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GEOPHYSICS

The Possible Boundary of Phase Transitions at a Depth of 350 km in the Transition Zone between Continents and Oceans

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INTRODUCTION

Clear arrivals of secondary waves of unknown origin recorded in the bulletins as I after the first arrival of a P-wave were frequently noted in the processing the data of seismological observations. The time differences I–P and the corresponding epicentral distances Δ were determined for the earthquakes in the Kuril–Japan and Kuril–Kamchatka zones. The ratios of the secondary wave amplitudes I to P-waves $\left(K = \frac{A_I}{A_P}\right)$ were measured. It was assumed that coefficient K gives information about the velocity peculiarities of different flanks of the Kuril arc. Analysis of the graphs of I–P $= f(\Delta)$, $K = f(\Delta)$ demonstrated that the dominating number of graph points are confined to three curves corresponding the exchange-reflected and refracted SPP-waves from the boundary in the upper mantle at depths of 100, 350, and approximately 400 km.

We plotted a summary histogram for the recurrence frequency of I–P(n_{I-P}) values for the Kuril zone and coefficient ($n(K)$) for different flanks of the Kuril zone (Fig. 1) to clarify the boundary between two media in the upper mantle. The first histogram $n_{I-P} = f(\Delta)$ has maxima in the interval of epicentral distances 1100–1200, 2000–2200, and 2800–2900 km. In the histogram (Fig. 1), the central maximum is best pronounced in the interval of epicentral distances 2000–2200 km, which correspond to exchange-reflected SPP-waves from the boundaries at a depth of 350 km. The vertical bars of the histogram $n_{AI/AP} = f(\Delta)$ for the Kamchatka earthquakes are displaced to the left by 100–200 km compared with the peak intervals of histogram $n_{I-P} = f(\Delta)$ for the earthquakes in the Kuril–Japan region. It is likely to be explained by the higher location of the reflecting boundary or the relatively higher wave velocity in the Kamchatka–Kuril region than that in the neighboring Kuril–Japan region.

VELOCITY PECULIARITIES OF THE MEDIUM IN THE FAR EASTERN ZONE

The velocities of seismic waves slowly increase from the foot of the crust to a depth of 130 km where the gradient of velocity variation is $\beta = 1.5 \times 10^{-3}$ s^{-1} [1]. In the depth interval 200–300 km (h_{av} = 250 km) β =

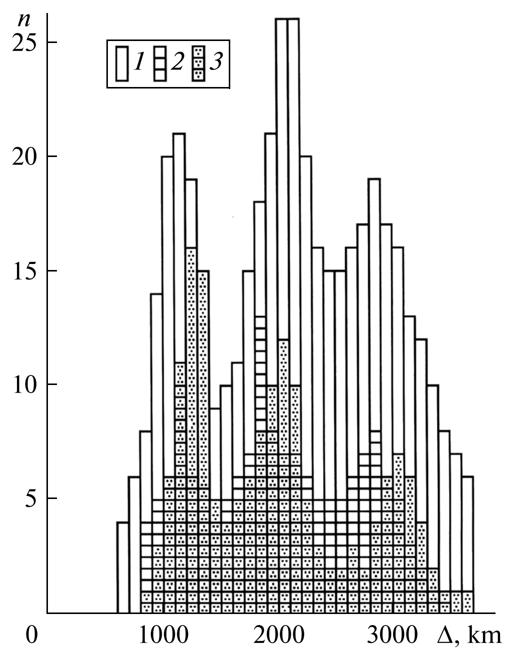

Fig. 1. Summary histograms of recurrences of secondary wave I arrivals and first arrivals of P-waves $n_{I-P} = f(\Delta)$ versus Far East earthquakes (*1*) and the ratio of the amplitudes of these waves (*2, 3*) depending on the epicentral distance [1, 10]. Notations: (*1*) recurrence of the Kuril earthquakes n_{I-P} of the differences I–P; (*2, 3*) recurrence of $n(K)$ ratios of the amplitudes of secondary waves to the amplitude of the first arrivals from earthquakes: (*2*) Kamchatka–Kuril region, (*3*) Kuril-Japan region.

