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Strong lateral variations of lithospheric mantle beneath cratons – Example from the Baltic Shield

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ABSTRACT

Understanding mechanisms for creation and evolution of Precambrian continental lithosphere requires to go beyond the large-scale seismic imaging in which shields often appear as laterally homogeneous, with a thick and fast lithosphere. We here present new results from a seismic experiment (POLENET-LAPNET) in the northern part of the Baltic Shield where we identify very high seismic velocities ($Vs \sim 4.7$ km/s) in the upper part of the mantle lithosphere and a velocity decrease of ~0.2 km/s at approximately 150 km depth. We interpret this velocity decrease as refertilisation of the lower part of the lithosphere. This result is in contrast to the lithospheric structure immediately south of the study area, where the seismic velocities within the lithosphere are fast down to 250 km depth, as well as to that of southern Norway, where there is no indication of very high velocities in the lithospheric mantle (Vs of ~4.4 km/s). While the relatively low velocities beneath southern Norway can tentatively be attributed to the opening of the Atlantic Ocean, the velocity decrease beneath northern Finland is not easily explained with present knowledge of surface tectonics. Our results show that shield areas may be laterally heterogeneous even over relatively short distances. Such variability may in many cases be related to lithosphere erosion and/or refertilisation at the edge of cratons, which may therefore be particularly interesting targets for seismic imaging.

1. Introduction

The understanding of the structure and evolution of ancient lithosphere has been subject of intense research over the last decade, involving geochemistry, geophysics, rock physics and numerical modeling. It is now well established that the lithosphere in terms of seismic velocities in these areas appear as thick and fast at a large scale (e.g. Gung et al., 2003; Debayle et al., 2005; Legendre et al., 2012) but lack of detail in the seismic models is proving a blocking point for providing well constrained input for numerical models of craton[1] stability and evolution over time. In particular, craton stability is controlled by the vertical and lateral variations in density and viscosity (e.g. Doin et al., 1997; Lenardic and Moresi, 1999; Lenardic et al., 2000; Yoshida, 2012), high viscosity probably being a result of low water contents and the refractory nature of the cratonic mantle lithosphere (Mei and Kohlstedt, 2000; Peslier et al., 2010). In spite of a general longevity of cratons, it is in exceptional cases possible to strongly weaken and possibly erode cratonic lithosphere, as well documented in the eastern part of the North China craton (e.g. Menzies et al., 1993; Lebedev and Nolet, 2003; Zheng et al., 2007; Huang et al., 2009; Xu et al., 2009) and more recently identified in the Saharan Metacraton (Abdelsalam et al., 2011).

In spite of a general similarity between different cratons over a scale of a few hundred to a thousand kilometers (Pedersen et al., 2009), with possibly some systematic difference between Archean domains and Proterozoic mobile belts (Lebedev et al., 2009; Debayle and Ricard, 2012), improvements in the resolution of tomographic models provide increasing evidence of significant lateral variations of seismic structure within cratons at a smaller scale (e.g. James et al., 2001; Poupinet et al., 2003; Bruneton et al., 2004a; Darbyshire et al., 2007, 2013). As we expect that thermal equilibrium is reached in cratons that have not been involved in recent tectonic activity, these variations are likely to be due to lateral variations of composition. Compositional variations within cratons are indeed observed over small scales, even within the same kimberlite pipe, as testified by analysis of mantle xenoliths (e.g. Pearson et al., 2003), but it is still a challenge from a geochemical point of view to observe and quantify systematic vertical and lateral differences of the mantle lithosphere composition at larger scales (few hundreds of kilometers) which would

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[1] We use the term craton in its broadest definition, i.e. designating it as an old and stable part of the continental lithosphere, most often composed of an assemblage of Archean and Proterozoic units.

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explain the seismic observations. Small differences in abundance of radiogenic elements in the lithospheric mantle could additionally enhance the effect of compositional changes on seismic wave velocities (Hieronymus and Goes, 2010), independently of whether such changes were present from the creation of the cratons, or due to subsequent refertilisation.

Combining seismic and geochemical observations into a comprehensive model of present and past structure of cratonic lithosphere therefore remains a challenge, as the scales of observation do not overlap. The best lateral resolution of seismic models in cratons are obtained by analysis of body waves, but such tomographies usually do not give access to absolute seismic velocities and have very poor depth resolution (e.g. Lévêque and Masson, 1999), limiting their value when we want to compare the results with xenolith data. Tomographic studies using surface waves have better depth resolution and have the advantage of yielding information on absolute shear velocities which are indicative of both temperature and compositional variations. The drawback of surface wave tomography using permanent seismological stations is that the lateral resolution is generally fairly poor. It is however possible to greatly improve the lateral resolution over a limited geographical area by using data from high density temporary seismic networks. Pedersen et al. (2003) and Bodin and Maupin (2008) show that it is possible to achieve a lateral resolution comparable to (at best half of) the investigation depth using such arrays. Due to the presence of seismic noise, dispersion curves with this kind of technique are practically associated with relatively large error bars which make it difficult to use them quantitatively.

In the present study, we follow on this concept while attempting a compromise between the end-members described above: we use dense networks of a few hundred km, which is of comparable size to the largest wavelengths that we study, but all data are combined into the measurement of the average dispersion curve for surface waves propagating across the array. The influence of noise and of heterogeneities outside the array is greatly reduced, and the problem is massively over determined so that the observed dispersion curve is associated with small errors; consequently the subsequent inversion for the shear wave velocity structure with depth is also well constrained. The comparative study between different seismic arrays can then provide well constrained insight into lateral variations in upper mantle structure.

