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The NARS-DEEP Project

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Abstract

The NARS-DEEP project involves the deployment of broadband seismological stations in Russia, Belarus and the Ukraine. Six stations were installed in 1995, two in 1997, and more stations were to be installed from 1998 onwards. The NARS-DEEP project was initiated as a temporary deployment, but funding from the European Community enabled the stations to become permanent. In this paper we present first results of the NARS-DEEP project. A surface waveform inversion for the upper mantle structure along a profile from Egypt to Spitsbergen shows evidence for strong variations in the shear-velocity structure for the different tectonic units. The most striking features of the model comprise strong lithospheric anisotropy beneath the Eastern Mediterranean and a lithospheric thickness of approximately 200 km beneath the shield areas. The crustal structure beneath the seismic station in St. Petersburg was investigated using the receiver function method. The results of a Monte Carlo inversion for the receiver functions of this station show evidence for a sedimentary layer with a thickness of less than 1 km overlying an upper crustal layer extending to a depth of approximately 16 km. The Moho depth cannot be resolved from the receiver functions of this station.

Keywords: crustal structure; upper mantle; lithosphere; shear-velocity; Russian Platform; surface waves

1. Introduction

Since 1983 Utrecht University operates the Network of Autonomously Recording Seismographs (NARS). This network consists of fourteen portable seismic stations, each consisting of three broadband (0.01–1 Hz) seismographs and an electronic recording device to store the data in digital form. The first NARS deployment (1983–1988) was as a linear array extending from the south of Sweden to the south of Spain (Nolet et al., 1986, 1991). After that, from 1988 to 1989, the network was deployed on the Iberian Peninsula in the context of the European ILIHA project (Paulssen, 1990). In the NARS-Netherlands project, from 1989 to 1993, NARS was configured as a dense array in the Netherlands, western Germany and Belgium (Paulssen et

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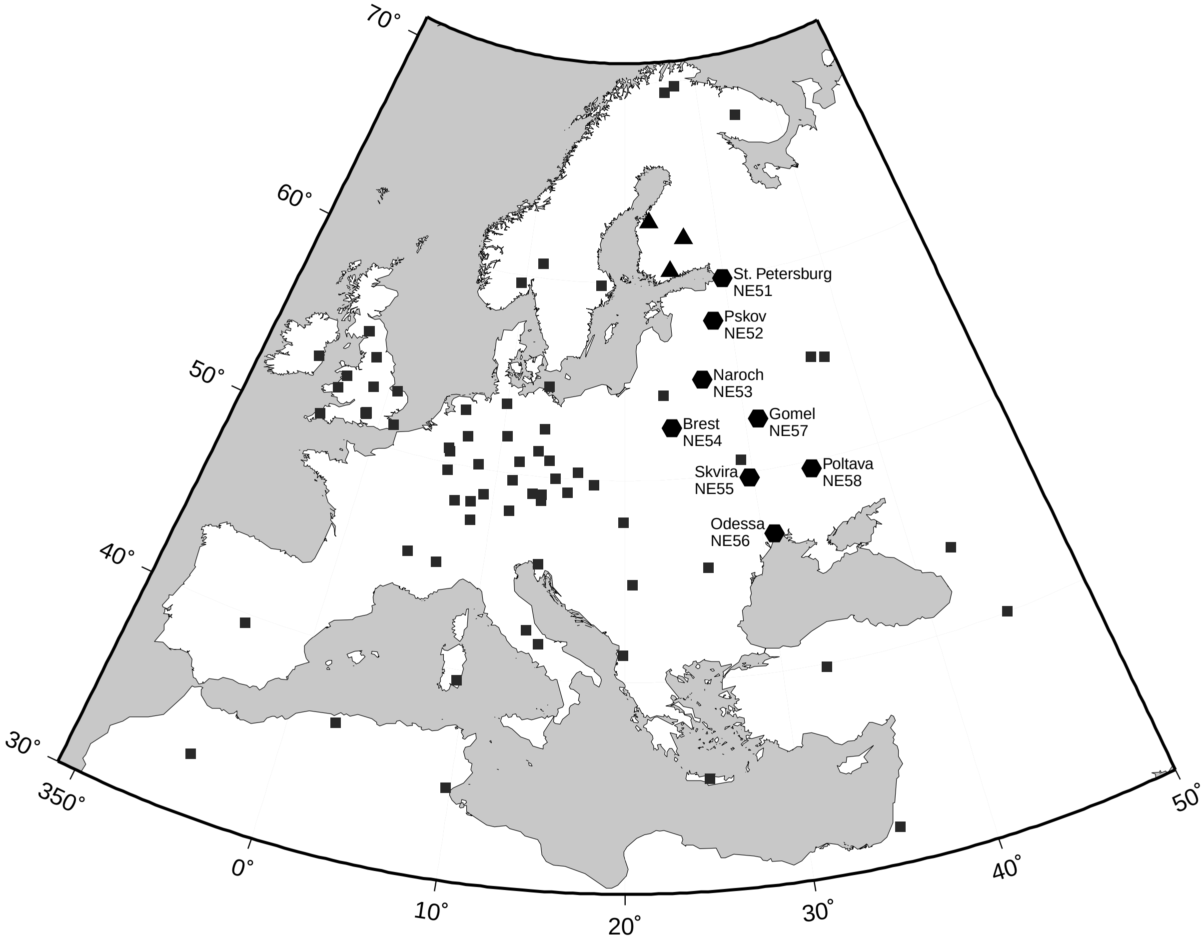