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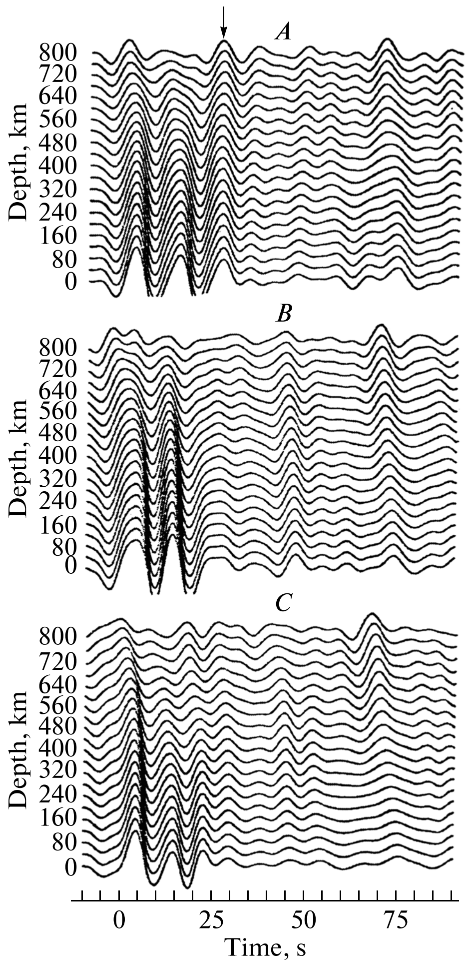

Fig. 2. Results of summation of transfer functions for the Primorye–Sakhalin region. Each path was obtained with the delays calculated for the test values of the source depth. Time delays are shown on the below. The time scale shows delays with respect to the longitudinal wave [7]. The arrow shows the boundary that the authors of [7] did not indicate at a depth of 300 km. *A*, *B*, and *C* are study regions: *A* is the zone of deep earthquakes; *B* is the zone corresponding to the horizontal location of plates; *C* is the zone without plates.

3.5×10^{-3} s^{-1},; in the depth interval 300–400 km (h_{av} = 350 km) $\beta = 3.6 \times 10^{-3}$ s^{-1}. Similarly for the depths 400–500 km (h_{av} = 450 km) $\beta = 6.6 \times 10^{-3}$ s^{-1}; and for 500–600 km $\beta = 9.5 \times 10^{-3}$ s^{-1}.

One can conclude from these data that the velocity gradient of P-waves begins to increase from a depth of 350 km becoming maximal at depths of 450 and 550 km. They are interpreted as the boundaries of phase transitions [2–4].

DATA THAT PROVIDE EVIDENCE ABOUT THE POSSIBILITY OF PHASE TRANSITIONS AT A DEPTH OF 350 KM

The authors of [5] revealed that in the case when a cold medium is located between two boundaries at 410 and 660 km, the upper boundary (410 km) moves up, while the lower one (660 km) moves down. If we assume that a cold zone is located at a depth of 350 km in the transition zone [6], the polymorphic boundary transition at 410 km can be displaced upwards by approximately 50 km.

The authors of [7] demonstrated that the previously existing method of determining the depths to the boundary has significant disadvantages. The reflection points used in [8] are located at a distance of several thousand kilometers from the source and receiver. In the case of strong lateral inhomogeneity, these factors can lead to significant errors in the estimates of the depth to the reflection boundary. In the investigations reported in [7], the authors used Ps-waves formed by exchange P at the seismic boundaries in the region of the receiver. The characteristic wavelengths and the distance to the exchange region can provide resolution one order of magnitude higher than in the previous works.

These Ps-waves are distinguished in the joint processing of the records from a large number of remote earthquakes. Each single record was projected on the SV and P axes, while the SV-component was standardized with the P-component. It is generally accepted to call the standardized SV-component the transfer function. Such a standardized function has a high resolution for the determination of the depths to the boundary. The results of summing of the transfer functions are shown in Fig. 2. In order to determine the transfer functions, we used the analog records of broadband SK and SKD seismographs in Russia and broadband stations in China.

