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P Wave Velocities in the Mantle

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Abstract—Based on record sections of seismic waves from crustal earthquakes (with source depths of no more than 33 km) recorded by the worldwide network, traveltime curves of refracted and reflected short-period longitudinal waves traveling in the mantle are constructed. The mantle velocity cross section obtained from these traveltime curves, which agrees well with observed data, yields evidence of two lower velocity layers. The first layer, about 162 km thick, has an upper boundary at a depth of 132 km and corresponds to a 10°–12° gap in the traveltime curve. The second layer, 180 km thick, has an upper boundary at a depth of about 1300 km and corresponds to a gap in the traveltime curve at 50°.

INTRODUCTION

Jeffreys [1939] constructed the Earth's velocity model from traveltimes of earthquake waves, based on the tables compiled by Jeffreys and Bullen in 1935. Afterward, these tables were updated, and their final version was apparently published in 1967 [Jeffreys and Bullen, 1967]. Actually, Jeffreys constructed the first standard velocity model of the Earth.

Similar traveltime tables and related velocity models of the Earth were constructed by other researchers. The most comprehensive of them were constructed by Gutenberg and Richter [1939]. Moreover, Gutenberg [1959] proposed a velocity model of the Earth differing from the Jeffreys model, most noticeably in the structure of the upper mantle and the F zone of the Earth's core.

Based on new traveltime tables of *P* waves from earthquakes and nuclear explosions [Herrin *et al.*, 1968], Taggart and Engdahl [1968] constructed a velocity cross section of the mantle with an Earth's core radius of 3477 ± 2 km.

Inverting traveltimes of short-period *PcP* and *P* waves by the Backus–Gilbert method, Engdahl and Johnson [1974] obtained a velocity cross section of the mantle with an Earth's core radius of 3484.2 ± 2.9 km.

In order to determine the *P* wave velocities in the mantle and to refine the Earth's core radius, Burmin [1994] analyzed the most comprehensive traveltime dataset of body waves, using the method described in [Burmin, 1993]. He examined the smoothed traveltime curves of *P* and *PcP* waves constructed by Kogan [1980] and the observed traveltime data of the mantle that were obtained by Herrin *et al.* [1968] (*P* waves) and Taggart and Engdahl [1968] (*PcP* waves).

The PREM model of Dziewonski and Anderson [1981] was based on both traveltimes of body waves and data on the Earth's free oscillations.

One of the modern, widely acknowledged seismological models is the IASPEI91 model (International

Distribution of *P* and *S* wave velocities in the mantle

H, km	v_p, km/s	*H*, km	v_p, km/s	*H*, km	v_p, km/s
0.00	6.01	640.00	10.07	1500.00	12.20
5.22	6.01	663.17	10.34	1600.00	12.30
5.22	6.03	717.65	10.70	1700.00	12.45
41.13	6.10	742.41	10.82	1800.00	12.65
41.13	7.96	765.61	10.92	2000.00	12.80
116.82	7.93	794.12	11.01	2100.00	12.95
116.82	8.45	797.48	11.01	2200.00	13.05
132.42	8.46	805.03	11.02	2300.00	13.15
132.45	8.20	810.37	11.03	2400.00	13.25
294.54	8.50	877.64	11.18	2500.00	13.35
294.60	8.87	954.83	11.40	2600.00	13.50
301.77	8.89	970.03	11.43	2700.00	13.60
344.90	9.03	973.81	11.43	2750.00	13.62
412.59	9.10	983.91	11.42	2780.00	13.65
412.59	9.30	1035.36	11.45	2800.00	13.64
476.11	9.64	1148.94	11.64	2830.00	13.60
508.01	9.79	1287.92	11.86	2860.00	13.56
519.66	9.83	1288.00	11.50	2893.000	13.50
555.04	9.95	1397.00	11.95	2893.000	8.1
640.00	9.95	1400.00	12.05		

