Lithosphere velocity structure of the Khibiny and Lovozero plutons (Eastern part of the Baltic shield) from receiver functions

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INTRODUCTION

The Kola region of the Russian Arctic is located in the northeast of the Baltic Shield and is widely known for its unique geology in regards to the presence of massive (fig. 1) Paleozoic intrusions. Approximately over 50% of Russian rare Earth elements (REE) resources are accumulated in the Khibiny and Lovozero plutons, which are among the 8 largest alkaline intrusions on the planet and provide a wide exploration field for a variety of scientists and industries as well. The plutons' igneous rocks are mostly exposed and accessible which makes them a reasonable and reliable reference for ultramafic-alkaline series in general. The research on mineral deposit formation is a vital question in science, and the existence of those complex intrusions with the abundant resources provides an opportunity to further deepen the knowledge in the field.

The internal structure of the plutons was investigated via geological and geophysical methods. Geophysical investigations of the area included magnetic, gravity and seismic studies. The amount of research focused on the deep structure beneath the Khibiny pluton is scarce, with the most significant being (Dricker et al., 1996) and (Egorova and Pavlenkova, 2015).

This research aims to further the knowledge of the Khibiny pluton's deep structure by analyzing the seismological data from APA and LVZ seismic stations collected for 20 years with the use of P and S receiver function (PRF and SRF) and modern technique of modeling. This provides detailed information of the earth's crust and upper mantle of the plutonic and shield regions velocity stricture. The unique nature of Khibiny provides the opportunity to investigate the origin of ultramafic-alkaline deposits which are not completely understood at the moment but are of significant importance.

