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Seismic model of the Earth's crust and upper mantle beneath the Fennoscandian Shield

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Abstract. Well-founded concepts of the crust and upper mantle structure of the Fennoscandian Shield were developed. Quantitative evidence for horizontal and vertical lithospheric heterogeneities was obtained. Highly detailed integrated geological and geophysical investigations, supported by superdeep drilling, have been conducted in the eastern part of the shield in recent years. Seismogeological crustal models of individual geotectonic provinces were constructed, which indicate that the structure of the crystalline crust displays a pattern of blocks, arranged hierarchically, with no persistent seismic boundaries across the entire shield. Both low- and high-velocity zones, correlatable with geological bodies, occur locally. The structural plans of contours and the velocities of various deep sections were shown to be inconsistent. We conclude that the upper mantle is laterally complex and heterogeneous, and that there is no asthenosphere in the classical sense of the word.

1 Introduction

The Fennoscandian Shield is the most extensive outcrop in the Early Riphean basement of the East European Platform, covering an area of some 1.1 million sq. km. It consists of Archean and Proterozoic crystalline rocks, of mainly felsic composition. Late Archean greenstone belts are common in the eastern part of the shield. The aim of the geological and geophysical studies carried out on the shield in recent years was to approach some practical problems and to solve fundamental problems in Early Precambrian tectonics and geodynamics, the petrology and evolution of crust-forming processes, as well as the deep geology and physics of the tectonosphere. In 2002, a set of digital maps, consisting of a geological map [1] of pre-Quaternary rocks, a map of the anomalous magnetic field $(\Delta T)_a$ and a 2 000 000 scale gravity map (σ = 2.67 g/cm^3) of the Fennoscandian Shield [2, 3] was released. The Fennoscandian Shield is a conservative structural unit, which has preserved its structural integrity and has maintained its elevated position for 1.5 Ga.

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2 Seismic heterogeneities of the lithosphere

2.1 Crustal structure of the Fennoscandian Shield and deep drilling

In recent years, more evidence for the velocity structure of the crust and upper mantle of the Fennoscandian Shield has been obtained by extending a network of seismological stations (*earthquake seismology*) and conducting deep seismic soundings on longitudinal deep seismic sounding (DSS) profiles (*explosion seismology*), where mantle waves were recorded at a distance of at least 1000 km. First and foremost, mention should be made of the Fennolora [4, 5] and Quartz [6] profiles. In the Fennoscandian Shield, over 50 deep seismic profiles were obtained in order to study the deep lithospheric structure of this major unit of the East European Platform [7-17]. The Earth's crust of the region was shown to display a heterogeneous 'mosaic' structure, with no persistent seismic boundaries across the entire shield. Both low- and high-velocity zones, correlatable with geological bodies, occur locally in the upper crust. The structural plans of velocity contours of various deep sections were shown to be inconsistent; major geotectonic provinces differ in crustal thickness and seismic heterogeneity; Early Proterozoic volcanogenic belts have higher velocities, considerable crustal thickness, and an anomalously high boundary velocity along the Moho.