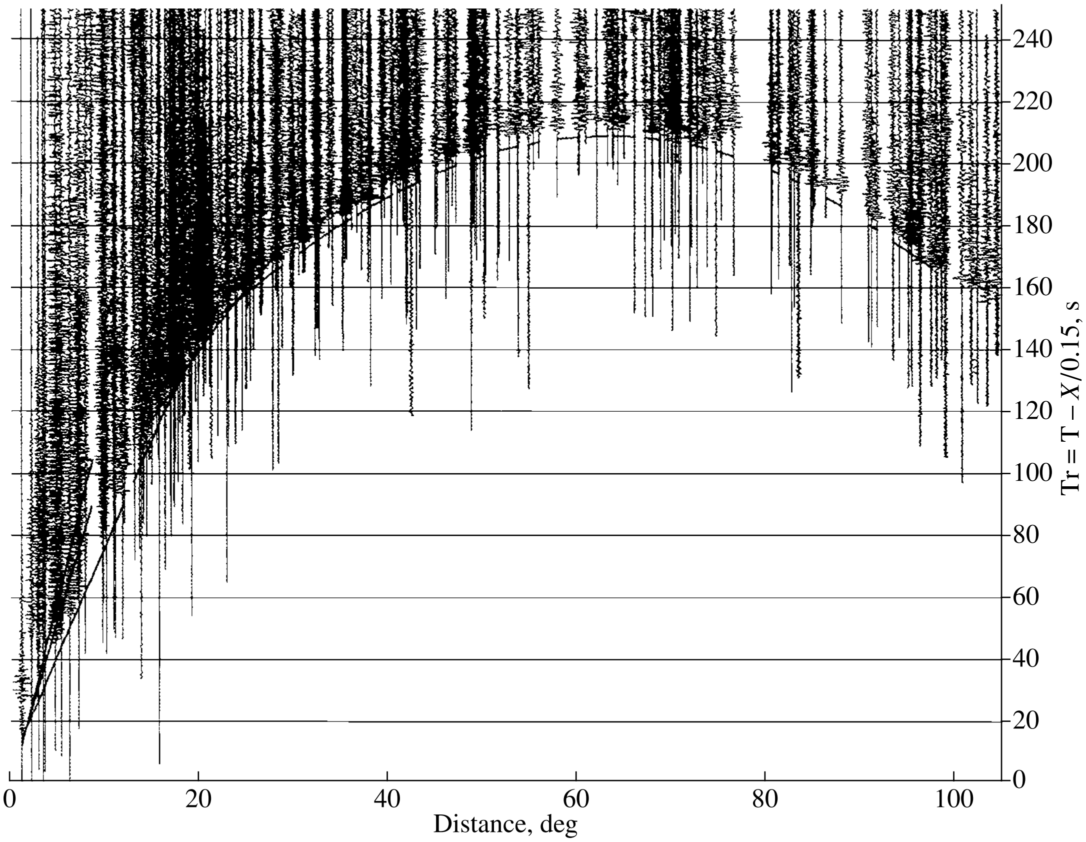

Fig. 1. Record section and the theoretical IASPEI91 mantle traveltime curve of refracted waves.

