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ON THE GRADIENTS OF ELASTIC-WAVE VELOCITIES AND TEMPERATURE BENEATH THE MOHOROVIČIĆ DISCONTINUITY

(BLACK SEA, INDIAN OCEAN)

In the present work an attempt is made to estimate the magnitudes of the change in elastic-wave velocities with depth in the layers of the Earth' s crust and beneath the Mohorovičić discontinuity in the subcrustal medium, from amplitude graphs of first arrivals at sufficiently large distances from the source. The mantle waves P^M observed during deep seismic sounding in the deep sea and ocean are close in their kinematic characteristics to head waves at the Mohorovičić surface, but in their dynamic characteristics (attenuation) they are in most cases similar to head waves only out to distances of about 100 km, while farther on the amplitudes usually increase with distance.

Fig. 1. Model of the medium (*a*) and amplitude graphs of P^M waves (*b*) for the western part of the Black Sea basin. 1, 2 –experimental amplitude graphs of latitudinal DSS profile No. 27 (*1*) and meridional DSS profile No. 25 (*2*). 3, 4 –theoretical curves for an inhomogeneous-layered medium with absorption (*3*) and for an inhomogeneous-layered ideally elastic medium (*4*). Amplitudes along the ordinate axis are in arbitrary units. Curves 4 are shifted downward by approximately 1.5 orders of magnitude until they coincide with the initial branches of curves 3.

The interpretation of these features is based on the substantial difference in the dynamic characteristics of the head wave propagating along the interface and of the refracted wave arising in the presence of a positive velocity gradient beneath this boundary. Taking into account that, for small values of the gradient, the head wave differs little both kinematically and dynamically from the case of a

Fig. 1. Model of the medium (a) and amplitude graphs of P^M waves (b) for the western part of the Black Sea basin. 1, 2 —experimental amplitude graphs of latitudinal DSS profile No. 27 (1) and meridional DSS profile No. 25 (2). 3, 4 —theoretical curves for an inhomogeneous-layered medium with absorption (3) and for an inhomogeneous-layered ideally elastic medium (4). Amplitudes along the ordinate axis are in arbitrary units. Curves 4 are shifted downward by approximately 1.5 orders of magnitude until they coincide with the initial branches of curves 3.

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Figure 2

Figure 2: Figure 2

homogeneous-layered medium ([1]), one may expect a comparatively sharp change in the character of attenuation of the first arrivals, beginning at some distance.

Figure 1 gives the experimental and theoretical amplitude plots of the first P^m waves, corresponding to the upper mantle for the western part of the Black Sea. The experimental amplitude plots were obtained from records of bottom seismographs. The model of the Earth' s crust for the calculations was chosen from GSS data ([2]). The calculations were carried out for three values of the velocity gradient of longitudinal waves beneath the Mohorovičić boundary (0.01; 0.02 and 0.03 $\sec^{-1}$) using a program developed by T. B. Yanovskaya*. As a basis for comparison, a model was taken that allows for absorption in the layers of the Earth' s crust and upper mantle, for which the best agreement was obtained

Fig. 2. Model of the medium (*a*) and amplitude plots of P^m waves (*b*) for the rift zone of the Arabian-Indian Ridge. **1** —experimental amplitude plot, **2** —theoretical curves for an inhomogeneous-layered medium with absorption. Amplitudes along the ordinate axis are given in arbitrary units

between the experimental and theoretical wave fields. It should be noted, however, that the effect of absorption on the shape of the amplitude curves of the waves P^m and P^m is insignificant (Fig. 1).

It is clear from the figure that comparatively small changes in the velocity gradient strongly affect the level of the right branch of the theoretical amplitude curve. From the right branch of the experimental amplitude plot, the value of the vertical velocity gradient was determined; it is equal to 0.017 $\sec^{-1}$. The accuracy of the determinations depends to a considerable degree on the scatter of the experimental points. In the case considered, the error in determining the gradient may be estimated as ± 0.003 sec^{-1}.

Analogous data for the rift zone of the Arabian–Indian Ridge are given in Fig. 2. The seismic section of the Earth' s crust and upper mantle was obtained as a result of interpretation of the hodograph system of refracted waves along the GSS profile situated along the rift trough ([4]). This zone has a specific structure: the velocities characteristic of the "basalt"layer and of the Mohorovičić surface of oceanic basins are absent; instead, layers with velocities of 7.2–7.5 and 9.0 km/sec have been found. Here the experimental amplitude plot of refracted waves associated with the lower layer is analyzed. It was constructed from records of an autonomous bottom seismograph located on the floor of the trough at a depth of 4400 m. The theoretical calculations were carried out for different velocity gradients in the fourth layer: 0.02; 0.03 and 0.05 sec^{-1}. The right branch of the experimental amplitude plot agrees well with the calculated plot for a gradient of 0.03 sec^{-1}. The deviation of the experimental points from the theoretical curve does not exceed 0.002 sec^{-1}.

To interpret the results obtained, we shall use the known dependence of the velocity of longitudinal waves V_r on pressure p, temperature T, and the chemical composition of rocks, which we shall characterize by the average

* The calculations were carried out by B. V. Kholopov.

atomic weight m of the rock. The gradient of the velocity V_p with depth H in this case is given by the formula

$$\frac{dV_p}{\rho g\,dH} = \left(\frac{\partial V_p}{\partial p}\right)_{T,m} + \left(\frac{\partial V_p}{\partial T}\right)_{p,m} \frac{dT}{\rho g\,dH} + \left(\frac{\partial V_p}{\partial m}\right)_{p,T} \frac{dm}{\rho g\,dH}. \tag{1}$$

We shall take the values of the derivatives entering the formula to be

$$(\partial V_p/\partial m)_{T,p} = -0.79\ ([5]), \qquad (\partial V_p/\partial T)_{p,m} = -4\cdot 10^{-4}\ ([6]), ([7]).$$

These values are small and do not introduce significant errors into the estimate by formula (1).

