CRUSTAL AND UPPER MANTLE SEISMIC VELOCITY STRUCTURE OF THE FORMER USSR FROM PEACEFUL NUCLEAR EXPLOSIONS (PNEs) AND CHEMICAL EXPLOSION DATA

Walter D. Mooney[1], Sergei Kostyuchenko[2], and A.V. Egorkin[2]

1. U.S. Geological Survey, Earthquake Hazards Team
2. GEON Centre, Moscow, Russia

Sponsored by U.S. Department of Energy
Office of Nonproliferation and National Security
Office of Research and Development

DOE IA No.: DE-AI04-98AL79758

ABSTRACT

In the past forty years, the Ministry of Geology of the former USSR committed vast funds to investigations of the structure of the continental crust and upper mantle by seismic methods. The former USSR is criss-crossed 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 and reflected compressional (P) and shear waves (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 updated maps of depth to basement and depth to Moho in Russia.

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

OBJECTIVE

To successfully monitor the Comprehensive Nuclear-Test-Ban Treaty (CTBT), accurate models of crustal structure are needed. We present here new, high-quality crustal structure models of the Former Soviet Union.

RESEARCH ACCOMPLISHED

1 Introduction

Seismology is particularly well-suited to measuring the properties of the Earth's crust and uppermost mantle due to the existence of the pronounced variations in seismic wave speeds both with depth and laterally. Seismological studies are capable of imaging structure at high resolution to depths of several tens of kilometers, and moderate resolution to depths of hundreds of kilometers. In the former Soviet Union (FSU), crustal and uppermost mantle studies have utilized controlled-source seismic-refraction data, including long-range profiles from nuclear sources. These profiles from Peaceful Nuclear Explosions (PNEs) and chemical explosions will be discussed below. Data from controlled sources have many advantages including: 1) the exact time and position of the seismic sources are accurately known; 2) there is no need to rely 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.

A large number of seismic profiles have been collected in the FSU since the early 1950's. An advance in technology has led not only to better instrumentation, but also to 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 al. (1995). Giese et al. (1976) summarize older methods of data analysis. Papers that summarize global crustal structure, including the FSU, include: Prodehl (1984), Meissner (1986), Soller et al. (1992), Tanimoto (1995), Pavlenkova (1996), and Mooney et al. (1998). From this, our model of global crustal thickness (Fig. 1) has been greatly refined, and a global average crustal thickness of 39.17 km has been determined (Fig. 2). Another important benefit of seismic profiling has been the cataloging of crustal velocities. The global average crustal velocity has been determined to be 6.45 km/s, and a histogram of average crustal velocity is given in Figure 3. This average crustal velocity implies that the bulk composition of the crust is equivalent to a diorite (Christensen and Mooney, 1995).

A major consideration when discussing seismic data is resolution. General statements about resolution are difficult to make, however, because of the variety in seismic techniques. 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, there is higher resolution when more closely-spaced data are available. However, physical laws limit the resolution of even a near-perfect data set. The Earth attenuates high frequencies such that signals penetrating deeper will contain relatively low frequencies. Typically, signals traversing the entire 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 one of the best sources of information on velocities within the continental lithosphere, but often more information is desired. It is often of interest to determine the composition of the lithosphere, for example, and for this laboratory measurements of the speed of sound in rock specimens believed to have once resided at depth within the lithosphere are compared to refraction data. Lithospheric composition can then be inferred. These studies are reviewed in Holbrook et al. (1992) and Christensen and Mooney (1995).

2 Background

About 32 PNE sources recorded on long-range profiles have been digitized and preserved in the FSU by using hardware provided by German collaborators in 1993. This digitizing system is located in the GEON Center in Moscow and is still operating. The 32 digitized PNEs are along the profiles known as Quartz, Kraton, Kimberlite, Rubin I and II, Meteorite, Rift, and Batholith I and II. An example of PNE data from the Quartz profile is given as Figure 4. These PNE profiles were digitized at 50 samples/s, usually for 10 minutes, depending on the record length of the original analogue field tapes. Thus, the time-window includes reflections from the Earth's core. While it is always possible to redigitize with other parameters, the data from these 32 PNEs can be considered as preserved. In addition, many nuclear shots were fired at Soviet test sites. Some of these shots were recorded on linear profiles or in fan (broadside) geometry. Only a portion of these records have so far been digitized, but more of this work is now being done.