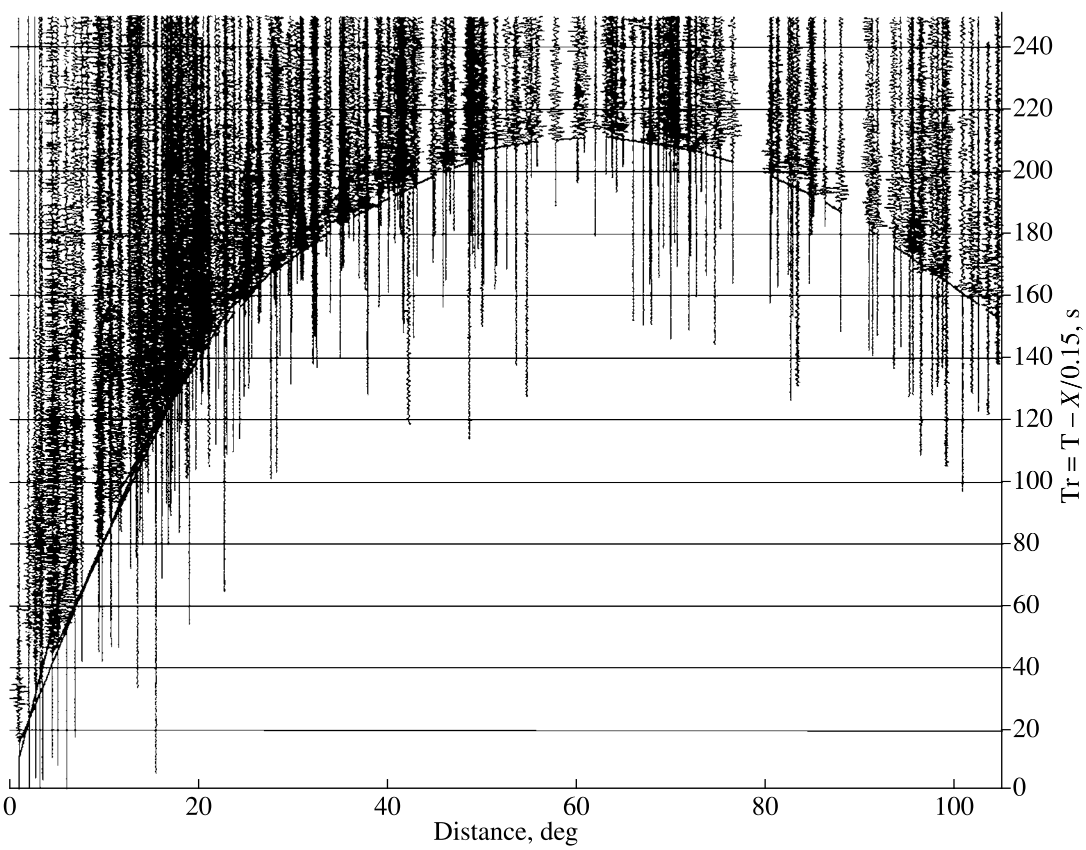

Fig. 2. Record section and the theoretical traveltime curve of refracted waves obtained from the new velocity model of the mantle.