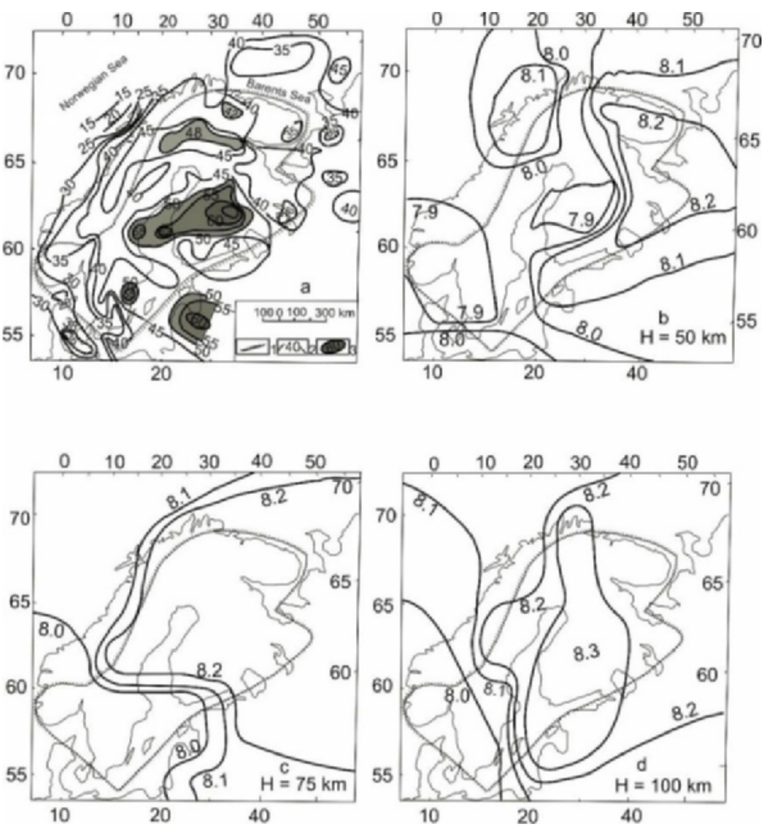

Fig. 1. Scheme of the Moho occurrence (a) and distribution of longitudinal wave velocities (isolines, km/s) within the lithosphere at depths of 50 (b), 75 (c), and 100 km (d). (*1*) Fennoscandian Shield boundary; (*2*) hypsographic curves of the Moho, km; (*3*) surface of velocity level 7.0–7.3 km/s (crustal_mantle layers).

An attempt has been made to understand the origin of seismic boundaries in the crystalline crust, taking into account the deep drilling record and available geological and geophysical information on the drilling area. The results of deep drilling in the Fennoscandian Shield for the Kola Superdeep Well, Russia (SG-3), drilled to a depth of 12262 m (1970–1990); Gravberg (GR) and Stenberg boreholes, Central Sweden, drilled to a depth of 6337 m (1986–1987) and 6529 m (1991–1992) respectively; Outokumpu Borehole (OU), SE Finland, drilled to a depth of 2516 m (2004–2005); Pogranichnaya Borehole (P-1), Sredny Peninsula, Murmansk Region, Russia, drilled to a depth of 5200 m (2004–2006); and the Onega borehole (ON), Central Karelia, Russia, drilled to a depth of 3537 m (2007–2008) were analyzed. Drilling has revealed major inconsistencies between predicted seismological models and the actual structure of the upper continental crust. Deep drilling has shown that the heterogeneities inferred from geophysical data in the upper crystalline crust are due to variations in the composition and physical state of deep-seated rocks. Therefore, approximate rock composition cannot be determined from elastic wave velocity alone. Our studies have supported the existence and origin of lowered elastic wave velocity in the upper crust, and have shown that rock layers do not become more homogeneous with depth. The origin of intracrustal seismic boundaries could be related to various factors, such as: variations in mineral composition, differences in the structural and textural characteristics of rocks, and the thermodynamic setting [14, 18, 19].

The model of the crystalline crust of the Fennoscandian Shield selected by the authors is a four-layer model with a longitudinal wave velocity of 5.9–6.2 km/s in the upper layer (upper storey); 6.3–6.5 km/s in the middle layer; 6.6–6.8 km/s in the lower layer and 7.0-7.3 km/s in the crust-mantle layer. The fourth high-velocity layer is well-defined in elevated earth crust areas (Figure 1a) and is often part of the third (lower) layer. It occurs presumably on DSS-profiles with long 280–350 km hodographs and cross-sections obtained by the PS earthquake converted wave method (ECW). The layers are separated by reflecting horizontal K1– and K2– layers and are separated from the upper mantle by the Moho with a velocity of 8.0–8.2 km/s. K1-boundary is at various depths. In the upper portion of the crust there occur high-velocity sites (intrusions) and low-velocity 3–8 km thick intercalations in individual blocks. It follows from modelling experience that K1–boundary commonly reflects the increased rock basicity of the column, which commonly results in elevated thickness. The K2–layer boundary is most probably due to variations in the rheological properties of the rocks at great depths. Therefore, variations in density are not related to it.

2.2 The Moho

Extensive seismic evidence for the region’s deep structure is now available. Multi-lateral experience has shown that the Moho is the most persistent seismic boundary, responsible for stable reflected, refracted and converted waves. Hence, this interface can be regarded as a basic seismic reference point, which can be mapped as a system of contour lines. The type of seismic waves used to identify this boundary is essential when compiling depth maps of the Moho topography. Therefore, the validity of map compilation can be estimated from the type of waves. The Moho beneath various parts of the shield can be reliably identified using refracted waves. These are used to estimate the boundary velocity along the surface of interest, and to interpret it as part of the crust or the upper mantle, depending on their value. Reflected waves are used to precisely estimate the depth of occurrence of a reflecting boundary, since they carry information about the average velocity of seismic waves in the overlying environment. However, they contain no evidence for the origin of underlying material – they do not show whether it is a reflecting boundary to the Moho or any other surface. Finally, converted waves are used to trace various boundaries in kinematics and dynamics, including the Moho, but they contain no evidence for the velocity of seismic wave

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propagation. Therefore, to identify the Moho among many other converted boundaries, one should use DSS data. Thus, reliable evidence for variations in the depth of occurrence of the Moho in an area can be obtained only by combining various methods.