An additional seven PNEs in northern Russia along the profiles Globe (4 PNEs conducted during the first year of the program, 1973), and Horizon (3 PNEs conducted in 1974) have not been digitized. Only paper records exist for these PNEs, and they have not yet been digitized from the paper records.

In southern Russia 5 PNEs along the profiles Region and 3 PNEs on the profiles Meridian have not been digitized because the data tapes are too old (1973-74) and not all tapes are available. Once again, these data are available only on paper records, to limited record times. In summary, some 15 PNEs have not been digitized due to the lack of adequate original field tapes. Conversely, all analogues tapes of PNE data along long-range profiles that can be digitized have already been digitized.

All long-range PNE profiles also had chemical shots with an average spacing of 70 km. These chemical shots have yields of 4,000 to 5,000 kg and were recorded by all stations, with high signal-to-noise ratios to about 200-250 km, and sometimes to greater distances. The recorders on these PNE profiles were at 10 km spacing (as was done for the recording of the PNEs), making these chemical data sparse in terms of resolution of crustal structure. The determination of detailed crustal structure usually requires recorders spaced at 2 km or less. Examples of these record sections for both PNE and chemical-source profiles may be found in Egorkin (1999a, 1999b).

The following chemical shot data have been digitized as of the year 2000: 80 shots on profile Quartz, 40-50 shots on Kraton, 40-50 on Kimberlite, and 40-50 on Rift. The following profiles have chemical shots yet to be digitized: Meteorite, Rubin I and II, and Batholith I and II. Additionally, since deep seismic profiling (refraction profiling) has been carried out in the FSU for more than 50 years, there are a large number of additional chemical shots that are not along PNE profiles that can be digitized. However, all data recorded since 1990 have already been digitized.

The GEON Center has established cooperative research programs with many international institutions, and has shared portions of their data based on common research interests. Among the institutions that have been involved are the U.S. Geological Survey, LLNL, GFZ-Potsdam, University of Karlsruhe, U. Copenhagen, and U. Wyoming. These cooperative agreements have generally involved financial support for the digitizing and duplication of data, the exchange of personnel, and joint publications.

3 Main features of crustal structure of the Former Soviet Union (FSU)
There have been many attempts to synthesize crustal structure both of the FSU and globally in terms of representative crustal cross-sections, and the most important parameters, including crustal thickness, mean crustal velocity, Pn velocity, depth of the Conrad discontinuity (defined as the seismic boundary between upper and middle/lower crust), and the thickness and mean velocities of main crustal layers (sediments, upper, middle and lower crust). This work has recently been done in the FSU to such an extent that new maps of depth to basement and crustal thickness have been produced (Figs. 5 and 6).

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 the depth to Moho, is between 30 and 50 km (Fig. 6). 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 can be quite complex and three-dimensional. 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 the velocity may increase gradually with increasing depth, producing no distinct intracrustal reflection.

CONCLUSIONS AND RECOMMENDATIONS

Any new information regarding the seismic structure of the Former Soviet Union would significantly improve the determination of seismic source parameters for the purposes of monitoring the Comprehensive Nuclear-Test-Ban Treaty. As much of the data for the FSU is now available in digital format, this wealth of new knowledge should be analyzed for greater insight and understanding into the crustal structure of the FSU.

REFERENCES

Braile, L.W., Keller, G.R., Mueller, S., and Prodehl, C., 1995. Seismic techniques. In: Olsen, K.H. (Editor), Continental rifts: Evolution, structure, tectonics. Elsevier, Amsterdam, pp.61-92.