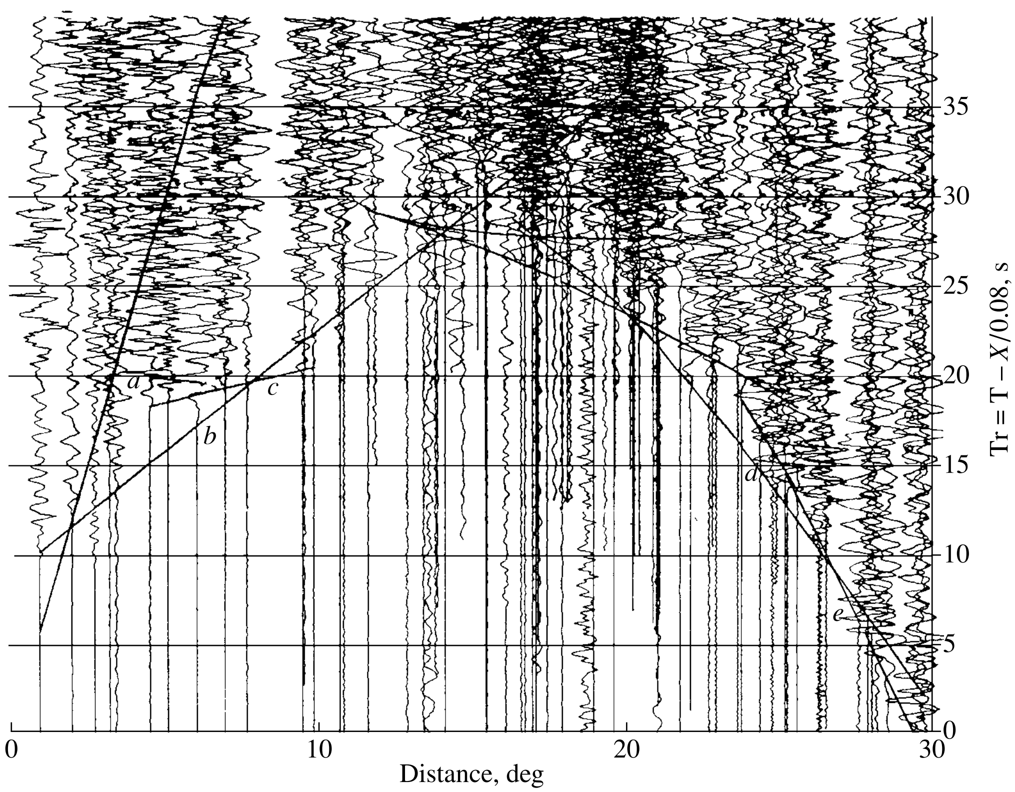

Fig. 3. Record section and theoretical traveltime curves obtained with a reduction to 0.08 deg/s from the new velocity model of the mantle at epicentral distances of 0°–30° and times of 0–40 s.

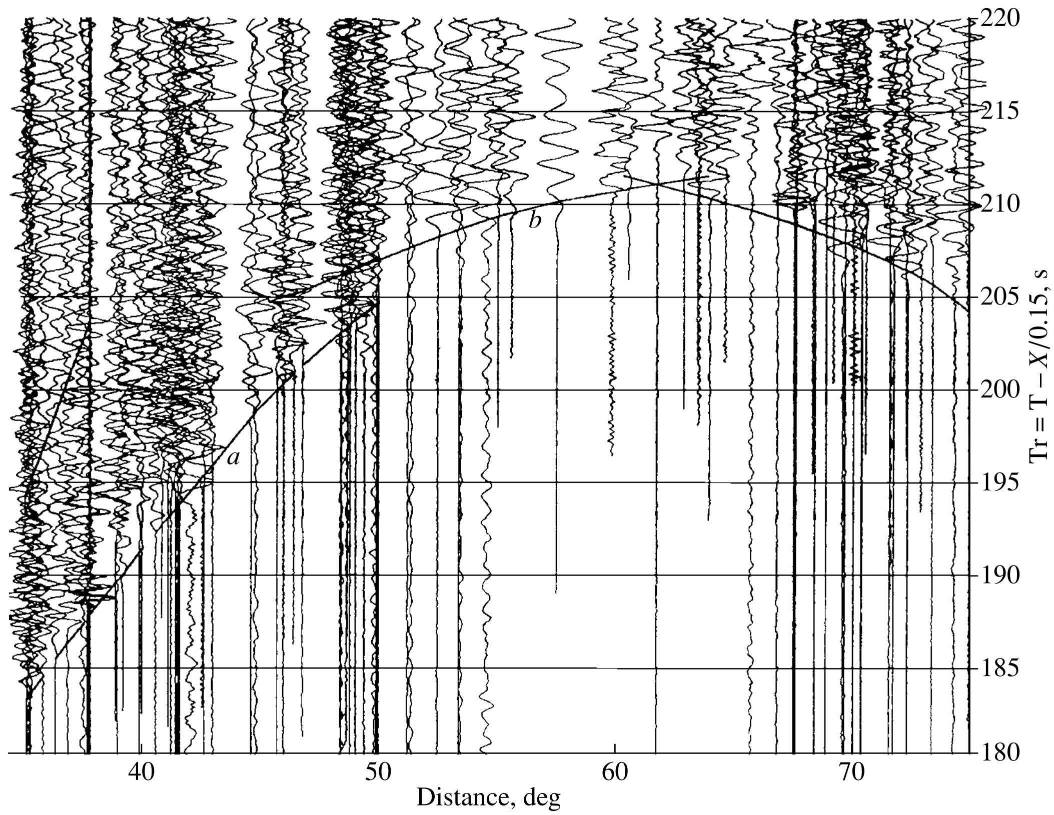

Fig. 4. Record section and theoretical traveltime curves obtained with a reduction to 0.15 deg/s from the new velocity model of the mantle at epicentral distances of 35°–75° and times of 180–220 s.

