CRUSTAL AND UPPER MANTLE SEISMIC VELOCITY STRUCTURE OF THE FORMER USSR

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ABSTRACT

In the past forty years, the Ministry of Geology of the former USSR committed vast funding to investigations of the structure of the continental crust and upper mantle by seismic methods. The former USSR is crisscrossed by a network of seismic profiles that are more detailed than in any other part of the world. There are three kinds of profiles: (1) short-range refraction; (2) Deep Seismic Sounding (DSS) profiles; and (3) ultra-long range seismic profiles using Peaceful Nuclear Explosions (PNEs). The main goal of the short-range refraction work was to image sedimentary cover and basement. Measurements were obtained using 48-60 channel analog instruments with 100 m receiver spacing, and seismograms were recorded on photographic paper by the wiggle trace method. The DSS observations were mainly used for crustal studies. The shotpoint spacing was 30-50 km, and three components of ground displacement were recorded. The refracted compressional (P) and shear waves (S), reflected (P and S) and converted waves were interpreted. Ultra-long range PNE-sourced profiles provided information on the structure of the crust and upper mantle to a depth of 670 km. For PNE profiles, up to 400 short-period (1.5-20 Hz), three-component seismometers were deployed every 5- 10 km to record ground motion. Thirty-nine PNE shots were detonated for these purposes, with intermediate chemical shots spaced at 40-70 km intervals. These chemical shots had charges ranging from 2000 to 5000 kg. The total length of all of these three types of profiles exceeds 80 thousand kilometers. We present a synthesis of these results in the form of new maps of crustal thickness and seismic velocity below the Moho discontinuity.

Key Words: crustal structure, former USSR, seismic refraction, Deep Seismic Sounding, Peaceful Nuclear Explosions

OBJECTIVE

High quality regional models of crustal structure are necessary for accurate seismic locations required by the monitoring of the Comprehensive Nuclear-Test-Ban Treaty (CTBT). This paper presents models of the seismic velocity structure of the lithosphere in the Former Soviet Union.

RESEARCH ACCOMPLISHED

1 Introduction

The properties of the Earth's crust and uppermost mantle are particularly well suited to measurement using seismological data due to the existence of the pronounced variations in seismic wave speeds both with depth and laterally. Seismological studies are capable of imaging high resolution structure to depths of several tens of kilometers, and moderate resolution to depths of 1 00's of kilometers. Here we discuss crustal and uppermost mantle studies from the Former Soviet Union (FSU) that have utilized controlled-source seismic-refraction data, including long-range profiles from nuclear sources. The chief advantages of such data are: 1) the exact time and position of the seismic sources are accurately known; 2) there is no reliance on either local nor teleseismic events that may occur infrequently and/or have an unsuitable spatial distribution; 3) the recording geometry of the seismic investigation may be planned in relation to the specific geologic target.

Since the early 1950's a large number of seismic profiles have been collected in the FSU. Advancing technology has led not only to better instrumentation, but also improved data processing and interpretation techniques. Useful recent reviews of seismic methods for determining crust and upper mantle structure have been provided by Mooney (1989) and Braile et a]. (1995), and Giese et al. (1976) provide older methods of data analysis. Papers that summarize global crustal structure, including the FSU, include Soller et al. (1992), Prodehl (1984), Meissner (1986), Tanimoto (1995), Pavlenkova (1996), and Mooney et al. (1998).

Resolution is a major consideration when discussing seismic data. Because of the variety in seismic techniques, however, general statements about resolution are difficult to make. In seismology, resolution is related both to data quality and physical laws. The quality of a data set is usually considered to be a function of the strength of the signal relative to noise (expressed as signal-to-noise ratio) and the number or density of measurements depending on the number of sources and receivers and their relative spacing. Generally, the more data are available, the higher is the resolution. However, physical laws limit the resolution of even near-perfect data set. The Earth strongly attenuates high frequencies so that signals penetrating deeper will contain relatively low frequencies. Typically, signals traversing the whole crust have peak frequencies of 5-20 Hz resulting in absolute accuracy of depth determination of not better than 2% to 5% of the depth (e.g., 1-2 km for a 40-km-thick crust).

