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Receiver function analysis of the crust and upper mantle in Fennoscandia – isostatic implications

Andrew Frassetto [*,1], Hans Thybo

Department of Geography and Geology, University of Copenhagen, Øster Voldgade 10, 1350 Copenhagen K, Denmark

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ABSTRACT

The mountains across southern Norway and other margins of the North Atlantic Ocean appear conspicuously high in the absence of recent convergent tectonics. We investigate this phenomenon with receiver functions calculated for seismometers deployed across southern Fennoscandia. These are used to constrain the structure and seismic properties of the lithosphere and primarily to measure the thickness and infer the bulk composition of the crust. Such parameters are key to understanding crustal isostasy and assessing its role, or lack thereof, in supporting the observed elevations. Our study focuses on the southern Scandes mountain range that has an average elevation >1.0 km above mean sea level. The crust–mantle boundary (Moho) is ubiquitously imaged, and we occasionally observe structures that may represent the base of the continental lithosphere or other thermal, chemical, or viscous boundaries in the upper mantle. The Moho resides at ∼25–30 km depth below mean sea level in southeastern coastal Norway and parts of Denmark, ∼35–45 km across the southern Scandes, and ∼50–60 km near the Norwegian–Swedish border. That section of thickest crust coincides with much of the Transscandinavian Igneous Belt and often exhibits a diffuse conversion at the Moho, which probably results from the presence of a high wave speed, mafic lower crust across inner Fennoscandia. A zone of thinned crust (<35 km) underlies the Oslo Graben. Crustal Vp/Vs ratio measurements show trends that generally correlate with Moho depth; relatively high Vp/Vs occurs near the coast and areas affected by post-Caledonide rifting and lower Vp/Vs appears in older, unrifted crust across the southern Scandes. Our results indicate that most of the observed surface elevation in the southern Scandes is supported by an Airy-like crustal root and potentially thin mantle lithosphere. To the east, where thicker crust and mantle lithosphere underlie low elevations, the presence of dense mafic lower crust fits a Pratt-like model for isostatic compensation. Because the Scandes mountains occupy the location of the ancient Caledonian orogeny, which created presumably much thicker crust and lithosphere by ca. 400 Ma, much of the dense lower crust or mantle lithosphere that is expected to form beneath large mountain belts must have been removed sometime afterwards to instill the current lithospheric architecture that underlies the region.

1. Motivation

The existence of high, rugged topography far from plate boundaries is a prominent feature of the passive margins around the North Atlantic Ocean (Japsen and Chalmers, 2000; Doré et al., 2002; Anell et al., 2009). These orogens show little evidence for recent, substantial crustal tectonic activity, and their ubiquity across these latitudes coincides with both past and present continental ice sheets and proximity to the Atlantic Ocean basin and Icelandic hotspot, providing an opportunity to investigate hypotheses ranging from the effect of glaciers on landform evolution to the surface manifestation of dynamic, mantle-scale processes (Nielsen et al., 2009; Anell et al., 2010; Gabrielsen et al., 2010). The Scandes mountains of southern Norway (Fig. 1) form a notable link in this chain of circum-Atlantic high topography. The original models for the formation of the Scandes are primarily derived from geomorphic observations, which indicate tectonically or dynamically driven recent uplift (e.g. Lidmar-Bergström et al., 2000; Gabrielsen et al., 2010) in conjunction with increased offshore sedimentation rates (e.g. Japsen and Chalmers, 2000; Anell et al., 2009, 2010). Recent studies advocate that the Scandes result from ice-driven erosion (the "glacial buzzsaw") of long-lived (>400 My) high elevations (e.g. Nielsen et al., 2009); this model utilizes constraints from apatite fission track data and observations of a small crustal root (Svenningsen et al., 2007). Vigorous debate continues over the merits of these opposing ideas (Gabrielsen et al., 2010; Chalmers et al., 2010; Nielsen et al., 2010; Steer et al., 2012).