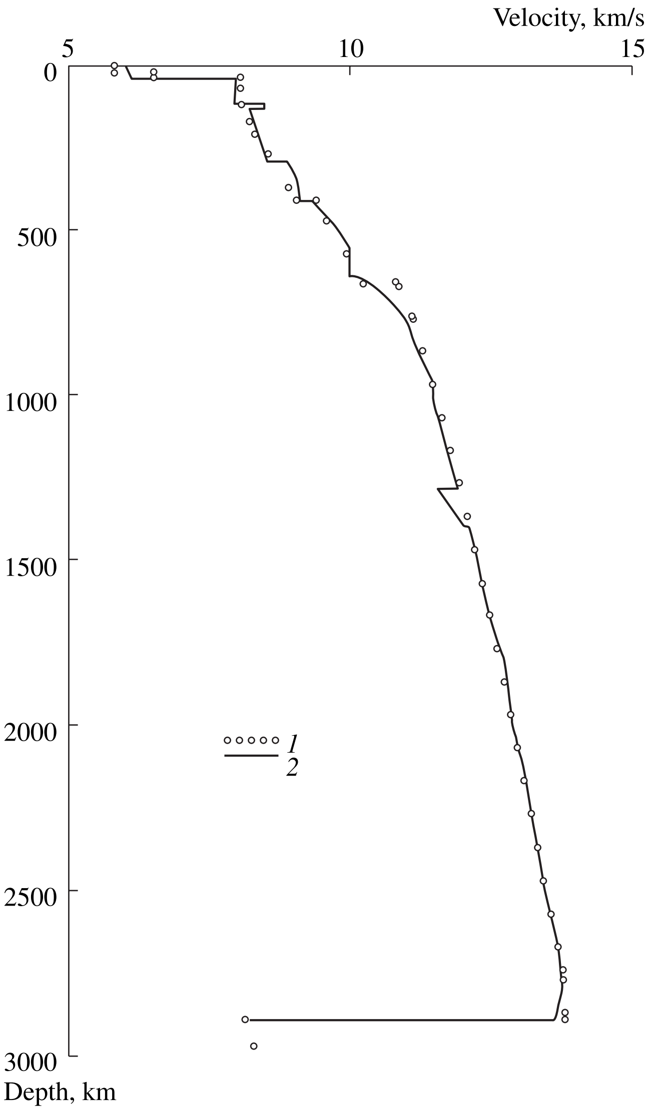

Fig. 5. Distribution of *P* velocities in the mantle: (*1*) IASPEI91; (*2*) velocity mantle model constructed in this work.

Association of Seismology and Physics of the Earth's Interior) [Kennett, 1992].

A feature common to all existing mantle velocity models is that traveltimes calculated on their basis are in poor agreement with *P* wave first arrivals in high frequency records, beginning from distances of 20° (Fig. 1). The reasons for this phenomenon are discussed below. Moreover, all of the aforementioned velocity cross sections are based on traveltime tables of seismic waves (as a rule, smoothed by an incorrect method (e.g., see [Arnold, 1968])), which makes it impossible to check the correctness of the wavefield interpretation (i.e., the construction of traveltime curves). This induced the author to revise the mantle velocity structure, using the up-to-date technique of traveltime data inversion [Burmin, 1994] and to compare theoretical traveltime curves with record sections of high-frequency (0.5–5.0 Hz) waves.

INITIAL DATA

The traveltime data to be interpreted were obtained from records of seismic waves crossing the mantle. Digital seismic data of the National Earthquake Information Center (NEIC) of the US Geological Survey gathered by the worldwide network from 1980 through 1987 were used. These data include records obtained with long-period, intermediate, and short-period seismographs. Records of short-period seismographs (a bandwidth of 0.1–6 Hz) were interpreted because of their higher resolution.

Records of all earthquakes with $M > 5.5$ that occurred in the aforementioned period at depths of no more than 33 km were examined, and seismograms providing the most distinct records of desired signals were chosen.

All records were filtered in the band 0.5–5.0 Hz and were reduced to the Earth's surface with due regard for traveltime differences and reverse migration. Data were represented as a record section of the vertical component reduced to 0.15 deg/s in the ranges of epicentral distances from 0° to 105° and times from 0 to 250 s (Figs. 1 and 2). Each record was normalized to the maximum amplitude in the trace. Overall, the record section contains 272 records.