Seismic refraction data provide information on velocities within the continental lithosphere. In many cases it is also of interest to infer the composition of the lithosphere, and for this a comparison can be made with laboratory measurements the speed of sound in specimens of rocks believed to have once resided at depth within the lithosphere. These studies are reviewed in Holbrook et al. (1992) and Christensen and Mooney (1995).

2.1 Main features of crustal structure of the Former Soviet Union

There have been many attempts to synthesize this structure in terms of the most important parameters, including crustal thickness, mean crustal velocity, Pn velocity, Conrad discontinuity (defining the seismic boundary between upper and middle/lower crust), thickness and mean velocities of main crustal layers (sediments, upper, middle and lower crust), and representative crustal cross sections. We have compiled this information for the FSU, but space limitations prevent us from presenting extensive examples.

The basic features of the crustal structure of the FSU were recognized by the 1960's (Ryaboy, 1966; Kosminskaya, 1968; Pavlenkova, 1973). The seismic velocity distributions vary widely in different geographic localities, and crustal models generally consist of two, three or more layers separated by velocity discontinuities or gradients. In relatively stable continental regions, the thickness of the crust, as

defined by depth to Moho, is between 30 and 50 km. Seismic velocities in the upper crustal layer (basement) are usually 5.6-6.3 km/s. At a depth of 10-15 km the seismic velocity increases to 6.4-6.7 km/s. In many stable continental interiors there is a third crustal layer with a velocity of 6.8-7.2 km/s. The seismic velocity below the Moho (Pn velocity) is typically about 8 km/s. The exact nature of the velocity-depth distribution is not always well defined. The evidence for distinct layers within the continental crust almost exclusively depends on the interpretation of second-arrival phases. In some regions, clear evidence of later arrivals confirms that the velocity increases discontinuously through intermediate layers within the crust, in other regions velocity may increase gradually with increasing depth producing no distinct intracrustal reflection.

The compilation of seismic crustal data around the world has also defined the characteristic primary crustal types connected with specific tectonic settings (Fig. 1). These models are well based on data from the FSU. Each primary crustal type was derived by averaging models determined from seismic refraction profiles recorded in crust of specific age or tectonic setting. The existing data are so numerous (Fig. 2) that in this summary paper only a few examples of results can be presented. Figure 3 shows Pn velocity for Western Russia.

2.2 Crustal Cross-Sections

Seismic profiles cover all tectonic structures of northern Eurasia (old and young platforms, shields and deep depressions, orogenic belts of different age and geological history, rifts, marginal and inner seas). In Figures 4 and 5, examples of the deep seismic studies from the FSU are summarized for three long-range profiles: (a) Black Sea - Dnieper-Donetz basin, (b) Baltic Shield - Urals - West-Siberian Plate and (c) West-Siberian Plate - Siberian Craton. The first profile was carried out in the 1960s using continuous profiling with distance between seismometers of 100 m and chemical explosions with 50-60 km interval (Pavlenkova, 1973). The lines from the Baltic Shield across the Urals to the West-Siberian Plate and from the West-Siberian Plate to the Siberian Craton were recorded with 10 km interval between seismic stations and two types of explosions: chemical ones and Peaceful Nuclear Explosions (PNEs). The latter ones enabled to study the upper mantle down to depth of 700 km (Egorkin et al., 1987, Beloussov et al., 1991, Mechie et al., 1993).

The crustal structure can be described by 4 basic layers with seismic mean velocities as follows: 2.0-5.5 km/s (sediments), 5.8-6.4 km/s (upper crust), 6.5-6.7 km/s (middle crust) and 6.8-7.4 km/s (lower crust). The first profile (Fig. 5a) crosses the Black Sea basin, Crimea Mountains, the Sivash basin, the Ukrainian Shield and the Dnieper-Donetz basin. In the Ukrainian Shield the crust has a thickness of more than 40 km and consists of three crustal layers of comparable thickness (I 0- 15 km). Beneath the basins, the Moho (M) is uplifted and the upper crust thins. Such changes become even more dramatic in the Black Sea area where the consolidated crust is only 20 km thick and where the upper and lower crustal layers disappear. The adjacent Crimean mountains have crustal "roots" and a crustal average velocity that is slightly lower than beneath the Ukrainian Shield.