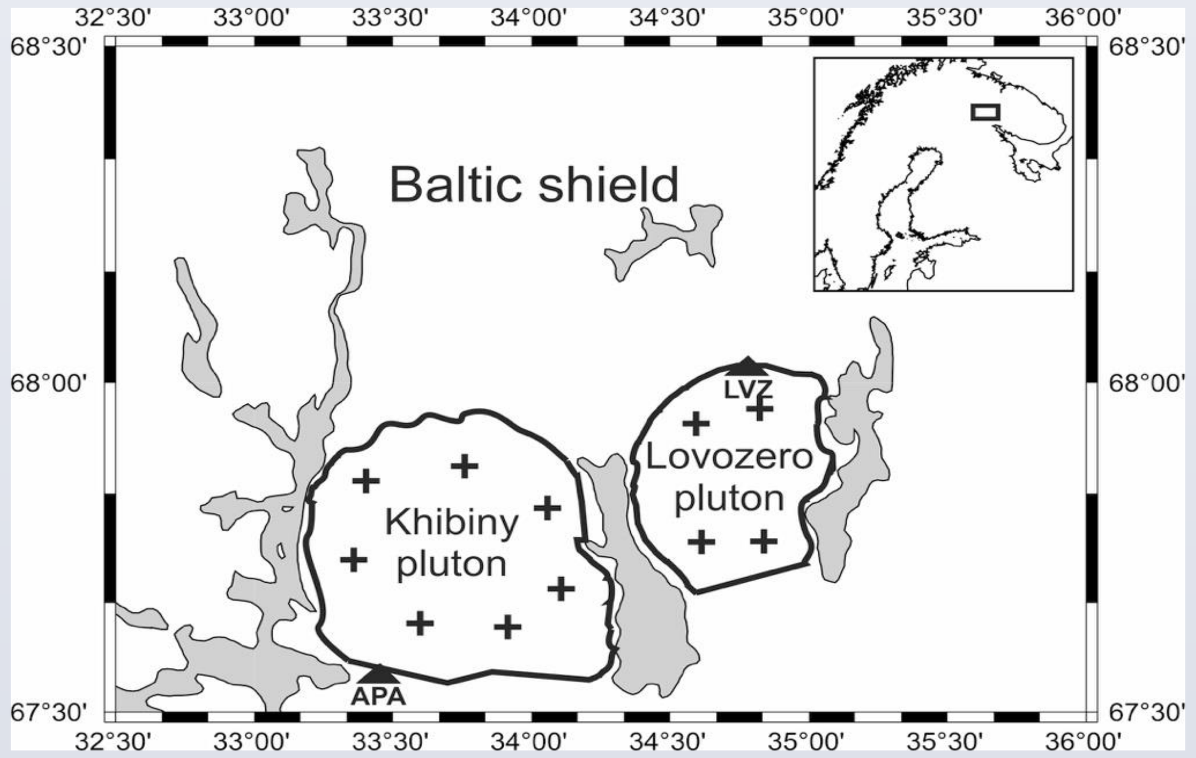

Fig.1 Scatch shows region of investigation and main igneous complexes – Khibiny and Lovozero plutons. Triangles marked the location of stations APA and LVZ

VELOCITY MODELS AND MANTLE STRUCTURE

For the given research we used broadband seismological data from two seismic stations – Lovozro (LVZ) and Apatity (APA) collected since 2000. We used the CMT catalogue (Dziewonski et al., 1981; Ekstrom et al., 2012) to obtain the necessary parameters of the earthquakes. Data of seismic events with magnitudes greater than 5.5 and epicentral distances between 40° and 100° from stations were collected for analysis and visually inspected for quality control. We used a well-known receiver function technique to restore the velocity section of the earth's crust and upper mantle. Joint inversion of PRF and SRF allows getting robust estimation of Vs distribution for the depth up to 300 km.

To calculate P receiver functions (PRF) we followed the approach described in dilates in (Vinnik, 1977). This methodology allows to pick put and analyze converted P-to-S waves and their multiples formed at seismic boundaries. This approach has been applied to all recorded seismic events in order to calculate the set of individual PRF. We got 220 and 232 individual traces for LVZ and APA station respectively.

One of important benefits of PRF is the possibility to investigate the mantle transition zone at depth 410-660 km. To obtain delay times between converted P-S waves from 410 and 660 boundaries individual PRF have been stacked with the moveout time corrections. Those corrections are to compensate the dependence of the travel times of the converted Ps phases on the epicentral distances. The stacked traces are constructed for a set of the trial conversion depths in the interval from 0 to 800 km. As both LVZ and APA are located relatively close to each other, we combined all 452 PRF to get a robust estimation of delay times of P410s and P660s phases (fig. 2). Our estimations of P410s and P660s phases are 43.6 and 67.6 sec respectively. Delay time between these phases is 24 sec that is close to "standard" according to the IASP91 model (Kennett and Engdahl, 1991). The individual times of each phase are slightly less than predicted by IASP91 (by 0.4 sec) and could indicate an increase of velocities in the upper mantle, but it is not unusual for cratonic regions (Artemieva, 2009).

In order to better analyze mantle phases, individual SRF traces for both seismic stations have been stacked with the moveout time corrections (fig. 3). The stacked traces are constructed for the trial values of the differential slowness in the interval from 0 to 1.0 sec/deg. The deeper the phase conversion boundary the higher the required value of differential slowness. To reveal main mantle phases we stacked all SRF for both APA and LVZ stations as we did for PRF. Main mantle phases are clearly visible – curst/mantle boundary (M), lithosphere/asthenosphere boundary (LAB), Lehmann (L) and 410 km boundary. These values more than four times bigger than noise. Lehmann discontinuity often corresponds to the bottom of the LAB (Lehmann, 1961). Taking into account that both L and LVZ are visible on the stack, it can be assumed that there is a low-velocity zone in the upper mantle of the region.