RESULTS OF INTERPRETATION

Examination of the theoretical traveltime curve of *P* refractions calculated from the IASPEI91 model and superimposed on the record section (Fig. 1) clearly shows that, beginning from 20°, this curve lies below first arrivals. In order to bring the theoretical traveltime curve into agreement with experimental data in the depth interval 150–300 km, a lower velocity layer should be introduced. This makes the theoretical curve much more consistent with experimental data (Fig. 2) as compared with the IASPEI91 model.

Record sections and the theoretical traveltime curve of refracted waves reduced to 0.08 deg/s are presented in Fig. 3 for distances of 0° to 30° and times of 0 to 40 s. The traveltime curve consists of several branches, shown in the record section in Fig. 3. Branch *a* corresponds to a wave with an apparent velocity of 6.0–6.1 km/s. It should be noted that the initial part of the traveltime curve was obtained by averaging a few traveltime branches corresponding to crustal waves. In this case, the thickness of the crust is 41.1 km (Fig. 6). Branch *b* relates to waves traveling in the depth interval 41.1–116.8 km at a velocity of ≈7.95 km/s. Branch *c* relates to a rapidly attenuating wave traveling in a thin layer (116.8–132.4 km) at a velocity of 8.45 km/s (see Fig. 5). A gap in the traveltime curve corresponding to a 162.1-km-thick lower velocity (8.25–8.3 km/s) layer is clearly recognizable. Branches *d* and *e* relate to