Fig. 1. Broadband stations in Europe. NARS-DEEP stations are indicated by hexagons, and NARS stations deployed in the context of the TOR project are indicated by triangles. The locations of other permanent broadband stations (squares) are taken from the 'station siting' list compiled by Zednik obtained from the ORFEUS Data Center (http://orfeus.knmi.nl).

al., 1990). In 1995, six stations were installed as part of the NARS-DEEP project with stations in Russia, Belarus, and the Ukraine (Paulssen, 1992; Snieder and Paulssen, 1993), and another two were deployed since 1997. The network now bridges the gap between densely instrumented western and central Europe and the sparser station distribution in the former Soviet Union (see Fig. 1).

The focus of NARS is to assemble earthquake data for seismological studies of the upper mantle, but a wide variety of investigations has been made possible ranging from a local study of the 1992 Roermond earthquake (Paulssen et al., 1992) to a tomographic waveform inversion using coupled surface wave modes (Marquering and Snieder, 1996). In this paper we present first results from the NARS-DEEP project: a surface wave study along a profile through the East-European continent, and a receiver function study for the seismic station in St. Petersburg.

2. The NARS-DEEP project

NARS-DEEP is an acronym of Network of Autonomously Recording Seismographs Deployed on the East European Platform. The timing of the project is related to political developments in the late 80's and early 90's. Before that time, it was

Table 1
Station locations

Station	Site	Latitude (ºN)	Longitude (ºE)	Elevation (m)	Installation
NE51	St. Petersburg (Russia)	59.881	29.826	20	July ’95
NE52	Pskov (Russia)	57.819	28.390	40	July ’95
NE53	Naroch (Belarus)	54.904	26.793	215	July ’95
NE54	Brest (Belarus)	52.568	23.861	200	July ’95
NE55	Skvira (Ukraine)	49.716	29.656	235	July ’95
NE56	Odessa (Ukraine)	46.676	30.899	30	July ’95
NE57	Gomel (Belarus)	52.603	31.081	129	July ’97
NE58	Poltava (Ukraine)	49.603	34.543	166	July ’97
NE61	Nurmijarvi (Finland)	60.509	24.649	105	October ’96
NE62	Kangasniemi (Finland)	62.112	24.306	124	October ’96
NE63	Kauhava (Finland)	63.047	22.668	55	October ’96