Christensen, N.I. and Mooney, W.D., 1995, Seismic velocity structure and the composition of the continental crust: a global view, J. Geophys. Res., 100, 9761-9788.

Egorkin, A.V., 1999a. Deep Seismic Studies based on three-component recording of ground motions, Izvestiya, Physics of the Solid Earth, 35, 566-585.

Egorkin, A.V., 1999b. Study of the mantle on super long-range geotraverses, Izvestiya, Physics of the Solid Earth, 35, 630-645.

Giese, P., Prodehl, C., and Stein, A. (Editors), 1976. Explosion seismology in central Europe - data and results. Springer, Berlin-Heidelberg-New York: 429 pp.

Holbrook, W.S., Mooney, W.D., and Christensen, N.I., 1992. The seismic velocity structure of the deep continental crust. In: Fountain, D.M., Arculus, R., and Kay, R.W. (Editors), Continental lower crust. Development in Geotectonics, vol. 23, Elsevier, Amsterdam, 1-43.

Kosminskaya, I.P., 1968, The method of Deep Seismic Sounding of the crust and upper mantle, Nauka, Moscow.

Kostyuchenko, S.L., Egorkin, A.V., Solodilov, L.N., Danilova, E.G., and Volkhonina, T.V., 1999. Russian Ministry of Geology map series, GEON Centre, Moscow, Russia.

Mechie, J., Egorkin, A.V., Fuchs, K., Ryberg, T., Solodilov, L., and Wenzel, F., 1993. P-wave mantle velocity structure beneath northern Eurasia from long-range recordings along the profile Quartz, Phys. Earth Planet. Int., 79, 269-286.

Meissner, R., The Continenal Crust: A Geophysical Approach, 426 pp., Academic Press, London, 1986.

Mooney, W.D., 1989. Seismic methods for the determining earthquake source parameters and lithospheric structure. In: Pakiser, L.C., and Mooney, W.D. (Editors): Geophysical framework of the continental United States. Geol. Soc. Am. Memoir 172, 11-34.

Mooney, W.D., Laske, G., and Masters, T.G., 1998. Crust 5.1: a global crustal model at 5□ x 5□. J. Geophys. Res., 103, 727-747.

Pavlenkova N.I., 1973. Wave fields and crustal models of continental type (in Russian). Naukova Dumka, Kiev, 253 pp.

Pavlenkova, N.I., 1996. Crust and upper mantle structure in northern Eurasia from seismic data. Advances in Geophysics, 37, 1-133.

Prodehl, C., 1984. Structure of the earth's crust and upper mantle. In: K.-H. Hellwege (Editor in Chief), Landolt Börnstein New Series: Numerical data and functional relationships in science and technology. Group V, Volume 2a: K. Fuchs and H. Soffel (Editors), Physical properties of the interior of the earth, the moon and the planets, Springer, Berlin-Heidelberg, pp. 97-206.

Ryaboy, V.Z., 1966, Crust and upper mantle structure from DSS profile Kapet-Dag-Aral Sea, Soviet Geology 5, 159-162.

Soller, D.R., Ray, R.D., and Brown, R.D., 1992. A new global crustal thickness model. Tectonics, 1; 125-149.

Tanimoto, T., 1995. Crustal structure of the earth. In: Ahrens, T.J. (Editor), Global Earth Physics: A Handbook of Physical Constants. AGU Ref. Shelf, vol. 1, Am. Geophys. Un., Washington, D.C., p. 214-224.