We use this approach for the Baltic Shield where we analyse data from a recent seismic experiment in northern Finland (LAPNET/POLENET, Kozlovskaya et al., 2006) and compare our results with those obtained by a similar approach (Cotte et al., 2001; Bruneton et al., 2004b; Maupin, 2011) in three close locations within the shield: south-central Finland (SVEKALAPKO array, Bock et al., 2001), southern Norway (MAGNUS array, Weidle et al., 2010), and southern Sweden (the somewhat less dense TOR array, Gregersen et al., 1999).

2. Study area

The Baltic Shield, also called Fennoscandian Shield, (Fig. 1) constitutes the northwestern part of the East European Craton. To a first order, it can be separated into two main areas: the Archean to the northeast and the Proterozoic towards the south and west (Gaàl and Gorbatschev, 1987). The Archean comprises the ∼3.2–2.5 Ga gneisses and greenstone belts in N–NE Finland and NW Russia, Archean basement covered with Paleoproterozoic sediments, and the Paleoproterozoic Lapland Granulite Belt (∼2.5–1.9 Ga). The Proterozoic combines the Svecofennian domain in south-central Finland and western Sweden (∼1.95–1.75 Ga) and the later Sveconorwegian domain (∼1.1–0.9 Ga) in SW Sweden and most of southern Norway, as well as the Transscandinavian Igneous Belt (∼1.85–1.65 Ga). Each of these main areas cover large age variations and tectonic complexities (Gorbatschev and Bogdanova, 1993; Bogdanova et al., 2008).

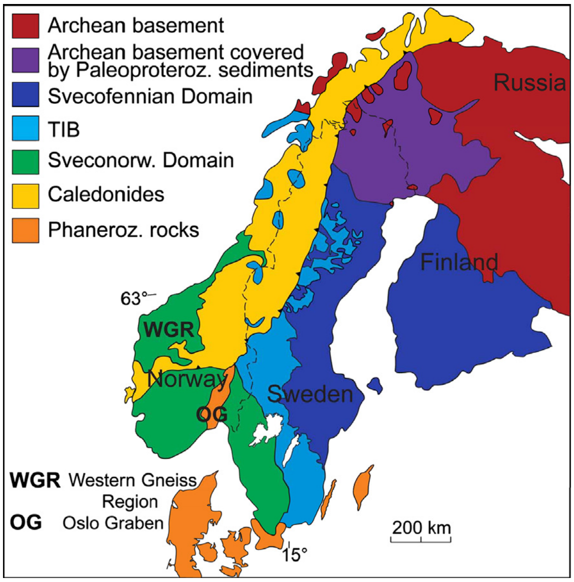

Fig. 1. Simplified tectonic map of the Baltic Shield. The three main domains are: 1. Archean, including Archean basement, Archean basement covered by Paleoproterozoic Sediments and the Paleoproterozoic Lapland Granulite Belt. 2. Proterozoic, composed of the Svecofennian domain, the Sveconorwegian domain and the Transscandinavian Ignous Belt ('TIB'). 3. Caledonides.

Except to the east and southeast, the Baltic Shield is bordered by non-cratonic areas: the Barents Sea platform is located north of the Baltic Shield, while we find the West-European Phanerozoic terranes to the south and the continental margin of the North Atlantic Ocean to the west. All these borders have been affected by several collisions and orogenic episodes during geological history. The last episode to the north and northeast is the late Neoproterozoic Timanian orogen (0.66–0.54 Ga; Roberts and Siedlecka, 2002; Pease et al., 2004). To the west and north-west, the Baltic Shield has been affected by the Caledonian orogeny (∼0.4 Ga; Roberts, 2003), following the closure of the Tornquist Sea to the south (0.44 Ga; Cocks and Torsvik, 2006).

A large effort has been carried out to collect active seismic data in Finland, the latest during the Finnish Reflection Experiment, FIRE. The FIRE report (Kukkonen and Lahtinen, 2006) provides an excellent review and relevant references of geophysical and geological constraints on the tectonic history in Finland. Of special interest to the LAPNET array is the subdivision of the Archean domain into small tectonic units which have been accreted and deformed during a very complex history including extensional and collisional events, as well as later Paleoproterozoic intrusions (e.g. Daly et al., 2006; Patison et al., 2006; Lahtinen et al., 2008). Fig. 2 shows a more detailed tectonic map of the area covered by the LAPNET array. In spite of the complexities, Poli et al. (2012) showed that the crustal shear velocities only vary by a few percent laterally (mainly associated with slightly elevated velocities within the Lapland Granulite Belt) so lateral variations in crustal structure are not likely to bias the average dispersion curve for the area.

Analysis of data from the temporary seismic broadband SVEKALAPKO experiment in south-central Finland revealed that the relatively unperturbed Svecofennian province in south-central Finland has a simple lithospheric structure with a thick lithospheric root (Sandoval et al., 2004; Bruneton et al., 2004a) which could be explained by approximately uniform composition across the whole thickness of the lithospheric mantle (Bruneton et al., 2004a). On the contrary, the part of the array located on Archean age crust