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A POLYASTHENOSPHERIC MODEL OF THE EARTH'S UPPER MANTLE ACCORDING TO SEISMOLOGICAL DATA

(Presented by Academician A. V. Peive, 21. IX. 1966)

The basis for constructing the model was provided by numerous instrumental observations of earthquakes in the Kuril-Japan zone (as well as strong earthquakes of the terrestrial globe). A joint analysis was carried out of the following quantities, varying with depth h or distance Δ (Fig. 1): 1) derivatives of empirical hodographs; 2) maximum earthquake magnitudes; 3) velocities of longitudinal waves, and also of channel waves P_a; 4) amplitudes of body waves; 5) ratios of velocities $v_P : v_S$ and amplitudes $A_{\max} : A_P$.

The first information on the presence in the upper mantle of the Kuril-Japan zone of two layers with reduced velocity was obtained in the analysis of the derivative of an empirical hodograph (1). The increase of the derivative (Fig. 1a) at epicentral distances of 450-600 km, 850-1000 km, and 1250-1400 km can apparently be explained by the fact that, into the relative shadow zones formed by reduced-velocity layers, waves of another type enter (in particular, waves reflected from subcrustal boundaries), with larger travel times than for direct waves.

In Fig. 2 are plotted all the strongest earthquakes of the terrestrial globe known from published data, with magnitude $M \geq 7$, for the period 1896-1962. The hatched band in Figs. 1b and 2 is the variation with depth of the magnitude of the strongest earthquake observed during this period. As a first approximation, it may apparently be assumed that the graph $M_{\max} = f(h)$ of the "limiting" magnitude characterizes the variation with depth of the strength limit of the rocks composing the mantle. Against the background of decreasing limiting magnitudes, distinct depressions of the curve $M_{\max} = f(h)$ are observed at depths of 60-80, 110-150, 230-300, and 400-470 km, indicating the presence in the mantle at these same depths of layers of weakened strength (asthenospheres). At approximately these same depths, Bot and Duda (2) noted depressions in the curve of released stresses.

Figure 1

Figure 1: Figure 1

The velocities v_P of longitudinal waves (Fig. 1b) were determined from observations of 63 Kuril-Japan earthquakes by means of the Gutenberg method (^{3}), with a mean error of $\sim \pm 0.15$ km/sec. Our data on the velocities of longitudinal waves are in general consistent with Gutenberg’ s data obtained for the Japan region (^{3,4}). The band of possible velocity sections proposed by the authors, with a width of ≈ 0.2 km/sec, was drawn taking Gutenberg’ s determinations into account. Along this band, four reduced-velocity layers are clearly distinguished: a_1 ($h = 60$-90 km), a_2 (120-160 km), a_3 (220-300 km), and a_4 (370-430 km), which practically coincide with the asthenospheres outlined by the curve $M_{\max} = f(h)$.

Reflecting boundaries in the upper mantle noted by a number of investigators are, in most cases, close to the roof or the floor of the asthenospheric layers identified by us. The waveguide character of these layers is indicated by the channel waves P_a and S_a distinguished on seismograms ($^{4-10}$). Usually two preferential values of the velocities of the waves P_a (8.0-8.06 and 8.3-8.35 km/sec) and S_a (4.4-4.45 and 4.5-4.58 km/sec) are noted. The formation

Fig. 1. Comparison of empirical data.
a –variation of the derivative of the traveltime curve for longitudinal waves with distance; α_i correspond to asthenospheric layers of reduced velocity. **b** –variation of the maximum magnitude of earthquakes with depth: 1 –probable band of values of $M_{\max}$; 2 –envelope of maximum magnitudes. **c** –velocity section for longitudinal waves: 1 –authors’ data; 2-5 –Gutenberg’ s data (2, 3 –reliable; 4, 5 –less reliable); 6 –band of possible velocity sections proposed by the authors; 7, 8, 9 –velocities of channel waves: according to Press and Ewing (6), Caloi and Gutenberg (5, 10), Magnitskii and Khorosheva (7); 10 and 11 –velocity sections according to Gutenberg and Jeffreys. **d** –amplitudes of the first displacements of longitudinal waves. **e** –logarithms of the ratios of maximum amplitudes to the first displacements in the longitudinal wave. **f** –amplitude curves for distances of 1500-3000 km (after Vayek and Shtel’ tsner (11)): 1 –for sH waves; 2 –for pH waves. **g** –band of transition curves.

the former is probably due to the asthenosphere a_2, the latter to a_3. Channel waves are observed over a wide range of epicentral distances (from 7 to 175°), which indicates the global extent of the asthenospheres as spheroidal mantle layers.