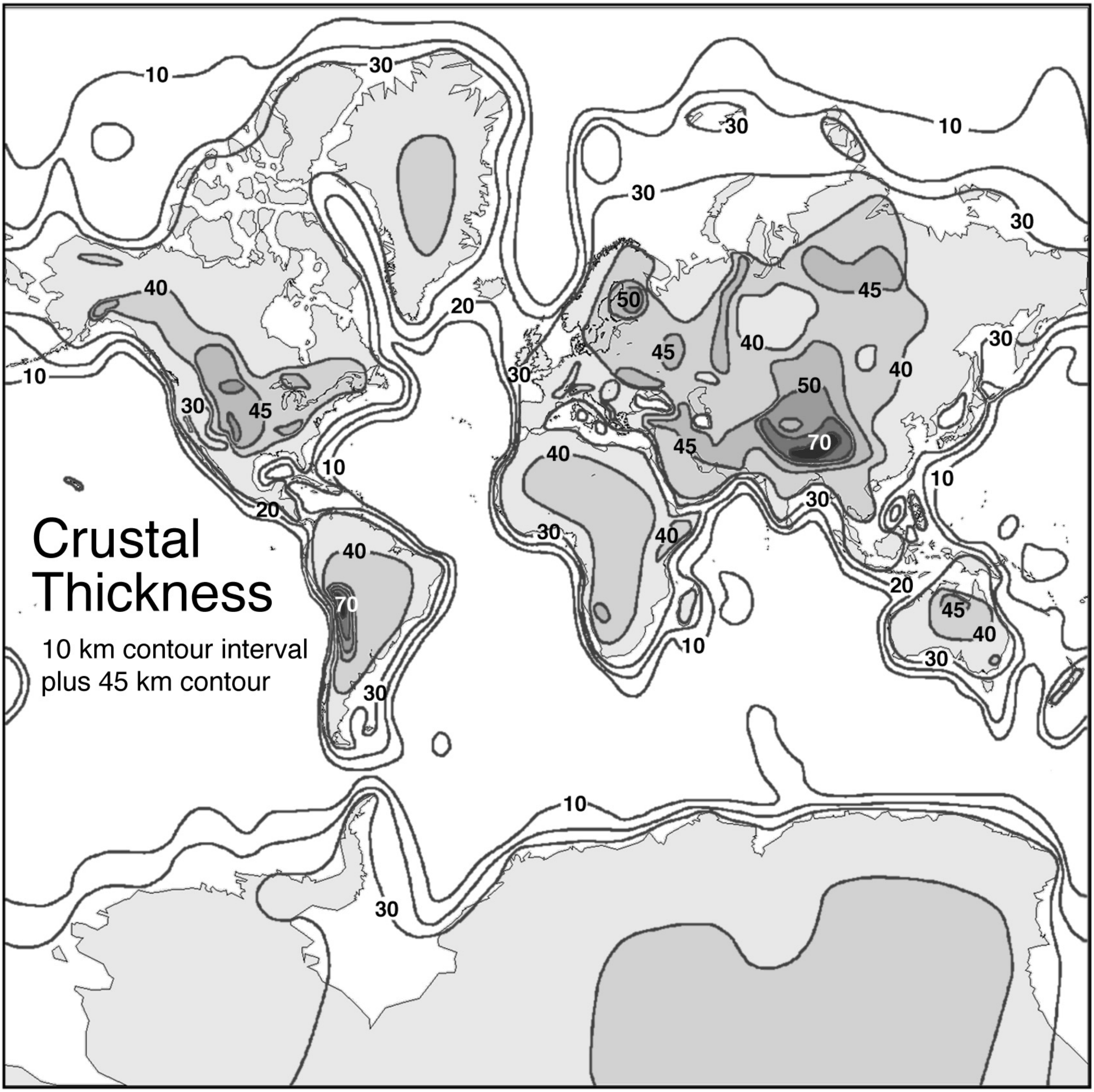

Figure 1. Mercator projection of crustal thickness based on seismic refraction profiles. (From Mooney et al, 1998.)