Transfer functions give the possibility to use a large number of remote earthquakes for scientific research, which allows us to determine the depth to the boundaries with a high accuracy. For example, investigators solved a problem about the dynamics of the lithosphere plate motion in this zone in the band of deep-focus earthquakes, which provides evidence that this method is very accurate. The authors managed to divide the study region into three bands and demonstrate that there is no lithospheric plate in zone *C*; in zone *B*, it is characterized by a gentle slope; and in zone *A*, the plate is not flat (Fig. 2). However, while analyzing the efficiency of transfer functions, the authors of [7] did not notice a clear intrusion in the zone at a depth of 300 km, which is especially important for the Far Eastern transition zone from the ocean to the continent.

The other group of scholars [9] conducted unique observations in the region of Japan using the GEOSCOPE system and the method described in [7] (the Inuyama station). The authors recorded the arrival times of waves in a wide band and traced lateral variations in the activated zone with a dominating period of 7–10 s based on the inversion with S-waves. A total of 50 summarized sections with a high signal-to-noise ratio was obtained in the region of the station using different methods. It was shown on the basis of these data that one of the most pronounced boundaries is observed at a depth of 350 km (Fig. 3).

Anomalous data of the velocity section plotted with the account for all requirements can provide evidence about the possibility of the polymorphic nature of the boundary at a depth of 350 km. It is noted in [10] that the velocities of P-waves are subjected to a sharp jump from 8 to 8.6 km/s at a depth of 360 km.

It is noted that an accumulation of hypocenters is observed within the seismic focal zone at a depth of 350 km, where the velocity increase occurs up to 0.6 km/s [1].

The majority of petrologists determine the depth range from 350 to 410 km in the chemical–mineralogical model of the Earth [3, 11] as the phase transition zone (olivine $\alpha \rightarrow$ spinel β). At the relatively low temperatures of the upper mantle in this interval, the zone of polymorphic transformations is extended by depth [2]. The main minerals in the pyrolite model of the mantle (61% of olivine, 25% of pyroxenes, and 14% of garnet) are subjected to a series of transformations under increased pressure [12]. For example, pyroxene and garnet from a depth of 350 km pass through a series of transformations to majorities with the garnet structure and ilmenite [4]. During these transformations the slope of the equilibrium curve $\frac{dP}{dT} = \gamma_P$ (P is pressure, T is temperature) is called the specific heat of the phase transition determined by heat Q released during the phase transitions. If the transition is in equilibrium, the dependence is $\frac{dP}{dT} = \frac{Q}{T(v_2 - v_1)}$, where v_2 and v_1 are the volumes in the beginning and at the end of transitions and T is the temperature of isothermal transition. This equation known as the Clausius–Clapeyron relation is expressed in [13] through the variations in the matter density ρ as $\gamma_P = \frac{Q\rho^2}{T\Delta\rho}$. Phase transition α–β in the mentioned depth interval is characterized by a denser consolidation ($\Delta\rho > 0$), a decrease in the potential energy, and heat release. The slope of the equilibrium curve γ_P is approximately equal to 2 MPa/K [3]. The transition is accompanied by a sharp density change $\frac{\Delta\rho}{\rho} \approx 0.07$ [9]. In this case, we can calculate the heat released during this phase transition. Knowing the physical characteristics of the upper mantle matter in the interval of 350–400 km, where the pyrolite density is 3.31 g/cm^3, the density change during the phase transition is 0.23 g/cm^3, and the temperature is 1400°C [2, 6], we obtain the heat of phase transition as $Q \approx 59$ J/g. These