* Corresponding author.
E-mail address: andyf@iris.edu (A. Frassetto).
[1] Now at Incorporated Research Institutions for Seismology, 1200 New York Avenue, NW, Suite 400, Washington, DC, 20005, USA.

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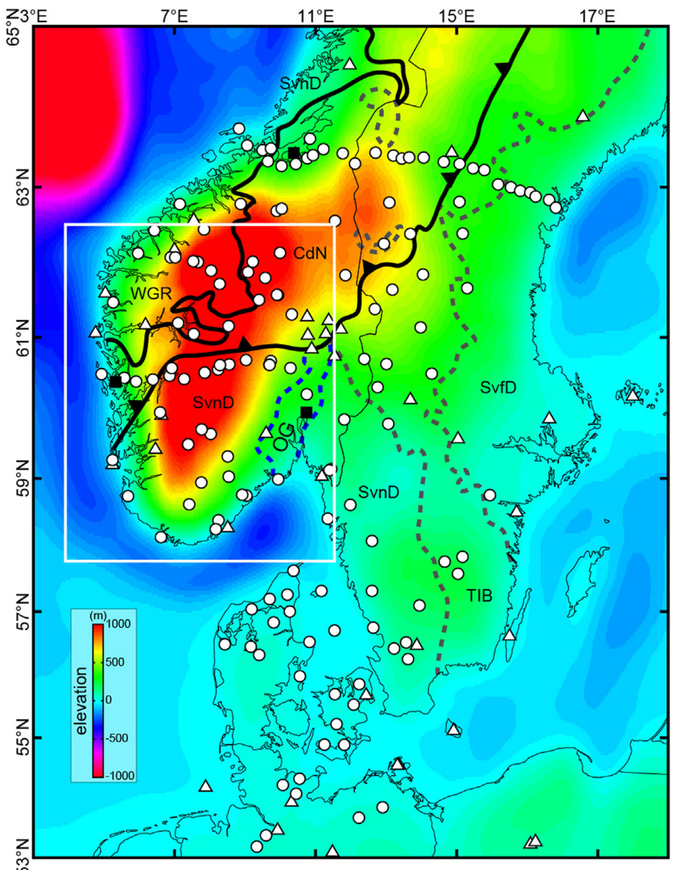

Fig. 1. One-half by one-half degree smoothed topography and bathymetry (in meters) for southern Fennoscandia and northern Europe. The seismic stations analyzed include temporary (circle) and permanent (triangle) deployments. The topography shows a broad dome of relatively high elevation in southern Norway. Generalized geologic boundaries after Gorbatschev (2004) are drawn and labeled, with abbreviations: SvnD—Sveconorwegian Domain, SvfD—Svecofennian Domain, OG—Oslo Graben (blue), TIB—Transscandinavian Igneous Belt (grey), WGR—Western Gneiss Region, and CdN—Caledonian Nappe Sequences. The subset of elevations highlighted in Fig. 11 is derived from measurements obtained from within the white box. The black squares from south to north represent the cities of Oslo, Bergen, and Trondheim. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Buoyancy forces related to the thickness and density of the crust support most of the observed elevation on continents (e.g. Watts, 2001). These forces are usually a combination of the *Airy* (varying thickness of crustal columns of similar density) and *Pratt* (varying density of crustal columns of similar height) end-member mechanisms of isostatic compensation. The Caledonian orogeny in present-day southern Norway had waned by ca. 390 Ma (e.g. Gee et al., 2008). Because of the recent tectonic quiescence of the region, the current mode of isostatic compensation for the southern Scandes may deviate from Airy isostasy, which is typically invoked for young orogens via recent tectonic crustal thickening, or involves an additional isostatic or dynamic component of support from the upper mantle. Unfortunately, the absence of an onshore sedimentary record corresponding to the post-orogenic history of southern Fennoscandia inhibits unique geodynamic interpretations of the evolution of the region (e.g. Anell et al., 2009). Characterizing the structure and properties of the crust and upper mantle is one of the few avenues to advance this discussion. Seismological constraints, including depth to the Mohorovičić Discontinuity (Mohorovičić, 1910; signifying the boundary between seismic wave speed in the crust and uppermost mantle and hereafter called the Moho), are vital to investigating how subterranean factors influence the topography in this part of Fennoscandia, which may serve as an analog for other parts of the Atlantic margins.