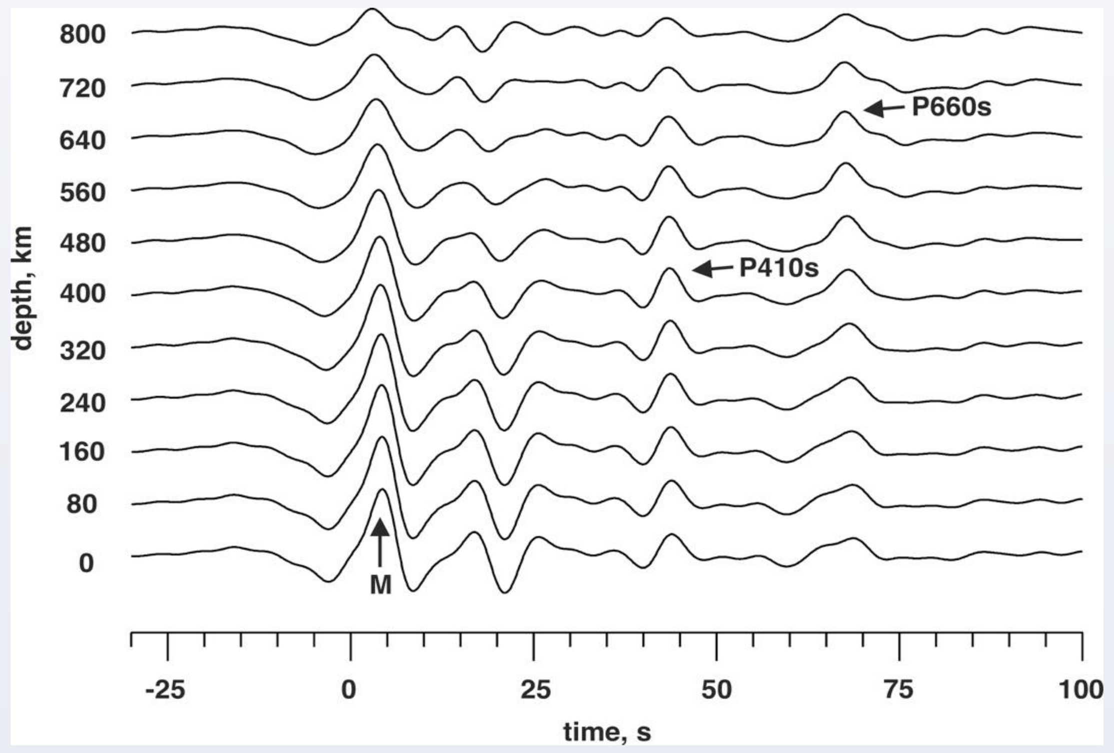

Fig.2 Stacked PRFs for both APA and LVZ stations. Move-out corrections for stacking are calculated for depth (in km) attached to the traces on the left-hand side. Arrows mark arrivals of converted waves from Moho (M) and boundaries at depths of 410 and 660 km