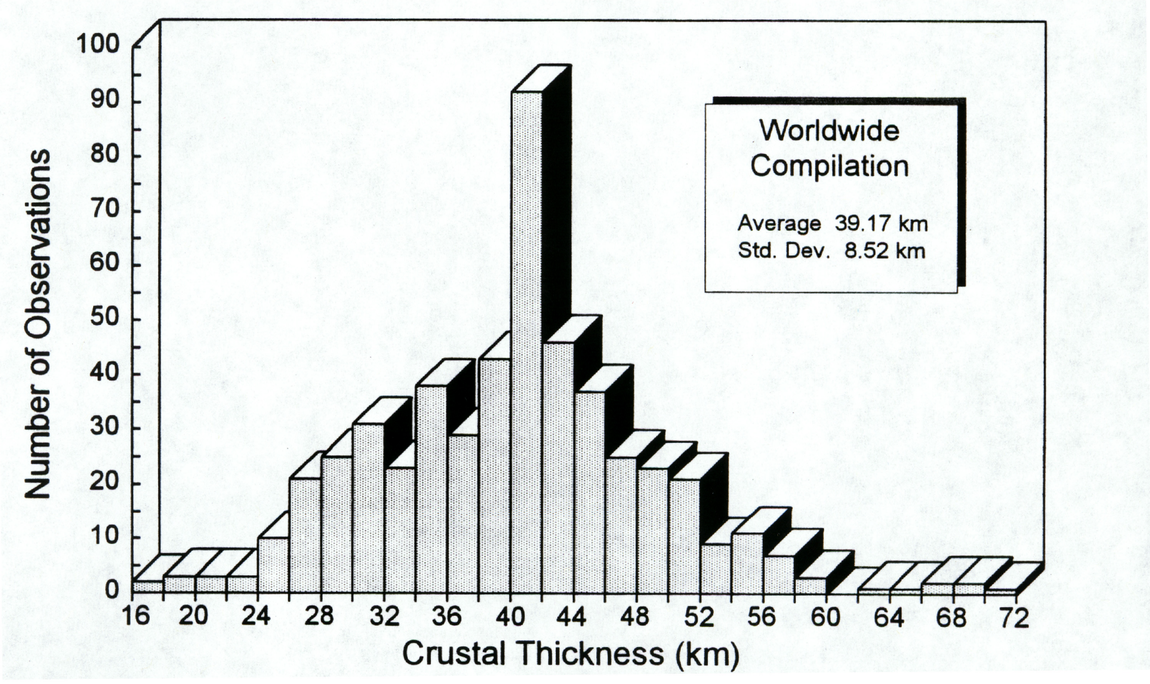

Figure 2. Histogram of thickness of continental crust. (From Christensen and Mooney, 1995)

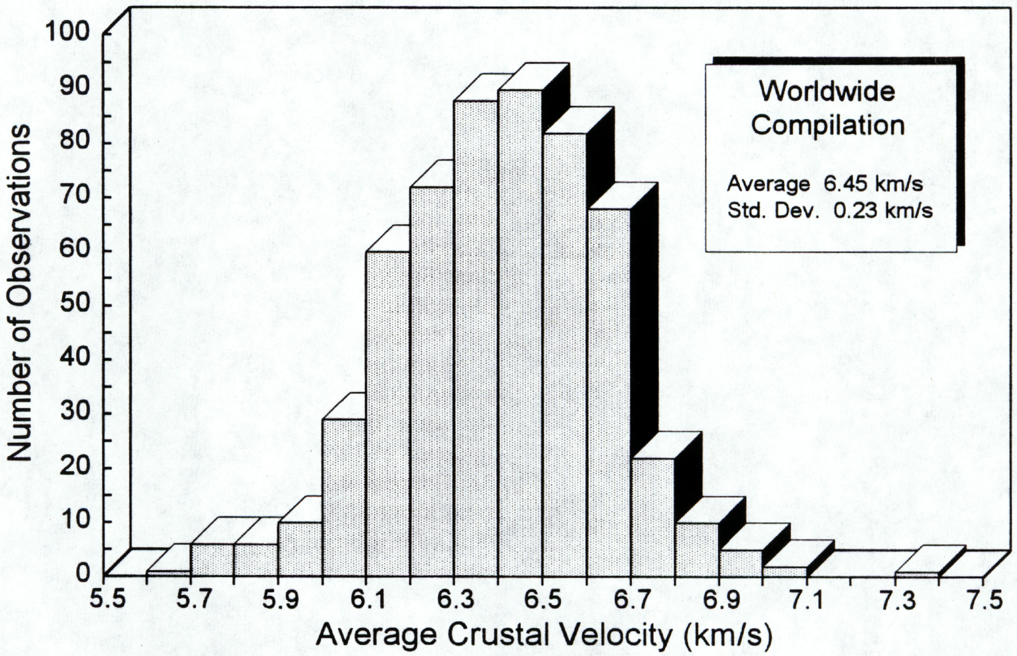

Figure 3. Histogram of average crustal velocity. (From Christensen and Mooney, 1995)