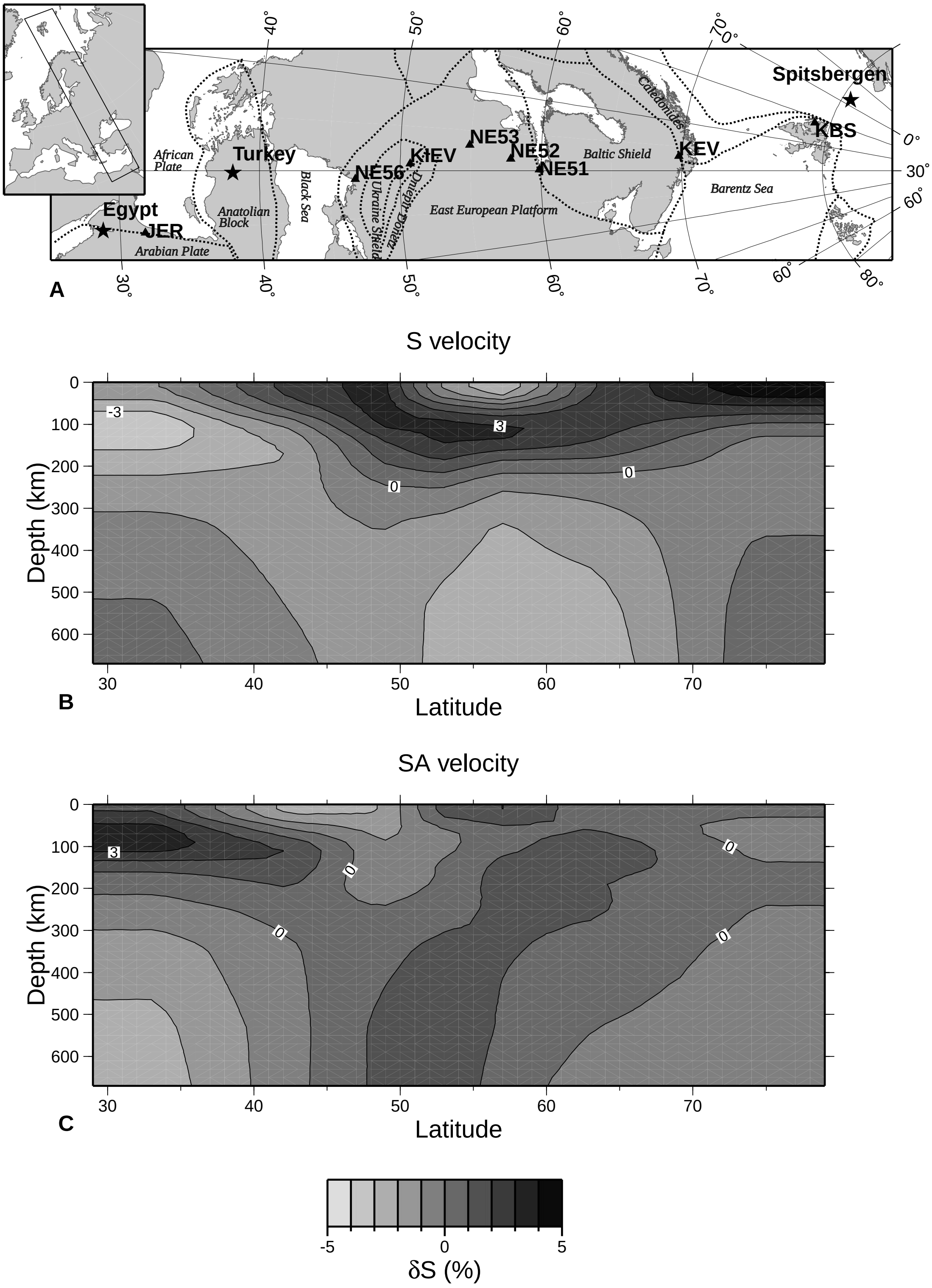
practically impossible to deploy seismic stations in the Soviet Union as part of seismological East–West cooperation. The establishment of the New Independent States (NIS) of the former Soviet Union has enabled East–West cooperation and the installation of seismic stations in Russia, Belarus and the Ukraine. Through a collaborative project of Utrecht University (Utrecht, The Netherlands), the Institute of Geological Sciences (Minsk, Belarus), the Institute of Geophysics (Kiev, Ukraine), the University of St.-Petersburg (St. Petersburg, Russia) and the International Institute for Earthquake Prediction (Moscow, Russia) it is now possible to record seismic waveforms in the NIS and to have data exchange. To this end, six seismic stations have been installed in Russia, Belarus and the Ukraine in July 1995, and two others in 1997. The locations of these stations are indicated by hexagons in Fig. 1, and the coordinates are given in Table 1. In addition, up to five stations will be installed in 1998. Furthermore, three stations are deployed in Finland since October 1996 in the context of the TOR-project [Tor Working Group, 1997] which extends the network further northwards (see Fig. 1, triangles, and Table 1. These stations are temporarily deployed.