The second profile (Fig. 5b) crosses the Baltic Shield, Western Russian Platform, Timan Ridge, Pechera Platform, Ural Mountains, and the West-Siberian Platform. All these tectonic units have a similar crustal structure, an important exception being the Timan-Pechera block. It is characterized by considerably lower crustal velocities, with the elsewhere present third high-velocity layer (Vp > 7 km/s) absent. The Urals have a pronounced "root" in Moho (M) topography, while the Timan Ridge is compensated by an increased thickness of the upper crust. A clear seismic boundary was revealed in the uppermost mantle where strong reflections indicate a velocity discontinuity (N) at depths of 75-105 km. The relief of this boundary shows an opposite correlation with the Moho. Seismic velocities between the two boundaries M and N vary from 8.0 beneath the Pechera and West-Siberian plates to 8.4 beneath the Urals. These changes clearly correlate with heat flow: the lower velocities correspond to higher heat flow areas. An anomalous zone was identified at the boundary between the old Russian plate and the younger Timan-Pechera unit. The thick dashed line in (Fig. 5b) traces this zone from a high-velocity intrusion in the crust to the boundary N where it is subducted beneath the Pechera Plate.

The third profile (Fig. 5c) characterizes the young West-Siberian plate and the Siberian Craton. Though of differing age, both platforms have a similar crustal thickness. The crustal structure changes mainly beneath

deep sedimentary basins. Common features are characteristic for the West-Siberian central basin and the Tunguss basin: in both cases the middle crustal layer remains the same, and the lower crustal thickness increases. The Vilui basin which is younger than the Tunguss basin has a clear uplift of the Moho. The upper mantle velocities hardly change along this profile. The only characteristic feature is the block of lower velocity in the central part of the West-Siberian plate. It corresponds to a large rift zone which crosses the plate from north to south. Another characteristic feature of this cross-section is a velocity inversion zone immediately above the N boundary at a depth of 100 km.

CONCLUSIONS AND RECOMMENDATIONS

Extensive seismic profiling data from the Former Soviet Union, including long-range profiles that were recorded from Peaceful Nuclear Explosions provide a vast geophysical database. Much of this data is now available in digital format, and thus can be re-evaluated in terms of the seismic velocity structure and attenuation of the crust and upper mantle to a depth of 700 km. The improved knowledge of the seismic structure, in turn, will enable significantly improved determinations of seismic source parameters as needed by the Comprehensive Nuclear-Test-Ban Treaty.