While constructing a scheme for the topography of the Moho, its depth of occurrence was analyzed to reveal discrepancies at profile intersection points. Data from more detailed monitoring systems were preferred. Reduced (reduction rate 8.0 km/s) time-distance graphs of the reference longitudinal waves refracted and reflected at the Moho were constructed and compared for all DSS profiles. Additional experimental data on the travel-time of the first arrivals of longitudinal crustal and mantle waves excited by major industrial or seismic explosions and recorded on DSS profiles or by seismological stations were analyzed. Average velocity values in the Earth's crust were generalized. Our studies have shown that the velocity before the Moho varies from 6.4 to 6.6 km/s, averaging 6.5 km/s.

Generalized data on average wave velocities in the Earth's crust and provisional maps for the Moho were used to estimate relative variations in the depth to the base of the crust, to construct a reference network of absolute depths to the Moho, and to reduce DSS, RS and PS ECW data [14, 20, 21].

The earth crust of North Europe varies in thickness from 25 to 62 km (Figure 1a). A maximum thickness of 62 km was estimated beneath the Svecofennian province of the Fennoscandian Shield in the Ladoga-Bothnian zone and 48 km in the Belomorian megablock–Karelian megablock jointing zone. A minimum thickness of 30 km was revealed beneath the South Barents Sea Depression. The crustal thickness is 40–42 km in the western Kola Peninsula and 35 km in the eastern, 40–42 km in the White Sea, 50 km in the Lake Ladoga area and 30 km in the Mezen syneclise area.

The above topographic scheme of the Moho shows its structure only in general terms. Actually, the surface could be constructed in a much more complex manner, because uplifting and plunging zones in some cross-sections have fairly large amplitudes. As the seismic monitoring systems were not dense enough, the additional study of these local sites is needed.

Thus, the crustal structure of the Fennoscandian Shield displays the following features:
a mosaically heterogeneous structure;

- no persistent seismic boundaries in the crust throughout the entire shield;
- both waveguides and high-velocity zones, correlated with geological bodies of certain composition, occur locally in the upper crust;
- the structural plans of velocity isolines are not consistent with the velocities of various deep sections;
- major geological provinces differing in crustal thickness and seismic heterogeneity;
- Early Proterozoic volcanic belts display elevated velocities, considerable crustal thickness and anomalously high boundary velocity along the Moho.

2.3 Lithospheric mantle

In this large portion of the shield and in the northern Russian Platform basement, i.e. in the Lapland-Middle Russian-South Baltic orogen [22] with a consolidated Archean continental-type crust that the world's best preserved Paleoproterozoic East Scandinavian basic large igneous province (EScBLIP), best represented by typical formations of plume origin, with economic orthomagmatic Cr, Ni, Co, Cu, Au, Pt, Pd, Ti and V deposits has been identified [23]. The lowest high-velocity portion of the earth crust along some of the ECW–DSS-profiles of this province [14, 24-26], data on the composition of hypoxenoliths in explosion pipes [27] and evidence for the high-density and high-velocity layers of the mantle lithosphere (Figures 1b, c, d) suggest that they contain tremendous quantities of plume basic rocks (mantle asthenoliths). They were produced by Paleoproterozoic magmatic basification which resulted from the plume underplating of the Archean continental lithosphere [23].

The 3-D velocity model for the lithosphere of the Fennoscandian Shield is presented as four section maps showing velocity contours for depths of 50, 70, 90 and 115 km (Figure 2). They illustrate variation in the velocity of longitudinal waves in four layers with constant thicknesses at depths of 40–60, 60–80, 80–100 and 100–130 km, respectively [14] In the upper mantle, between the crust–mantle boundary and a depth of 130 km, the velocity of longitudinal waves varies from 8.0 to 8.7 km/s. Various velocity heterogeneities occur, ranging from 10 to 40 km vertically and from 50 to 500 km laterally. There are no low-velocity anomalies, where the velocity of longitudinal waves decreases to 8 km/s. Conversely, high-velocity (8.4–8.7 km/s) bodies were identified. Velocity anomalies are conspicuous both at depth and in shallower sections. The continuity in the distribution of velocity structures in layer I is broken in layers II, III and IV (depths of 60–80, 80–100 and 100–130 km). Their velocity variation range is higher (8.2–8.6, 8.4–8.7 and 8.5–8.7 km/s) than in layer I. The structural plans of velocity contours for the various deep sections of the upper mantle are inconsistent. In the mantle, the greatest variations in velocity on tomographic sections are observed in the Archean portion of the shield (Lapland–Kola–Karelian Province). Located here is the Kandalaksha–Dvina paleorift, which is clearly reflected on tomographic sections. Most geologists believe that this Paleozoic activation zone in the Arkhangelsk Kimberlite Province is likely to contain diamondiferous pipes.