The scientific goal of NARS-DEEP is to refine Earth models for the East-European Platform and to determine the pattern of seismicity and the mechanism of earthquakes (Bukchin, 1995). Special attention is given to the deep structure of the East-European craton, and the possible presence of low S-velocities in the mantle under the Ukraine (notably the Djnepr–Donetz depression). The goals of this project are embedded in the general context of the EUROPROBE initiative, and for this reason NARS-DEEP is part of the EUROPROBE project (see Gee and Zeyen, 1996).

3. A seismic profile along the 30ºEast meridian

In this section we present results of a study of the S-velocity structure under the East-European continent using data of the NARS-DEEP project. We only give a brief overview of the approach here; full details of this study are given by Muyzert et al. (1999).

Three events, one in Turkey (October 1, 1995, $M_w = 6.0$), one in Egypt (November 12, 1995, $M_w = 7.2$), and one near Spitsbergen (May 14, 1996) were recorded along the line of NARS stations complemented by stations operated by the IRIS consortium. The locations of the events and stations which recorded the events are shown in Fig. 2A. The stations and events approximately lie along the 30ºEast meridian and allow a detailed investigation of the upper mantle shear-velocity structure along this profile. The vertical and tangential components of ground motion were used to model the fundamental and higher mode Love and Rayleigh wavetrains. This was done by a partioned waveform inversion Nolet (1990) with a modified version of PREM (Dziewonski and Anderson, 1981) as a starting model (crustal thickness of 40 km and a


Spitsbergen
KBS
KEV
Caledonides
Baltic Shield
Barentz Sea
NE53
NE52
NE51
KIEV
NE56
East European Platform
Dniepr-Donetz
Ukraine Shield
Black Sea
Turkey
African Plate
Anatolian Block
Egypt
JER
Arabian Plate
30°
40°
50°
60°
70°
80°
0°
A
S velocity
-3
3
0
Depth (km)
Latitude
B
SA velocity
C
δS (%)
-5
5

constant shear-velocity of 4.6 km/s down to 220 km depth). The path-averaged SH- and SV-velocity structures were thus obtained for each source–receiver pair. The results showed discrepancies between the SH- and SV-velocity structures suggestive of seismic anisotropy. The path-averaged velocity perturbations were then inverted to determine the lateral variations along the profile. The cell boundaries of this inversion correspond to the latitudes of earthquakes and stations except for that of NE52 because synthetic tests showed that the velocity structure of cell NE51–NE52 could not be resolved. The average shear-velocity was defined as $S = (\mathrm{SH} + \mathrm{SV})/2$ and the apparent shear wave anisotropy as $SA = (\mathrm{SH} - \mathrm{SV})/2$. The inversion of the path-averaged velocities to the S and SA velocities in each cell is a linear inversion which is regularized by smoothing and norm damping.