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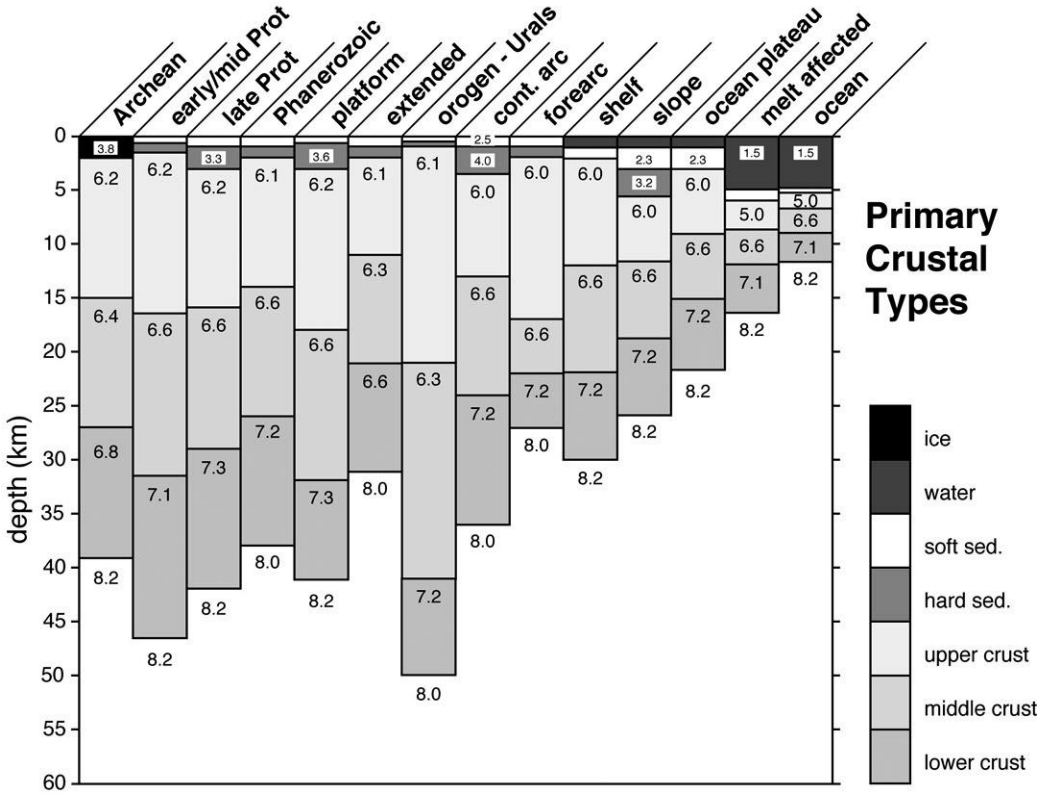

Figure 1. Velocity structure of the primary crustal types developed from seismic refraction data worldwide, including the results summarized here for the Former Soviet Union (FSU). These crustal types represent averages, and specific regions may deviate by as much as 50% in thickness from these values.