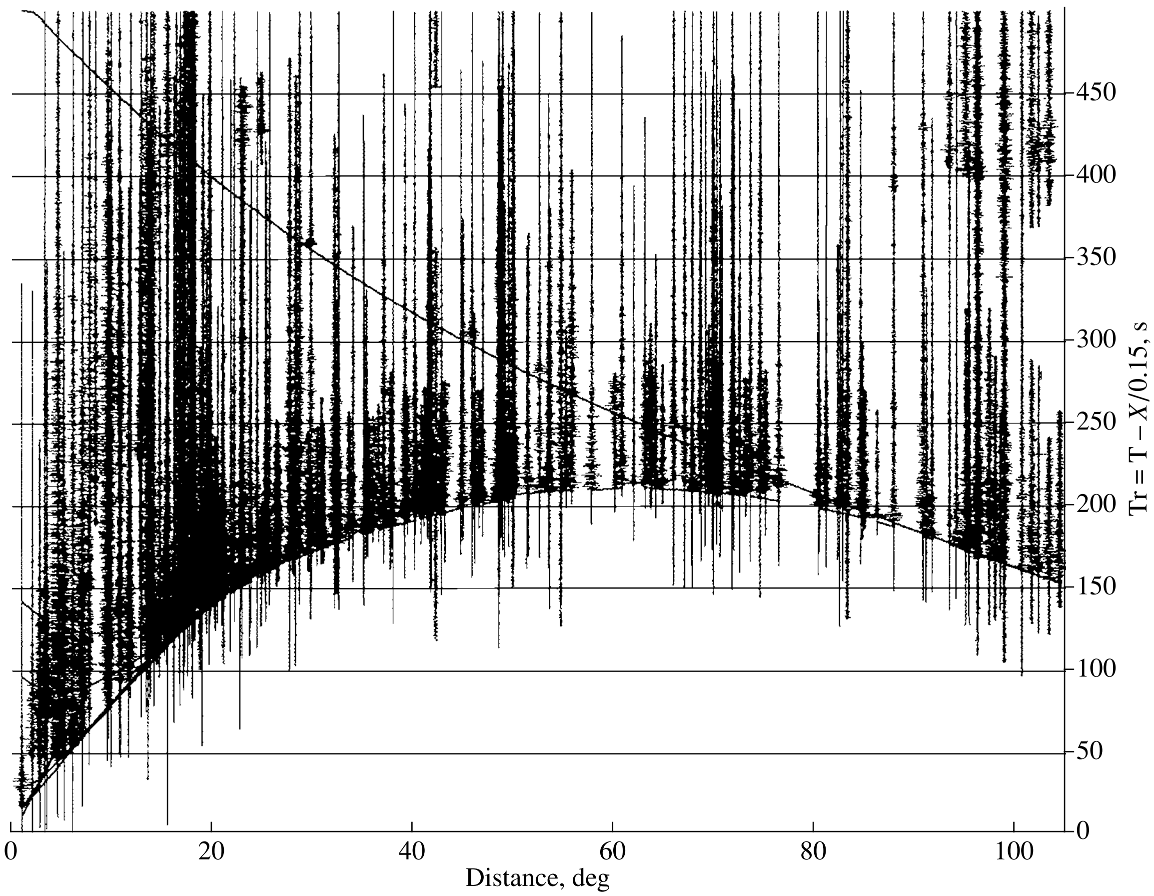

Fig. 6. Record section and theoretical traveltime curves of refracted and reflected waves obtained from the new velocity model of the mantle.

waves traveling below the lower velocity layer ($Z >$ 294.5 km); their apparent velocities range from 8.87 to 9.95 km/s. It is noteworthy that seismic records whose first arrivals are enveloped by branch *c* are obtained at various stations from widely spaced earthquakes, which is evidence for a global nature of the 10° gap in the traveltime curve. Note that the waveguide in the Gutenberg model is at approximately the same depths [Gutenberg, 1959]. Moreover, many models obtained on long profiles from nuclear explosions contain waveguides in the upper mantle, albeit at somewhat different depths [Mechie *et al.*, 1993; Ryberg *et al.*, 1998]. However, theoretical traveltime curves were not compared directly with record sections in these works. Although synthetic seismograms were calculated from these models, it is difficult to judge the validity of the waveguide parameters and depth estimated by these authors.

Similar to IASPEI91, the model developed here includes a velocity jump at a depth of 640 km, although it is somewhat smaller than in IASPEI91 and the velocity gradient under the discontinuity is higher up to a depth of about 1000 km (Fig. 5).

A record section reduced to 0.15 deg/s is presented in Fig. 4 for epicentral distances of 35°–75° and times of 180–220 s. A jump in the refraction traveltime curve (branches *a* and *b*) related to a waveguide with an upper boundary at a depth of 1288 km (Fig. 5) is well observable at an epicentral distance of 50°. As seen from Fig. 5, velocity curves nearly coincide below this waveguide down to the *D*'' zone. The velocity distribution in the *D*'' zone was determined in [Burmin, 1994] from the *PcP* traveltime curve.

The whole theoretical traveltime curve calculated from the new velocity model of the mantle in the 0°–105° range of epicentral distances is compared with record sections in Fig. 2. A brief but rather detailed description of the method used for the determination of the velocity curve is given in [Burmin, 2004].

Figure 6 shows the reflection traveltime curve, which agrees well with *PcP* first arrivals. We should note that the amplitude of the reflections is small despite considerable velocity jumps of both *P* and *S* waves at the core–mantle boundary. The reflections are unrecognizable in the majority of seismograms (Fig. 6). This is quite explicable if one takes into account that the reflection coefficient is directly proportional to the difference $v_1 \times \rho_1 - v_2 \times \rho_2$, where v_1 and ρ_1 are the velocity and density above the boundary and v_2 and ρ_2 are the respective values under the boundary [Savarenskii, 1972]. This difference for *P* waves is many times smaller than its value for *S* waves.

CONCLUSION

In our opinion, the use of traveltime tables alone, unsupported by the visualization of the entire wavefield, makes it impossible to check the validity of the wavefield interpretation and, hence, of the construction of a traveltime curve taking account of structural features of the real elastic medium. Disregard of the wavefield structure in the interpretation of observed data, i.e., in the construction of a velocity model, generally leads to disagreement between a theoretical traveltime curve and the wavefield, which cannot be recognized in comparison between the theoretical and experimental traveltime curves. Joint analysis of high-frequency (0.5–5.0 Hz) record sections of strong earthquakes and theoretical traveltime curves can provide a more detailed and substantiated velocity model of the mantle (see Fig. 5 and the table).