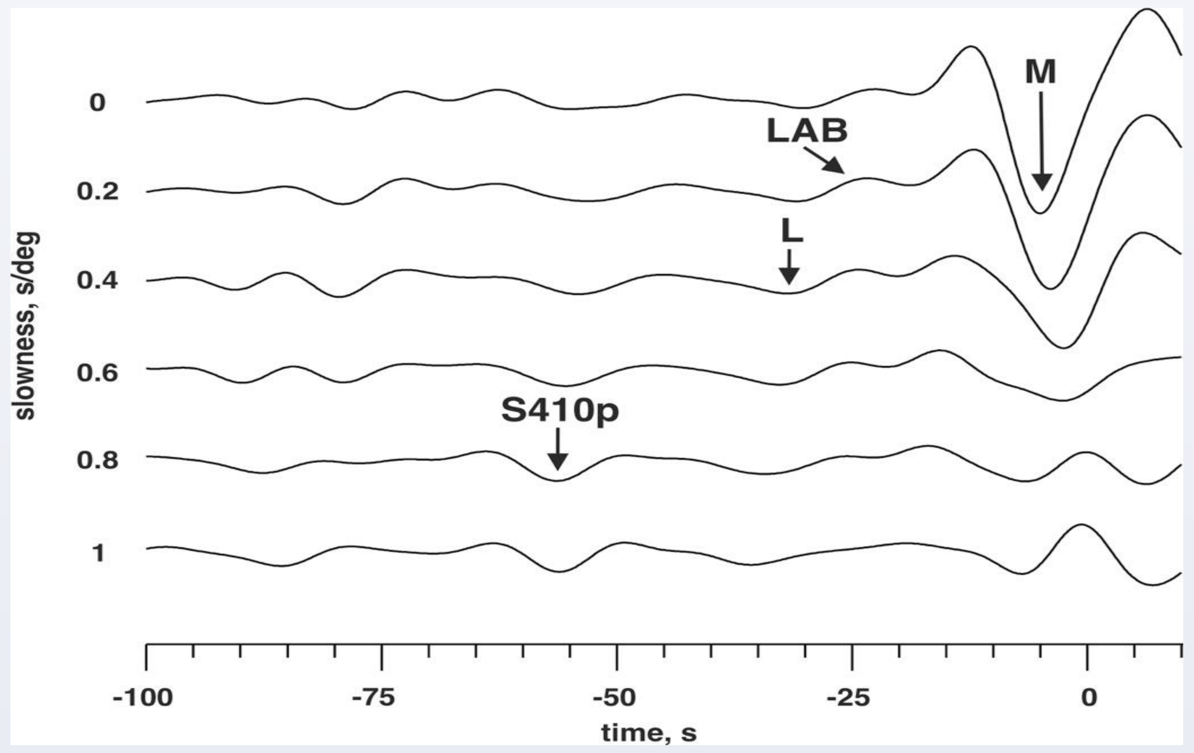

Fig.3 Slant stack of SRFs for both APA and LVZ stations. Detected mantle phases are shown by arrows – M for the crust/mantle transition (Moho), LAB for the lithosphere/asthenosphere boundary, L for the Lehmann boundary, S410p for the converted phase from the 410-km discontinuity

INVERSION

To restore velocity sections joint inversion of PRF and SRF have been used. Search for the optimum models is conducted by using the Levenberg – Marquardt algorithm (Press et. al., 2007). The synthetic receiver functions are calculated using Thomson–Haskell matrix algorithm (Haskell, 1962). The trial model consists of thirteen layers; its free parameters are the S-wave velocity, Vp/Vs ration, and the thickness of each layer. To obtain the final distribution of the variable parameters, the space of model parameters was split into cells. The final solution is presented as a field of condensation of minimized random initial models, the synthetic PRF and SRF from which best match the observed data. Obtained a posteriori distribution functions are visualized using a color code (fig.4).

To evaluate the detailed seismic structure of the Khibiny and Lovozero plutons along with the structure of the Baltic shield dataset of calculated RF was split into four subsets with respect to the relative location of seismic stations and plutons (fig. 1). All subsets have been inverted separetly. For each subset 15,000 random individual models were calculated. To obtain final velocity sections, we selected about 1% of models from each subset that best fits the observed data (fig. 4).

All models, apart from LVZ-pluton (c), have shown a sharp Moho boundary at a depth of 40±1 km. Crustal structure characterized by a gradient increase in Vs from 3.2 to 3.9 km/s for all models except the Khibiny pluton (fig.5 d). The crustal velocity structure of this pluton shows almost stable Vs close to 3.8-3.9 km/s. Distinctive feature is the low-velocity zone at depth from 5 to 11 km where Vs drop from 3.7 to 3.4 km/s. The upper mantle structure shows slightly increased (by ≈ 2%) Vs with respect to the IASP91 model. The most prominent feature of the mante structure is the presence of the low-velocity zone at a depth of 90 – 140 km.