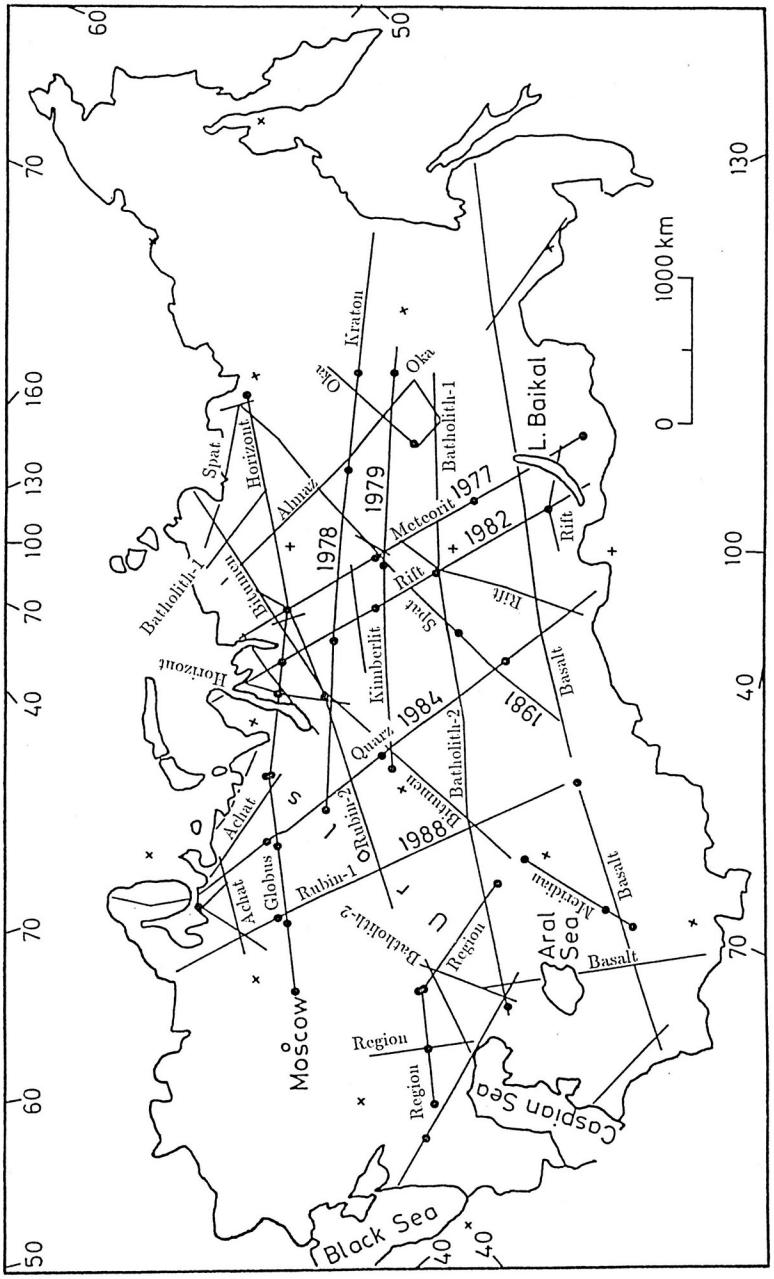

Figure 2. Location of map of long-range profiles completed in the Former Soviet Union using PNE (solid dots) and numerous chemical shots (not included).