The preferred model, selected on the basis of a trade-off analysis between model roughness and data-misfit, is shown in the middle and bottom panels of Fig. 2. The middle panel of Fig. 2B shows marked variations in the average upper mantle shear-velocity structure. At the southern end of the model, beneath the Mediterranean, low velocities are found. The average velocity increases beneath Turkey: the average velocity under Turkey and the Black Sea is described by a high-velocity zone overlying an asthenosphere with 5% lower velocity than the starting model. The velocities increase further under the East European Platform where the thickness of the high-velocity lithosphere increases to a depth of approximately 200 km. Beneath the Barentz Sea this lithospheric thickness decreases again to roughly 100 km. The pattern of apparent anisotropy is rather different (see Fig. 2C): the strongest anisotropy (6% faster SH-velocities than SV-velocities) is observed for the Mediterranean at a depth of approximately 100 km.

Fig. 3 shows the fit to the data of the Egypt event, as an example. The starting model gave travel times which were 16 to 6 s early for the fundamental mode Rayleigh wave train going from NE56 to KBS (i.e. with increasing distance). For the fundamental mode Love wavetrain the starting model was 6 s early (NE56) to 13 s late (KBS). As can be seen in Fig. 3, the waveform fits to the data for the final model are very good.

Lastly it was checked whether apparent anisotropy is really required by the data. The data misfit of the best fitting isotropic model appeared to be significantly worse than for models which include anisotropy. Yet, the best isotropic model was found to be remarkably similar to the best S-velocity model of the anisotropic inversion shown in Fig. 2B. This implies that there is little trade-off between the average (S) and the apparent anisotropic (SA) velocity structure in the inversion.

The seismic anisotropy inferred for the shear-velocity structure beneath the Mediterranean is very similar to the anisotropy observed for the Pacific Ocean by Nishimura and Forsyth (1989), and is suggestive of an oceanic interpretation for the Mediterranean. This is in accordance with the hypothesis of an oceanic plate in the Eastern Mediterranean based on tectonic reconstructions as proposed by Dercourt et al. (1986). The high-velocity lid in our model is very thin ($<$100 km) which would imply a relatively young oceanic lithosphere ($<$100 Ma), in agreement with the reconstructions from Dercourt et al. (1986).

The model shows increasing lid thickness from Turkey to Kiev. This part of the Eurasian continent consists of different tectonic blocks such as the Anatolian block and the Black Sea region which were pressed onto the Ukrainian Shield and East European Platform in the Late Cretaceous. Below the East European Platform between Kiev and NE51 (St. Petersburg, Russia) the seismic velocities are high to a depth of 200 km. The seismic velocities beneath the Archean Baltic Shield from NE51 to KEV (Kevo, Finland) are slightly lower than for the younger East European Platform, but the anomaly extends to a similar depth. Finally, on the segment between KEV and KBS (Spitsbergen) the thickness of the lithosphere is decreased again to approximately 100 km.

Fig. 2. (A) Map along the 30ºEast meridian, showing stations (triangles), earthquake locations (stars), and tectonic regions. (B) Shear-velocity model of the upper mantle between Egypt and Spitsbergen. The average of the SH- and SV-velocity is shown as relative perturbation of the starting model (see text). (C) Apparent anisotropy ((SH + SV)/ 2) along the same profile.