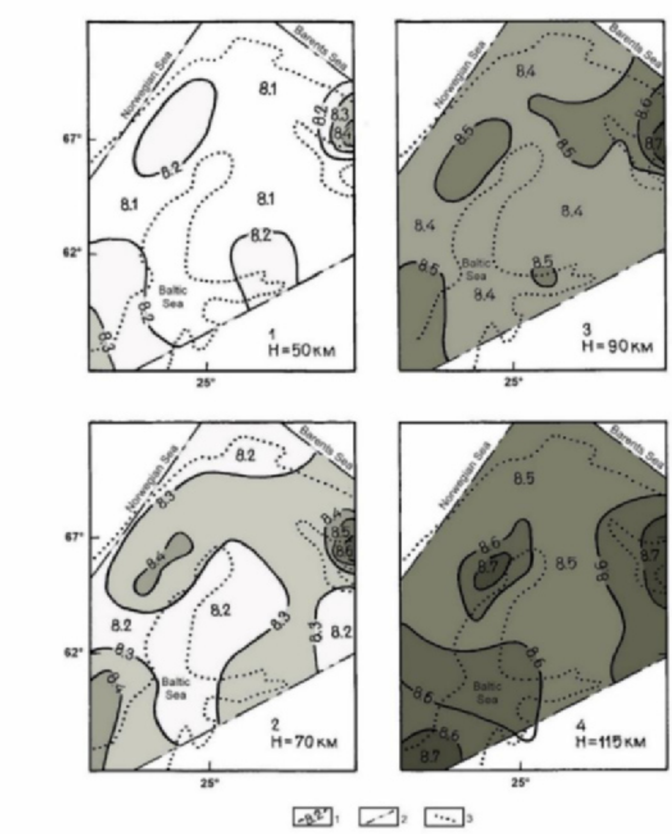

Fig. 2. Scheme of velocity distribution in the lithosphere at depths of 50, 70, 90 and 115 km [14]: *(1)* black lines – velocity contours (km/s); *(2)* dash lines – contours of the velocity estimation region; *(3)* dotted lines – contours of Scandinavia.

The results obtained by three methods for processing experimental data provide a better understanding of the geometry of seismic boundaries and the distribution of seismic wave velocities. The behavior of velocity contours may be indicative of anisotropy, although the effect of model errors in interpretation is also possible. Analysis and interpretation of the travel times of mantle-wave first arrivals from large industrial (nuclear) and ordinary explosions recorded at longitudinal profiles by DSS equipment and a network of seismological stations have provided more evidence for the structure of the upper mantle. Its structural characteristics, manifested as an interleaving of lens-shaped zones through which seismic waves travel, were studied in more detail. No thick low-velocity zone in the upper mantle of the Fennoscandian Shield, generally believed to be associated with the conventional concept of the asthenosphere as a zone of partial melting, has been detected from longitudinal wave velocity. A lens-shaped model of the upper mantle is most consistent with the pattern of complex tectonic movements observed at the surface than a model of a rigid lithosphere underlain by a mobile asthenosphere.

3 Conclusion

Anomalously high velocity layers and laterally heterogeneous layers were identified. There is no common asthenosphere as a partial-melt zone. The velocity of these layers, of at least 8.1 km/s, increases from the Moho to 8.5 km/s at a depth of 200 km, and to 9 km/s at a depth of 270 km. Extensive reflecting horizons, observed at depths of about 400 and 700 km, display a global distribution. Available seismic data were analyzed and generalized, and deep lithospheric sections of Precambrian shields in the Earth's Northern Hemisphere were constructed. Vertical and horizontal velocity heterogeneities with relatively high velocity values were identified in the upper mantle of shields. The asthenospheric layer is either thin or is absent.

Our results suggest a deep origin of subsurface structures, and provide evidence for the influence of upper mantle processes on the evolution of the Earth's crust. However, the relationship between crustal structures and the structural characteristics of the upper mantle shows a complex pattern, which often changes on transition from one region to another. Investigating this pattern will provide a better understanding of the reasons for, and the mechanisms of, tectonic processes in the crust.

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