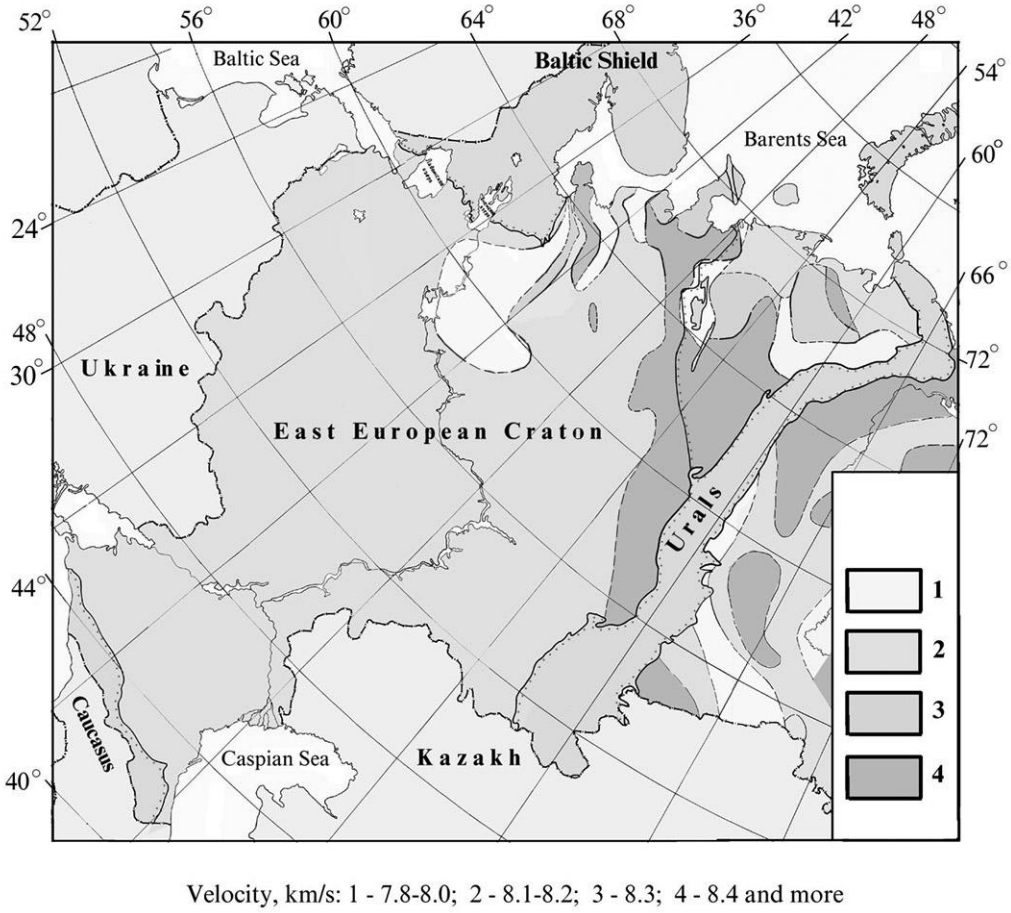

Figure 3. Seismic velocity on the top of the uppermost mantle (Pn velocity) for Western Russia from seismic refraction profiles. The average value is 8.1 km/s, but the individual profiles show values in the range 7.8 to 8.4 km/s due to (1) seismic anisotropy, (2) temperature effects and (3) compositional variations. A map for the entire territory of the Former Soviet Union is presently being prepared by the project.

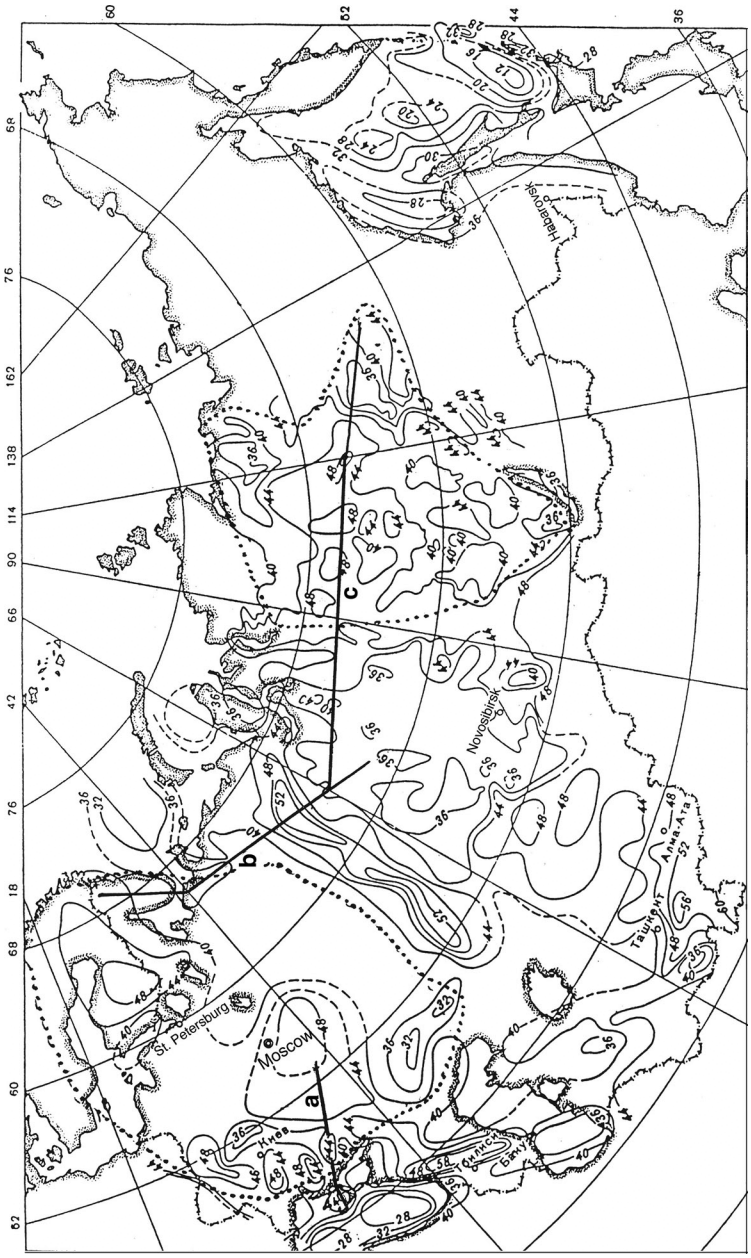

Figure 4. Map of the thickness of the crust of the FSU (thin contour lines) derived from seismic data (Pavlenkova, 1996). Thick lines labeled a, b, c indicate the locations of the three cross-sections in Figure 4