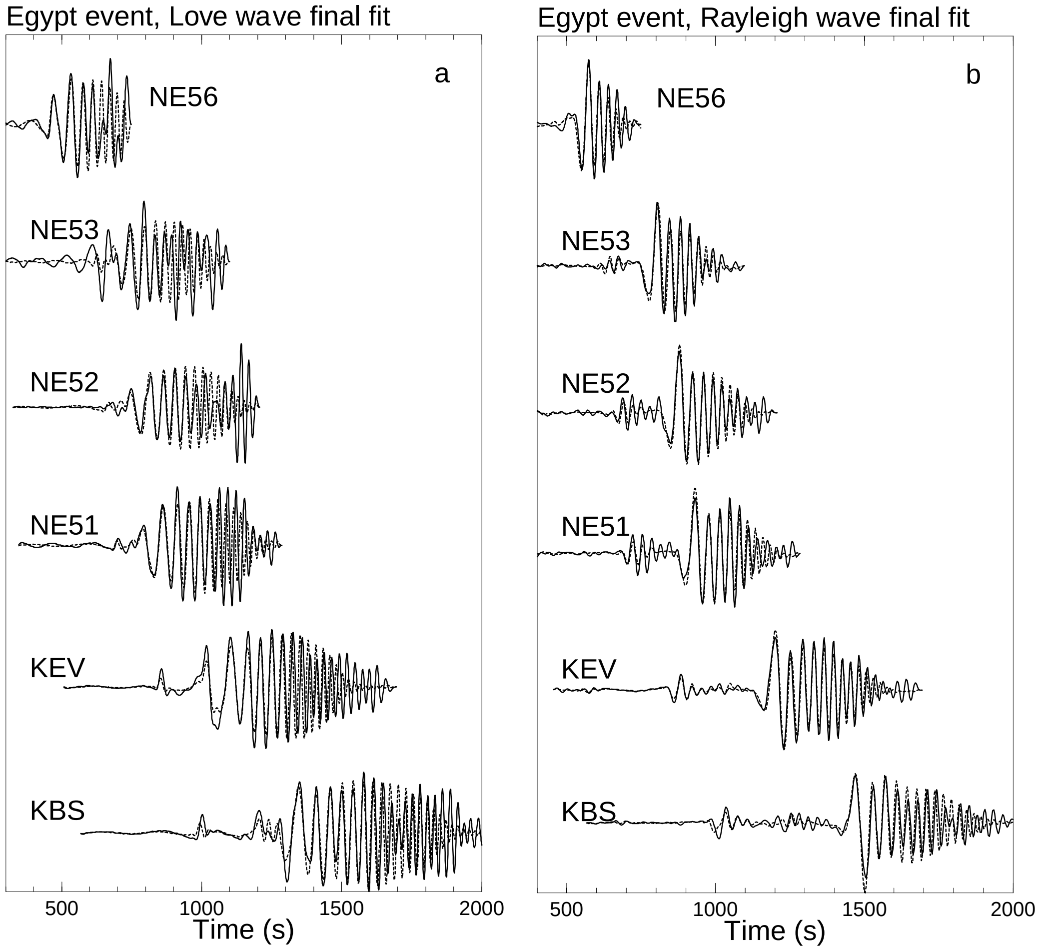


Fig. 3. (a) Waveform fit of the Love waves for the Egypt event filtered between periods of 25 and 100 s. Solid lines represent the data, dashed lines the synthetic seismograms. (b) Same as (a) for Rayleigh waves.

4. The crustal structure beneath NE51, St. Petersburg

In another study with the NARS-DEEP data, the crustal structure beneath station NE51 (St. Petersburg, Russia) is investigated by the receiver function method (e.g. Langston, 1979). The essence of the approach is that the radial component of the P-wave coda for teleseismic events is dominated by P-to-S-converted phases from the crust and their subsequent S-wave reverberations. The receiver function of a seismogram is obtained by deconvolving this radial component by the vertical component, which is dominated by direct P-wave signal. The receiver function is thus eliminated from the effects of the source time function, and is strongly influenced by the shear-velocity structure beneath the station through the remaining S-wave arrivals. Receiver functions can be modeled using a Thomson–Haskell or propagator-matrix method (see e.g. Aki and Richards, 1980) for flat-layered crustal models. In our approach modeling is done using a Monte Carlo inversion to find the robust features of the best fitting models. This limits the number of free parameters that can be used, but has the advantage that information can be obtained about the most robust features of the best fitting models.