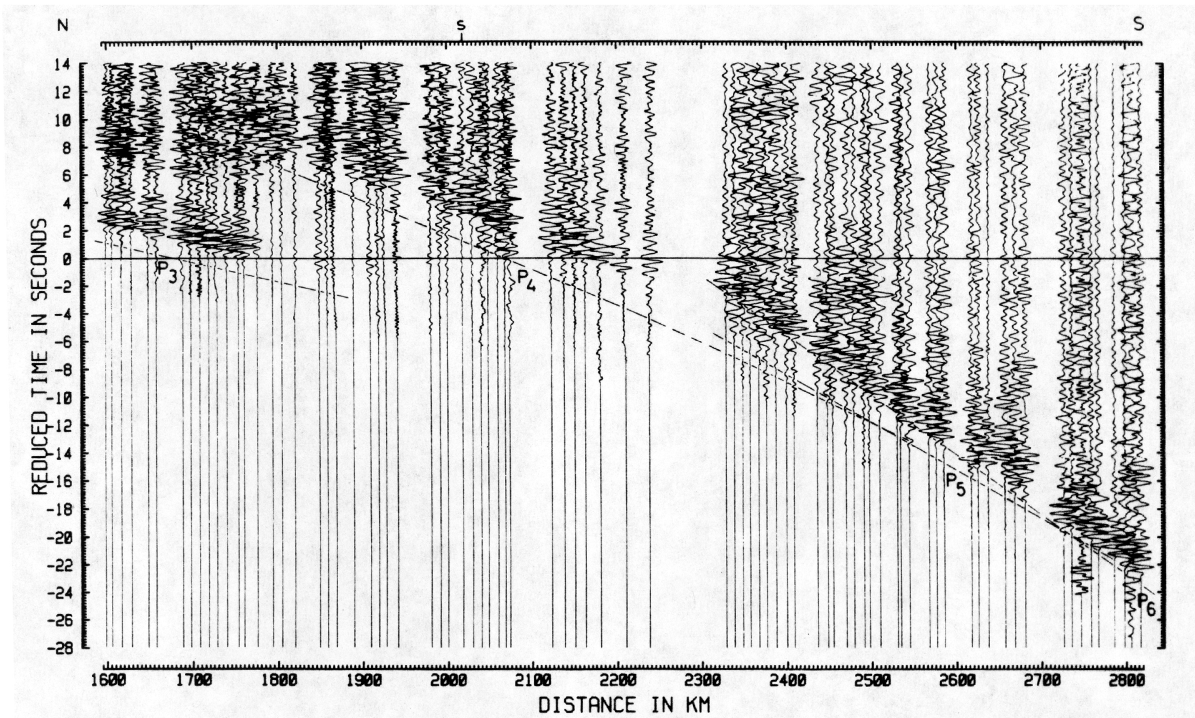

Figure 4. Trace normalized P-wave record section for the vertical component data from the northern PNE recorded along the Quartz profile to the south in the distance range 1600-282 km. Phase P3 from the upper mantle and phases P4, P5, and P6 from the mantle transition zone between 420 and 850 km depth.
(From Mechie et al, 1993)