The inferred velocity model of the mantle is distinguished by the presence of two lower velocity layers in the upper part of the mantle. The first layer, about 162 km thick, has an upper boundary at a depth of 132 km and relates to a 10° gap in the traveltime curve. Since the record sections were constructed from data of various earthquakes obtained at various stations, this waveguide is global.

The second layer, 180 km thick, has an upper boundary at a depth of 1288 km and relates to a 50° gap in the traveltime curve. Although this gap is less expressed in the record section, it is well recognizable on a larger scale with a reduction to 0.15 deg/s (Fig. 4).

Unfortunately, due to significant attenuation of *S* waves, they are not traceable in high-frequency record sections. Apparently, special observations at high-resolution seismic stations are necessary to record high-frequency *S* waves. The resolution of instruments is known to be mainly controlled by the level of seismic noise (microseisms) at the recording site.

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REFERENCES

1. E. P. Arnold, "Smoothing Travel-Time Table," Bull. Seismol. Soc. Am. **58** (4), 1345–1351 (1968).
2. V. Yu. Burmin, *Numerical Methods of Seismic Traveltime Data Inversion* (Nauka, Moscow, 1993) [in Russian].
3. V. Yu. Burmin, "Determination of Seismic Wave Velocities in Mantle and the Earth's Core Radius from *P* and *PcP* Traveltimes," Vulkanol. Seismol., No. 4, 84–97 (1994).
4. V. Yu. Burmin, "Seismic Wave Velocities in the Earth's Core," Fiz. Zemli, No. 6, (2004) [Izvestiya, Physics of the Solid Earth **40** (2004)].
5. A. M. Dziewonski and D. L. Anderson, "Preliminary Reference Earth Model," Phys. Earth Planet. Inter. **25** (4), 297–356 (1981).
6. E. R. Engdahl and L. E. Johnson, "Differential *PcP* Travel-Time and the Radius of the Core," Geophys. J. R. Astron. Soc. **39** (33), 201–209 (1974).
7. B. Gutenberg, *Physics of the Earth's Interior* (New York, 1959; IL, Moscow, 1963).
8. B. Gutenberg and C. Richter, "On Seismic Waves," Beitr. Geophys **54**, 94–136 (1939).
9. E. Herrin, W. Tucker, J. Taggart, *et al.*, "Estimation of Surface Focus *P* Travel-Time," Bull. Seismol. Soc. Am. **58** (4), 1273–1291 (1968).
10. H. Jeffreys, "The Times of *P*, *S,* and *SKS* and the Velocities of *P* and *S*," Month. Not. R. Astron. Soc., Geophys. Suppl. **4**, 498–536 (1939).
11. H. Jeffreys and K. E. Bullen, *Seismological Tables* (London, 1967).
12. B. L. N. Kennett, *IASPEI 1991. Seismological Tables* (Research School of Earth Sciences. Australian National University, 1992).
13. S. D. Kogan, "Traveltimes of *P* Reflections from the Core, the Radius of the Core, and Properties of the Core/Mantle Transition Zone," Izv. Akad. Nauk SSSR, Fiz. Zemli, No. 12, 3–14 (1980).
14. J. Mechie, A. V. Egorkin, K. Fuchs, K., *et al.*, "*P*-Wave Mantle Velocity Structure beneath Northern Eurasia from Long-Range Recordings along the Profile Quartz," Phys. Earth Planet. Inter. **93**, 269–286 (1993).
15. T. Ryberg, F. Wenzel, A. V. Egorkin, and L. N. Solodilov, "Properties of the Mantle Transition Zone in Northern Eurasia," J. Geophys. Res. **103** (B1), 811–822 (1998).
16. E. F. Savarenskii, *Seismic Waves* (Nedra, Moscow, 1972) [in Russian].
17. J. Taggart and E. R. Engdahl, "Estimation of *PcP* Travel-Time and Depth to the Core," Bull. Seismol. Soc. Am**.** **58** (4), 1293–1303 (1968).