In our inversion of seventeen receiver functions, clustered in three stacks, we generated 30,000 random, 3-layered models with varying shear-velocity and thickness. The P-velocity in the uppermost layer

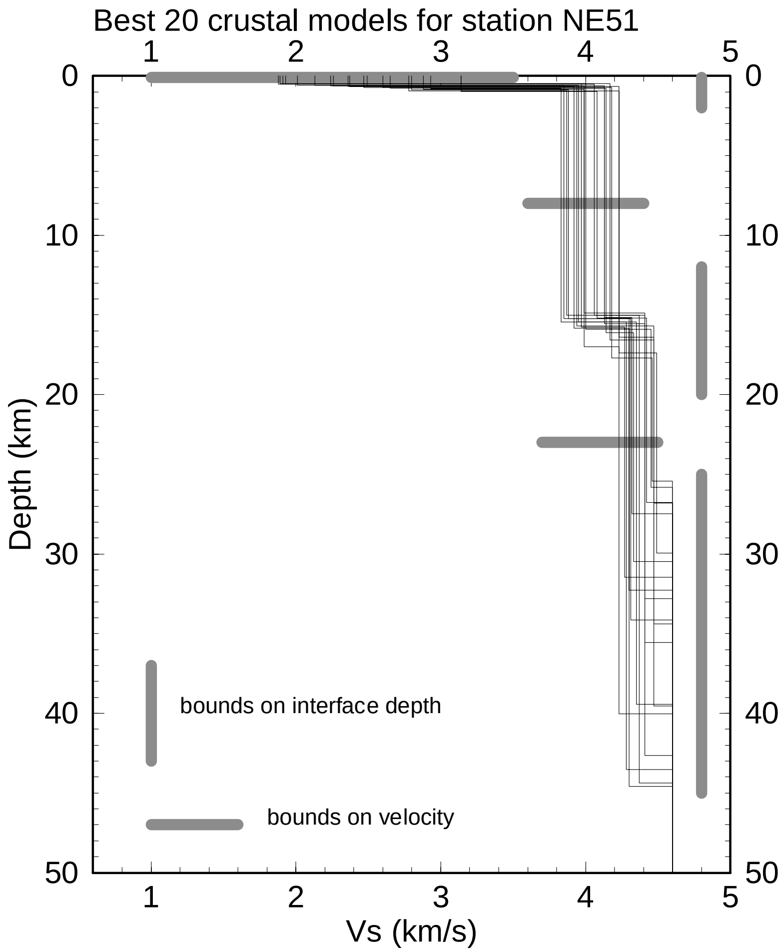


Fig. 4. Best twqenty crustal shear-velocity models obtained from a Monte Carlo receiver function inversion for station NE51 (St. Petersburg).

was allowed to vary, in the other two layers it was coupled to the S-velocity according to a Poisson medium. The best fitting models, of which 20 are shown in Fig. 4, consistently show that a thin (0.5–1 km thick), low S-velocity sedimentary layer overlies an upper crustal layer which extends to a depth of 15–17 km. The shear-wave velocity in the uppermost sedimentary layer (2–3.3 km/s) obviously trades off with the thickness of the layer. A similar, but less pronounced effect is seen for the upper crustal layer which has S-wave velocities between 3.8 and 4.2 km/s. The obtained values for the lower crustal shear-velocity are higher than 4.2 km/s. The Moho depth (or another lower crustal transition) is not resolved by receiver functions, because all transitions in the allowed depth range (25–45 km) give an equally acceptable fit to the data. It thus seems that the impedance contrasts between the sediments and upper crust and between the upper and lower crust have a dominant effect on the receiver functions of station NE51.

The inferred thickness of the uppermost sedimentary layer for St. Petersburg nicely fits in the map of the basement depth of the former USSR as compiled by Kostuchenko and published by Pavlenkova (1996). The midcrustal transition at a depth of roughly 16 km is typical for a transitional type of crust as defined by Beloussov and Pavlenkova (1984). This type of crust is transitional between continental and oceanic, and is suggested for the St. Petersburg area by Pavlenkova (1996).

5. Conclusion

In this paper we presented first results of a surface wave and a receiver function study. They show that the shield areas have a lithospheric thickness of approximately 200 km, and that the crustal structure of St. Petersburg is of a transitional nature being neither typical continental nor oceanic in character, the upper mantle shear-velocity structure beneath the Eastern Mediterranean appears anisotropic and typical for oceanic lithosphere.

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