crust in the dipping layer and an overlying serpentinised mantle wedge. This structure could be part of a once contiguous eastward dipping Caledonian (or older) subduction zone along the eastern margin of Laurentia, connected with the so-called "Flannan reflector", offshore northern Scotland (Smythe et al., 1982; Snyder and Flack, 1990; Warner et al., 1996) that shows very similar geometrical and geophysical properties (Schiffer et al., 2015b).

In this study, we will substantiate the interpretation of a fossil subduction zone in East Greenland, by a detailed multi-disciplinary approach, including density, isostatic and petrological modelling. In particular, we will quantitatively differentiate between a set of selected end-member models that include a fossil subduction setting and alternative geometries and compositions.

2. Geological setting

The geological and topographic expression of the North Atlantic Realm (NAR) is considered to be mainly shaped during the past 500 Ma, with the Palaeozoic Caledonian orogeny (circa 425 Ma), rifting, continental break-up accompanied by an extreme magmatic outburst

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(circa 60 Ma), and the formation of the North Atlantic and its passive continental margins.

2.1. The Caledonian orogeny

The Caledonian orogeny was the consequence of continental drift and resulting collision of three palaeocontinents, Laurentia, Baltica and Avalonia and a number of microcontinents and terranes during the closure of the Iapetus Ocean in the Ordovician to Early Devonian (Cocks and Torsvik, 2011).

The general tectonic development of this Himalayan-type orogeny is understood, but details of timing, direction, location and the number of involved subduction events are unknown. General agreement exists, about an early, east-dipping subduction event along the eastern and southern margin of Laurentia, in the British Caledonides (Grampian phase) and northern Appalachians (Taconian phase), followed by a west-dipping subduction of Iapetus oceanic lithosphere and Baltica beneath Laurentia (Scandian phase) (Karabinos et al., 1998; Dewey, 2005; Leslie et al., 2008; van Staal et al., 2009).

The surface geology is well-studied in Scandinavia (e.g. Gee et al., 2008), which applies also for the ice-free regions in East Greenland (Henriksen, 1999; Henriksen and Higgins, 2008b) and indicates a generally bivergent orogeny (west-vergent in East Greenland and east-vergent in Scandinavia, Roberts, 2003; Gee et al., 2008; Leslie et al., 2008). In East Greenland, the eastern part of the surface geology is dominated by Caledonian thrust sheets lying atop of Archaean basement, while the western part is composite of post-Caledonian sedimentary basins and Tertiary flood basalts and intrusions (Gee et al., 2008; Henriksen and Higgins, 2008b; Gasser, 2013; see Fig. 1). The Caledonian foreland basin and the western Caledonian Deformation Front are exposed in the north and disappear beneath the ice sheet south of 79° N for most of the length of the orogen (Fig. 1).

A large age variation of magmatic and high grade metamorphic rocks from roughly 360 Ma to 500 Ma are indicators for a complex and prolonged orogenic and collisional evolution (Steltenpohl et al., 2003; Gasser, 2013; Corfu et al., 2014, and references therein).

This evidence has led to different tectonic scenarios of the East Greenland and Scandinavian Caledonides, departing from a simple, west-dipping Scandian subduction, including a late eastward intracratonic underthrusting (Gilotti and McClelland, 2011), early west-dipping (Brueckner and van Roermund, 2004; Brueckner, 2006) as well as east-dipping subduction (Roberts, 2003; Gee et al., 2008; Streule et al., 2010).

2.2. Continental break-up and magmatism

A long period of passive lithospheric relaxation and post-orogenic collapse of the Caledonian mountain range followed since the Devonian, reactivating some of the Caledonian faults and adding much complexity to the original Caledonian structures (Andersen et al., 1991; Dewey et al., 1993; Fossen, 2010).