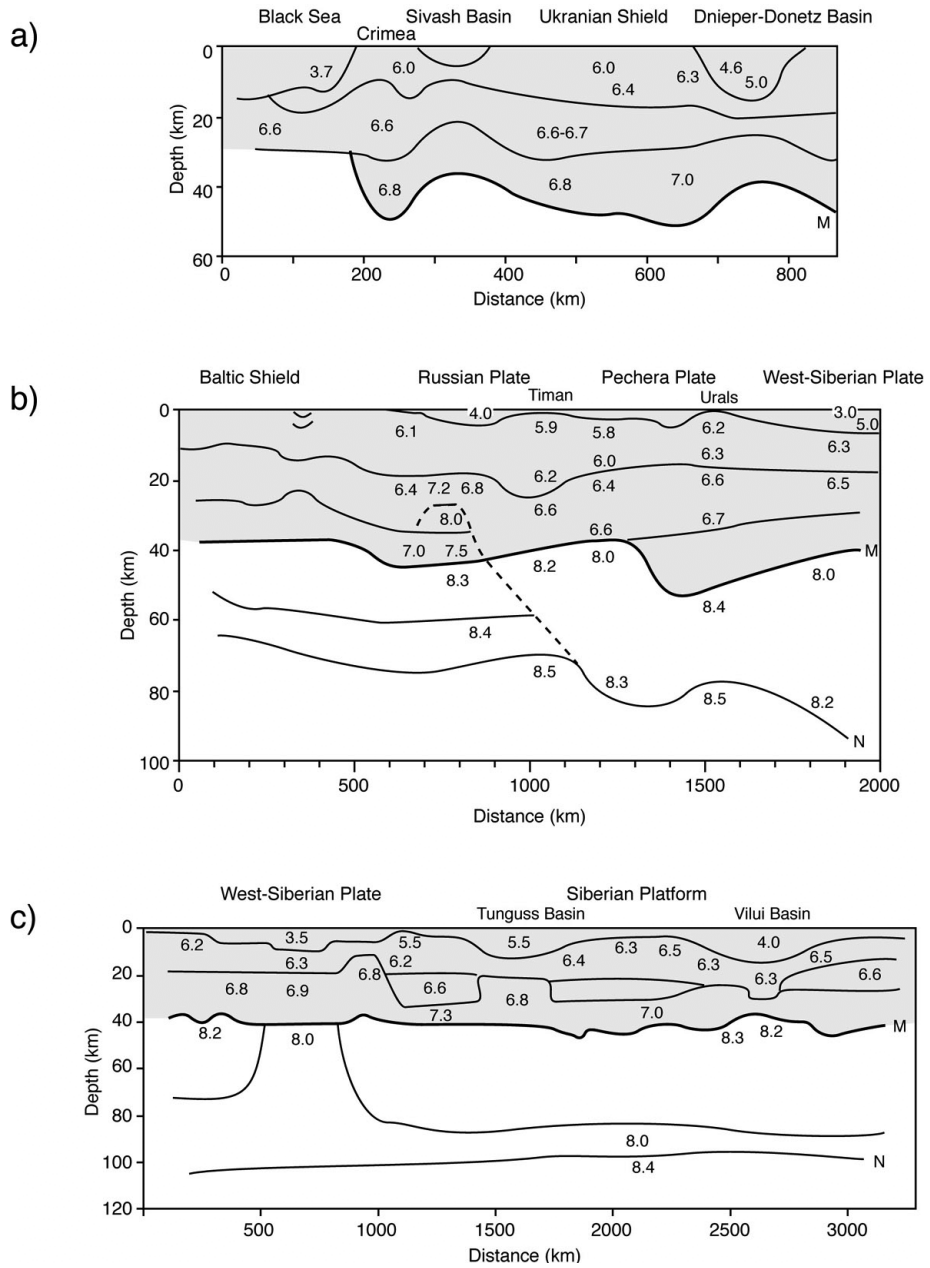

Figure 5. Three cross-sections of the crust and uppermost mantle. Locations indicated in Figure 3. Note that the horizontal scale varies. Cross-sections (b) and (c) are based on both chemical and PNE seismic refraction.