The greatest difficulty is presented by estimating the value of the derivative $(\partial V_p/\partial p)_{T,m}$. At present there is fairly extensive experimental material for estimating the dependence of V_p on pressure p. These data show that the value $(\partial V_p/\partial p)_{T,m}$ depends not only on the type of rock (ultrabasic, basic, acidic), but even within one group of rocks these values may vary considerably from one specimen to another ([8]). In addition, the values of the derivative depend substantially on pressure. To estimate the pressure at the depths where the velocity gradients were obtained, we shall use the schemes of the structure of the Earth' s crust in Figs. 1 and 2. Thus we find the pressure beneath the bottom of the Black Sea at depths of 19–25 km to be 4–5 kbar, and beneath the rift in the Indian Ocean, 3–4 kbar. It is easy to see that this is a pressure range in which the effect of compression of spherical and ellipsoidal pores is still significant ([9]), while the pressures beneath the Indian Ocean are such that one may also expect a noticeable influence of the closure of crack-type pores. These circumstances greatly complicate the estimate of the derivative $(\partial V_p/\partial p)_{T,m}$.

Table 1

Rock	V_p, km/sec	$(\partial V_p/\partial p)_{T,m}$, km/sec · kbar	Source
Peridotite	8.4	0.086	([10])
»	8.3	0.053	
Pyroxenite	8.2	0.073	
Average	8.3	0.071	
Dunite	8.1	0.050	([11])
»	8.1	0.035	
»	8.0	0.065	
Eclogite	7.9	0.045	
»	7.7	0.065	
Average	8.0	0.052	
Dunite	8.1	0.045	([8])
»	8.1	0.040	
»	8.3	0.020	
Average	8.2	0.035	
Granite (trossular)	8.7	0.065	([8])

Taking into account the values of the velocity V_p for the case of the Black Sea, equal to 8.2–8.3 km/sec, and comparing them with the experimental data, we find that the most suitable in terms of velocity values are the data for two specimens of peridotite and one specimen of pyroxenite, which were extracted from boreholes at depths of about 1000 m on the Kola Peninsula and showed no noticeable traces of secondary alteration ([10]). The data obtained for specimens of three dunite and two eclogite nodules from the lavas of Hawaiian volcanoes may also be considered sufficiently close ([11]). These data are given in Table 1, where, for comparison, some data on dunites from ([8]) are also given; their characteristics, however, are absent. To estimate the temperature term in formula (1), the value of the geothermal gradient at the corresponding depth is necessary; we find it from the usual formula

$$q = K\, dT/dH. \tag{2}$$

The heat flow q for the bottom of the Black Sea has the value $0.9 \cdot 10^{-6}$ cal/sec · cm^2 ([12]). Taking the value of the thermal-conductivity coefficient, with allowance for the temperature effect, to be 0.009 ([8,13]), this gives a value of about 10° km^{-1} for the geothermal gradient. Taking into account the value

derivative

$$(\partial V_p/\partial T)_{p,m} = -4 \cdot 10^{-4}$$

we obtain for the thermal term in formula (1) the value −0.012. The left-hand side in (1), for a velocity-gradient value of 0.017 sec^{-1}, is equal to 0.051 km/sec · kbar.

Thus, from (1), after substitution, we obtain the following relation:

$$0.051 = (0.071 - 0.035) - 0.012 - 0.79\, dm/\rho g\, dH.$$

Or, if we discard the value $(\partial V_p/\partial \rho)_{T,m} = 0.035$ km/sec · kbar, obtained from samples whose relation to conditions beneath the floor of the Black Sea is unclear, we obtain:

$$0.051 = 0.061 - 0.012 - 0.79\, dm/\rho g\, dH.$$

From the relations presented, it is evident that, within the accuracy of the observational data used, the gradient of longitudinal-wave velocities in the upper mantle beneath the floor of the Black Sea is fully explained by the effects of increasing pressure and temperature. No conclusions about variation with depth of the mean atomic weight can be drawn on the basis of the available data.

The same conclusion may also be drawn with respect to the data on the gradient of longitudinal-wave velocities in the upper mantle beneath the rift zone in the Indian Ocean. The main difficulty in interpretation here is posed by the unusually high values of longitudinal-wave velocities V_p—9 km/sec—obtained for the uppermost parts of the mantle in this region. If these values are confirmed, it will inevitably be necessary to recognize a special mineralogical composition of the subcrustal layer in this area. At the same time it should be borne in mind that, despite the high velocities, the density of the top of the mantle cannot be taken substantially higher than 3.4 g/cm^3, so as not to come into contradiction with gravimetric data. Thus, here there must be a violation of the relation between density and velocity obtained by Birch ([11]),

$$V_p = -3.10 + 3.35\rho, \tag{3}$$

which gives a density value of 3.61 g/cm^3. This again points to an unusual mineralogical composition of the mantle. However, there are as yet no grounds for making any specific conclusions on this question. It can only be supposed that the mean atomic weight of the mantle m in this region is reduced to 21 instead of 21.6, which is characteristic of rocks of the presumed composition of the upper mantle in other regions.

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Note: Figure translations are in progress. See original paper for figures.