This approximately 340 Ma long lasting period transitioned into active rifting culminating in continental break-up and sea-floor spreading in the early Cenozoic (Skogseid et al., 2000; Nielsen et al., 2007; Gernigon et al., 2015). Break-up was accompanied by a large magmatic outburst, which affected large parts of the NAR, leading to the formation of the North Atlantic Igneous Province and the Iceland Melt Anomaly (Saunders et al., 1997). This magmatic event is commonly associated to the impingement of a mantle plume (e.g., Fitton et al., 1997; Tegner et al., 1998) but also plate tectonic origins are proposed (e.g., Korenaga, 2004; Foulger et al., 2005).

2.3. Present-day passive margins

The magma-rich passive margins along the North Atlantic are accompanied by high topography in East Greenland, Scandinavia and the British Isles. The evolution of this high-elevation, low-relief topography is matter of significant debate (e.g. Nielsen et al., 2009b; Pascal and Olesen, 2009; Chalmers et al., 2010). The occurrence of this distinct topographic expression has been explained by the idea that these landscapes are peneplains created by erosion of ancient topography to sea level and recently uplifted to their present elevation (Japsen and Chalmers, 2000; Lidmar-Bergström and Näslund, 2002). For this uplift a series of processes has been proposed (Doré, 2002), among others, dynamic support from the sub-lithospheric mantle, e.g. by asthenospheric diapirism (Rohrman and van der Beek, 1996). Contrary to this, others favour models where the present topography constitutes remnants of the original Palaeozoic Caledonian mountain

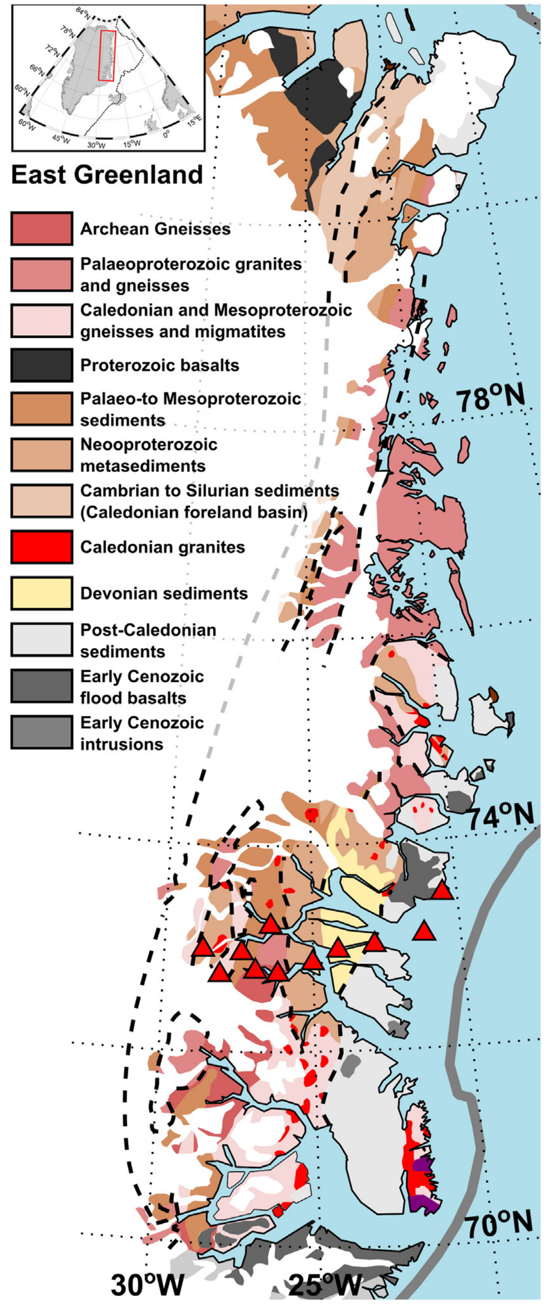

Fig. 1. Geological map of the East Greenland Caledonides (Henriksen, 1999; Henriksen and Higgins, 2008a; Gasser, 2013). Red triangles – locations of the CF array-stations. Stippled black lines – major faults. Thick grey line – continent ocean transition. Inset figure shows an overview of the North Atlantic and the position of the map. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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