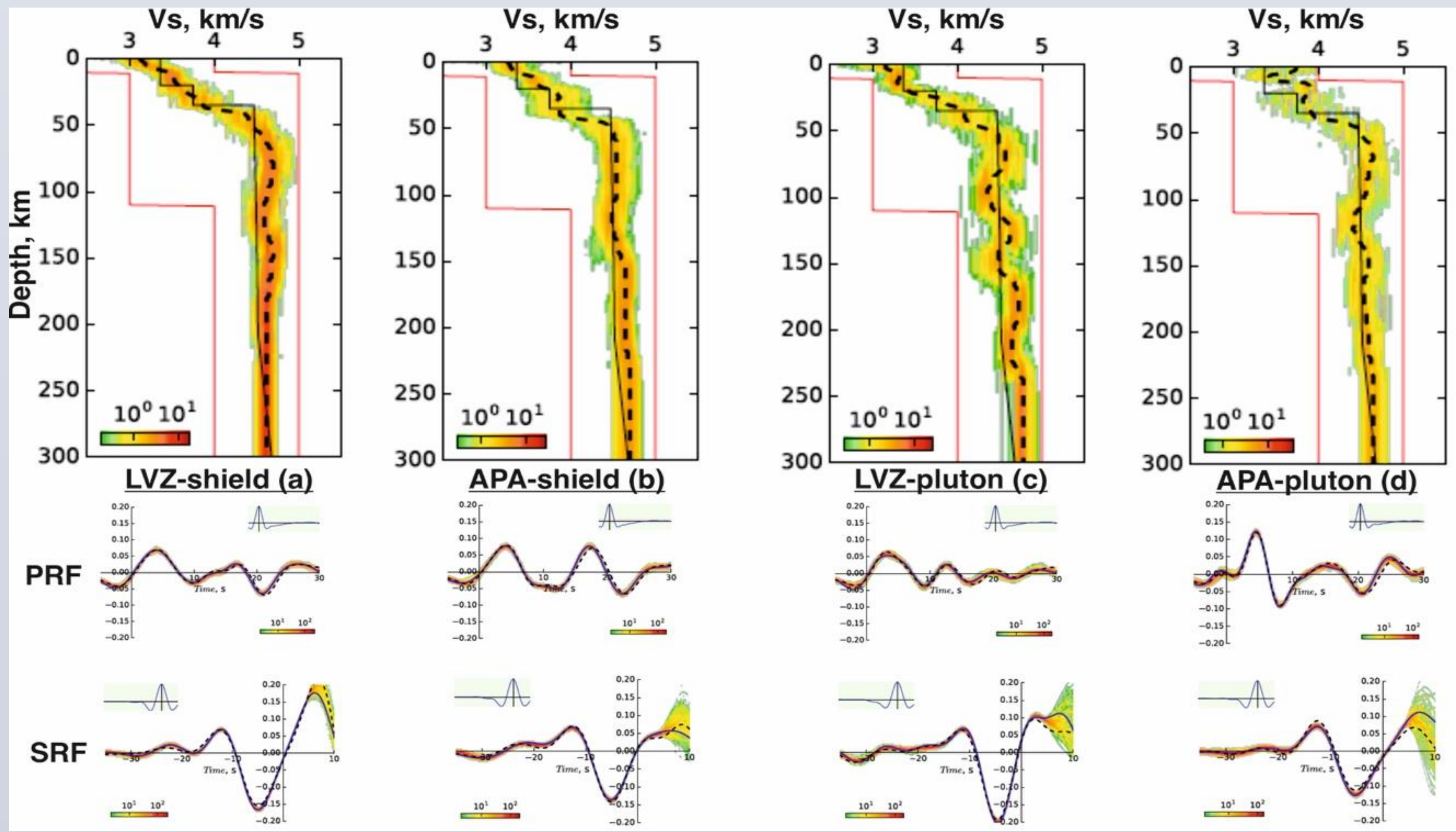

Fig. 4 S-wave velocity models for each selected subset for stations APA and LVZ. Models represent structure related to plutonic (c,d) and shield (a,b) regions, obtained by joint inversion of PRFs, SRFs and travel-time residuals. Probabilities are shown in colours (red for high and green for low). Dash lines shows median models. The corresponding synthetic PRFs and SRFs are shown with the same color code. Red lines represents the limits of the search. Black lines represents the IASP91 model. The observed PRFs and SRFs are shown by blue lines. Note a low-velocity layer between 90-km and 140-km depth.

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