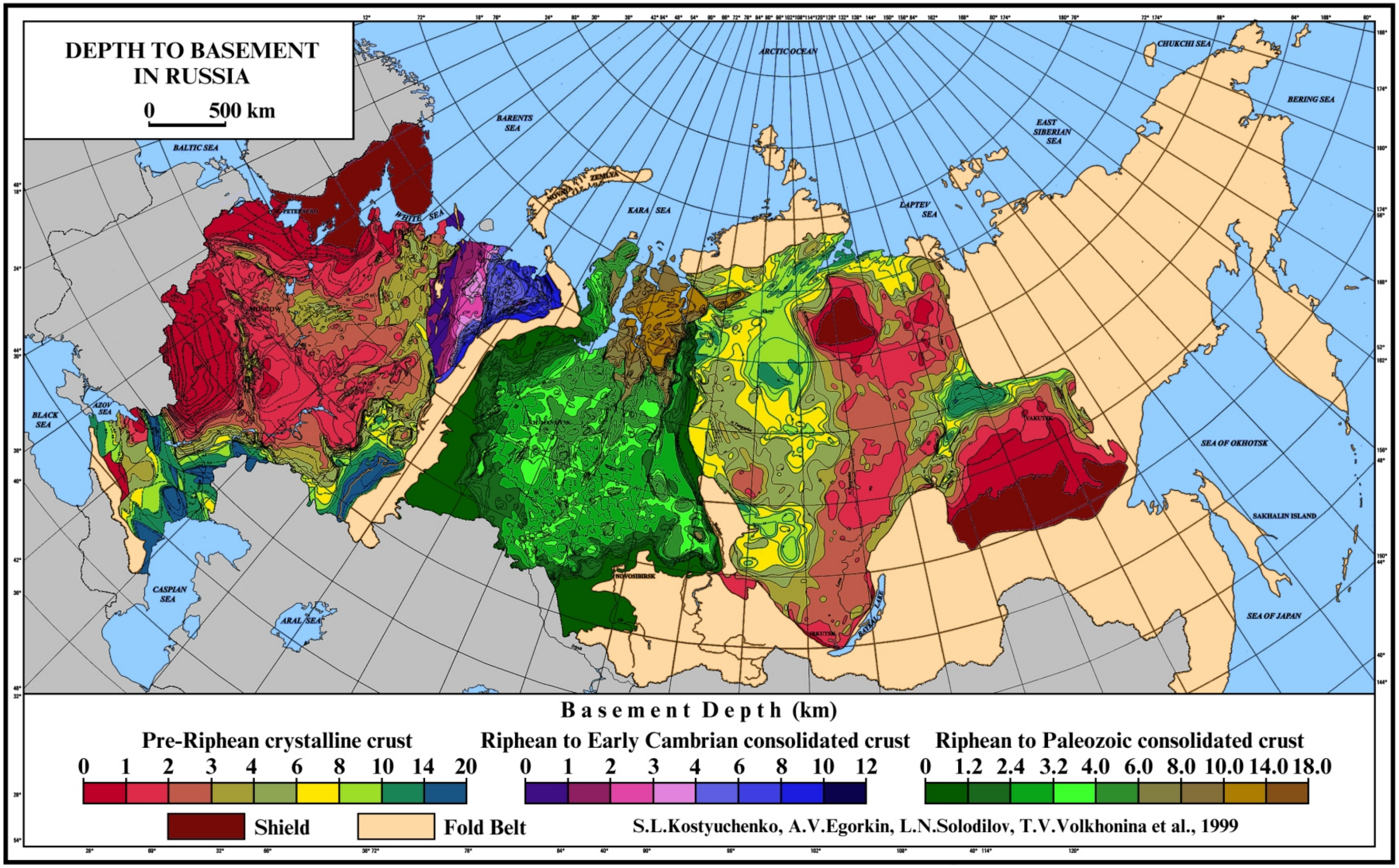

Figure 5. Newly updated map of Russia showing depth to basement produced by S.L. Kostyuchenk et al (1999) of the GEON Centre, Russian Ministry of Natural Resources, Moscow, in cooperation with the U.S. Geological Survey, Menlo Park, California.