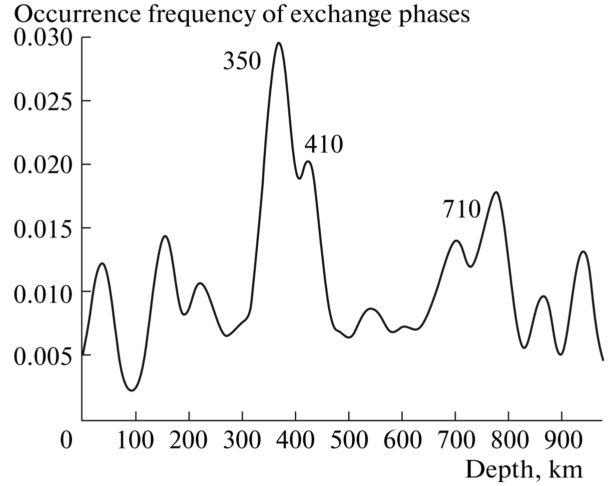

Fig. 3. A histogram of the occurrence frequency of PSv-waves [9] plotted using the method described in [2] and the GEOSCOPE system (the window is within 7–60 s, filtration with an interval of 25 km) based on the data of the Inuyama station (Japan).

values characterize the upper part of the C zone from a depth of 350 km under the deep depressions of the Sea of Japan and the Sea of Okhotsk.

CONCLUSIONS

The boundary at a depth of 350 km is reliably distinguished based on methods from different fields of geophysics. This boundary can have various physical nature (inversion of seismic velocities, boundary of polymorphic transformations, anomaly of deep temperatures, etc.).

As a result of our research, we distinguished the boundary of phase transitions at a depth of 350 km under the Far Eastern marginal seas, which coincides with the empirical data reported in [9] that showed significant elevation of the boundary from 410 to 360 km.

REFERENCES

1. R. Z. Tarakanov, *New Hodographs for P and S-P-waves in the Far East Region* (Far East Branch, RAS, Vladivostok, 2005) [in Russian].
2. V. N. Dobretsov, A. G. Kirdyashkin, and A. A. Kirdyashkin, *Deep Geodynamics* (Izd-vo Siberian Branch, RAS, filial “Geo,” Novosibirsk, 2001) [in Russian].
3. V. N. Zharkov, *Internal Structure of the Earth and Planets* (Nauka, Moscow, 1983) [in Russian].
4. W. R. Poirier, *Introduction to the Physics of the Earth’s Interior* (Univ. Press, New York, 1991).
5. S. Lebedev, S. Chevrot, and R. D. Van der Hilst, Science **296**, 1300–1302 (2002).
6. V. V. Gordienko, A. A. Andreev, S. K. Bikkenina, L. L. Van’yan, O. V. Veselov, V. V. Erokhov, E. G. Zhil’tsov, O. V. Zavgorodnyaya, S. K. Kulik, I. M. Logvinov, A. M. Lyapishev, E. R. Martanus, Yu. F. Moroz,

V. V. Soinov, V. N. Solov'ev, and R. Z. Tarakanov, *Tectonics of the Pacific Margin of Asia* (Far East Branch, RAS, Vladivostok, 1992) [in Russian].

7. L. P. Vinnik, G. L. Kosarev, and N. V. Petersen, Dokl. Akad. Nauk **353** (3), 379–382 (1977) [in Russian].
8. P. M. Shearer and T. G. Masters, Nature **355**, 791–796 (1992).
9. J. L. Thiot, J. P. Montagner, and L. Vinnik, Phys. Earth Planet. Inter. **108** (1), 61–80 (1998).
10. K. L. Kaila, V. G. Krishna, and H. Narain, Bull. Seismol. Soc. Amer. **61**, 1549–1570 (1971).
11. A. E. Ringwood, *Composition and Petrology of the Earth's Mantle* (McGraw-Hill, New York, 1975).
12. V. A. Magnitskii, *Internal Structure and Physics of the Earth* (Nauka, Moscow, 2006) [in Russian].
13. Landau, L.D. and Lifshits, E.M., *Statistical Physics* (Nauka, Moscow, 1964) [in Russian].
14. V. P. Trubitsyn, A. N. Evseev, A. A. Baranov, and A. P. Trubitsyn, Izv. Phys. Solid Earth **44** (8), 603–614, (2008).

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