The composite amplitude curve $A_1 = \lg A_P = f_2(\Delta)$ of the first displacement in the longitudinal wave (Fig. 1e) was constructed from observations of 9 shallow Kuril-Japanese earthquakes. The points in the graph show values averaged over 25 adjacent, in Δ, amplitudes. The troughs of the amplitude curve at distances of about 450-600, 800-950, and 1200-1600 km are zones of relative shadow and

Figure 2

Figure 2: Figure 2

are apparently caused by a decrease in velocities in the layers a_0, a_1, and a_2. Similar troughs are also noted on the Vaněk and Stelzner curve (^{11}), indicating the presence in the mantle also of layers a_3 and a_4 (Fig. 1e).

The curve $\gamma = f_3(\Delta)$ (Fig. 1d) of the logarithm of the ratio of the maximum displacement $A_{\max}$ (with the main contribution from transverse waves) to the first displacement in the longitudinal wave has extrema at practically the same distances as the curve A_1. This makes it possible to suppose that: 1) the asthenospheres are waveguides not only for longitudinal waves but also for transverse waves; 2) transverse waves are absorbed in the asthenospheres more intensely than longitudinal waves, which may be associated with the increased plasticity of the material of the asthenospheric layers.

The band of transition curves $\Delta = \varphi(h)$, relating the distance Δ at which the ray emerges at the surface to the depth h of its maximum penetration (Fig. 1zh), was constructed from the velocity section, com-

Fig. 2. Change in the maximum magnitude of earthquakes with depth. **1–3** – strong earthquakes: **1** –of the Pacific belt excluding the Kuril-Japanese zone; **2** –of the Kuril-Japanese zone; **3** –of other seismically active regions of the globe; **4** –probable band of values of $M_{\max}$.

···a compromise among the Jeffreys, Gutenberg, and Wadati sections. It makes it possible to establish, as a guideline, what depth in the mantle is mainly responsible for the nonmonotonicity in the dynamic and kinematic characteristics of waves observed at distance Δ. From Fig. 1 it is evident (see arrows) that the troughs of the amplitude curve correspond to asthenospheric layers of reduced velocity, and the rises to layers of increased velocity.

The ratio of the velocities of longitudinal and transverse waves at the depth of the earthquake focus was determined from the tangent of the inclination angle of the Wadati graph at the mean epicentral distance corresponding to the point of inflection of the hodographs of the P and S waves. Observations of 67 Kurile-Japanese earthquakes with focal depths of 30-650 km were used. Against the background of an increase from 1.74 (at the base of the crust) to 1.84 (at $h = 650$ km), the velocity ratio has maxima at depths $h = 50$; 85; 130 and 250 km (the axes of the waveguides), equal respectively to 1.84; 1.86; 1.83 and 2.03. Elevated values of v_P/v_S (1.81-1.87) in the asthenospheres are also noted from observations of channel waves P_a and S_a $^{(4-10)}$. Minimum values of the ratios are observed at depths of 60; 110; 150 and 270 km and are respectively 1.74; 1.64; 1.7 and 1.7.

It may apparently be assumed, while remaining within the framework of the concept of the mantle medium as elastic and isotropic, that in the asthenospheres the shear modulus μ decreases sharply; as a result, the velocities of both types of body waves decrease in them,

$$v_P = \sqrt{(\lambda + 2\mu)/\rho}, \qquad v_S = \sqrt{\mu/\rho}$$

and their absorption increases, to a greater degree for transverse waves. Increased absorption of transverse waves in the Kurile–Japanese zone at depths of 60–100 km is also indicated by other authors (12,13).

Thus, the upper mantle within the Kurile–Japanese zone (and possibly the entire Pacific ring) may be represented as consisting of alternating layers of increased and decreased strength. The asthenospheric layers are characterized by reduced seismic-wave propagation velocities, increased plasticity of the material, and reduced seismic activity. The layers alternating with the asthenospheres possess the opposite properties. It is assumed that the most probable regions for magma formation are the areas where asthenospheres intersect the zone of deep faults.

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