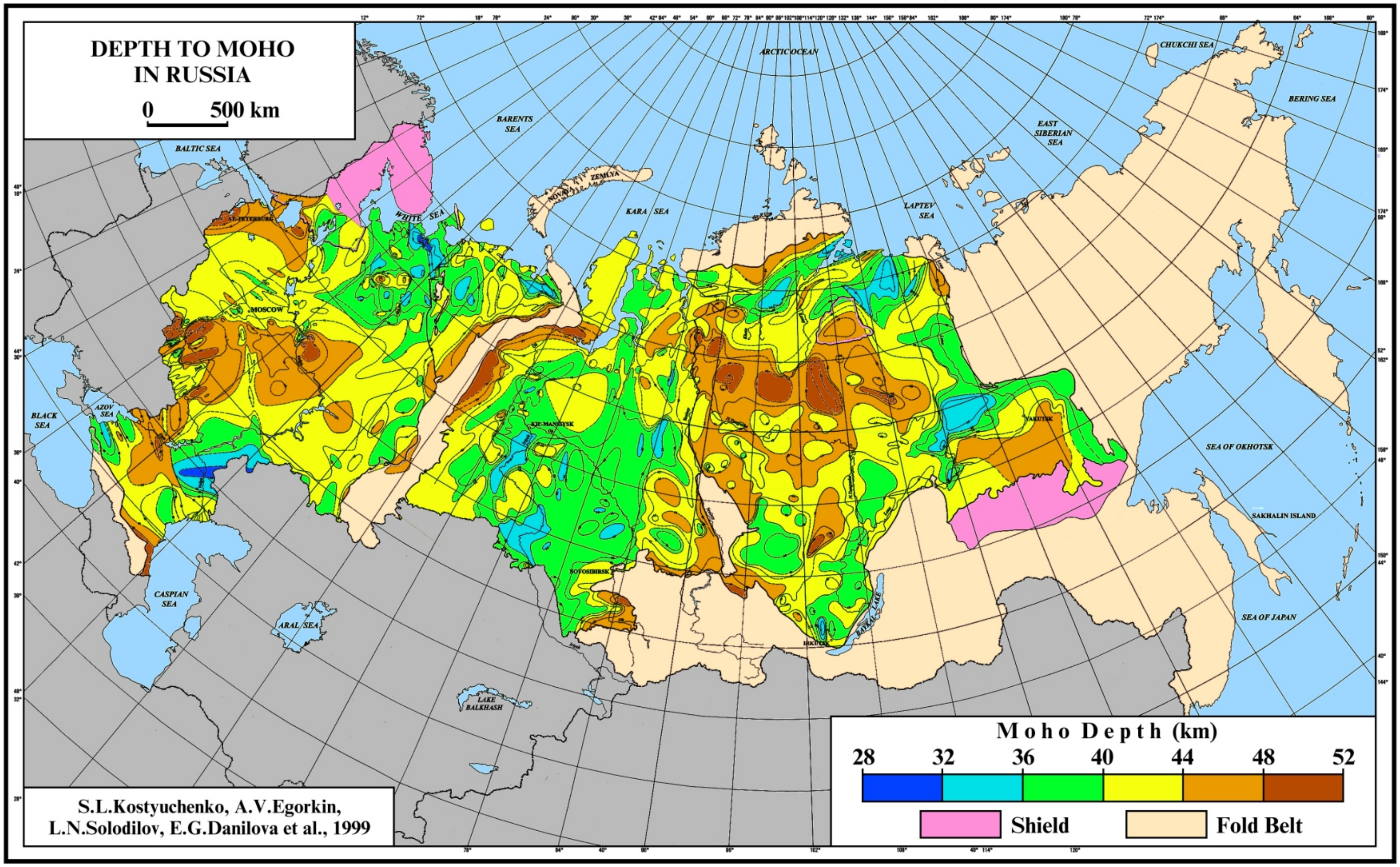

Figure 6. Newly updated map of Russia showing depth to Moho, produced by S.L. Kostyuchenk et al (1999) of the GEON Centre, Russian Ministry of Natural Resources, Moscow, in cooperation with the U.S. Geological Survey, Menlo Park, California.