The number of relevant seismic studies in Fennoscandia has grown recently. Regional tomography across Norway and surrounding regions (Bannister et al., 1991) detected a zone of relatively slow upper mantle beneath portions of the southern Scandes and adjacent Norwegian margin. Similarly resolved crustal thickness measurements (Kinck et al., 1993) demonstrated clear differences between the southern Scandes (35–40 km), west-central Sweden (thicker, >45 km), and the Oslo Graben (thinner, <35 km). Recent tomographic studies (Köhler et al., 2012; Medhus et al., 2012; Wawerzinek et al., 2013) all confirm the presence of a relatively confined zone of low wave speed upper mantle beneath southwest Norway. Maupin et al. (2013) presents a detailed summary of these findings.

Recent studies have focused on the southern Scandes (Svenningsen et al., 2007; Stratford et al., 2009; Stratford and Thybo, 2011a, 2011b; England and Ebbing, 2012). Two transects of broadband/short-period seismometers analyzed by Svenningsen et al. (2007) were the first temporary seismic stations deployed across the mountains and imaged a small crustal root to ∼43 km depth. Their teleseismic migration procedure assumed a one-dimensional crustal wave speed model. The controlled source seismic survey MAGNUS-REX (MAntle investiGations of Norwegian Uplift Structure-Reflection EXperiment) (e.g. Stratford et al., 2009) produced much greater detail in its crustal thickness and wave speed measurements, but two of its three transects were confined to the same areas. Stratford et al. (2009) found the maximum Moho depth beneath the southern Scandes to be comparatively shallower at 38–40 km, decreasing towards the coast and Oslo Graben. Analysis of P- and S-wave refractions located a relatively fast, mafic lower crust beneath easternmost Norway that is absent under the southern Scandes. The crust throughout the Scandes is predominantly felsic-to-intermediate composition (Stratford and Thybo, 2011a, 2011b).

Most recently, England and Ebbing (2012) analyzed the SCANLIPS deployment, a transect of broadband seismometers at the northern extent of the southern Scandes near Trondheim. Their single station forward models and receiver function transect show that the Moho increases in depth from ∼34 km along the coast to ∼42 km under the highest elevations extending into Sweden. Modeled receiver functions also show a high wave speed layer of lower crust that generally matches regional gravity measurements when converted to density.

Repeatedly imaged, the observed locally thicker crust led investigators to postulate that the southern Scandes are in Airy isostatic balance (e.g. Svenningsen et al., 2007). Stratford et al. (2009) found slightly thinner crust overall and confirmed that the root is offset from the highest average elevations and surrounded by thinner crust. Additionally, the crustal wave speed structure and calculated bulk density is substantially different between the Scandes, the Oslo Graben, and westernmost Sweden (Stratford and Thybo, 2011a, 2011b).

Conclusions drawn from these studies retain caveats, having been limited in their geographic sampling, confined primarily to the crust, or lacking complementary resolution in adjoining parts of Sweden. Initial observations to the east (BABEL Working Group, 1993b; Kinck et al., 1993; Abramovitz et al., 1997; Olsson et al., 2008) hint that the Moho is deeper in this region, possibly due to the added presence of a high wave speed lower crust. Well-constrained measurements of crustal wave speed are limited to controlled source transects and previous receiver function studies use non-unique or overly simple assumptions for the crustal wave speed structure.

Although the studies outlined above produced valuable new constraints on first-order structure and composition of the crust