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GEOPHYSICS

Experimental Study of the Influence of Water on Elastic Wave Velocities in Dunite and Serpentinite (on the Nature of the Low-Velocity Zone in the Upper Mantle of the Earth)

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Abstract—Longitudinal wave velocities (V_P) in rocks were measured experimentally in dunite (olivinite) and serpentinite at a water pressure of 300 MPa and temperatures of 20–850°C. It is shown that the strong decrease in V_P in dunite (by ~3 km/s) observed within the range of 400–800°C results from penetration of water into rock along microfractures and from the formation of hydrous minerals (mostly serpentine) along the boundaries of mineral grains as a result of water–olivine interaction. It is suggested that serpentinization or the formation of similar hydrous minerals in olivine-rich mantle rocks under the influence of deep fluids may result in the formation of zones of low-velocity elastic waves in the upper mantle at great depths (~100 km).

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According to the fundamental seismological models of B. Gutenberg [1], the zone of low seismic velocities occurs in the upper mantle of the Earth at a depth of 70–100 km. Modern deep seismic studies support the presence of such a zone in many regions. The most detailed data were obtained in Russia in super-long profiles formed by nuclear explosions. Layers with a low velocity (waveguides) were distinguished in these profiles within the ancient and young platforms at a depth of ~100–150 km [2]. Extensive works in North America with registration of nuclear tests (the projects Nevada Test Site, GNOME, and Early Rise) showed the presence of a low-velocity layer at a depth of ~100 km as well. This layer is observed over the entire continent. This provides the basis for consideration of this layer as a global pattern in the upper mantle structure beneath the continents. In addition, reflecting seismic boundaries were distinguished at depths of ~150, ~200, and ~300 km in the upper mantle of northern Eurasia [2, 3]. These boundaries form multiphase reflected waves providing evidence for the complex structure of these boundaries represented by the low-velocity zones [3] or multilayer packets with alternating layers of low and high velocities [2]. The calculations show that the jumps in wave velocities in individual layers may be significant (≥0.5–0.8 km/s).

It is still considered in geophysical publications that the nature of these zones in the upper mantle is an unsolved petrophysical problem, and there are numerous discussions on this issue. The low-velocity layers in the upper mantle were usually explained by partial melting, but the idea of a waveguide at a depth of ~100 km was taken with a grain of salt by some seismologists, since it was hard to imagine partial melting at such a depth and there was not enough experimental material to distinguish such a waveguide reliably. Most likely, this was the reason for the absence of this layer in general models of the upper mantle [4].

The nature of this layer was also explained by the concentration of deep fluids [5], but such interpretation was almost not supported, because measurements of elastic properties (V_P and V_S) of mantle rocks were usually performed under the "dry" conditions. Experimental studies of V_P and V_S in rocks at high pressure of water and high temperature are still insufficient [6].

RESULTS OF EXPERIMENTAL STUDIES

In this study, elastic wave velocities were measured in the samples of dunite (olivinite) and serpentinite at a water pressure of 300 MPa and in the temperature range from 20 to 850°C. The chemical composition of rocks is given in Table 1. Experiments were performed in a high-pressure gas apparatus with internal heating

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Table 1. Chemical composition of the studied samples of dunite, serpentinite, and minerals formed in dunite in experiments under water pressure (wt %)

Mineral	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	NiO	Cr_2O_3	Σ
Dunite	40.89	0.05	0.31	7.20	0.14	50.12	0.17	0.08	0.06	0.04	–	0.38	99.45
Serpentinite	37.96	0.01	0.03	4.13	0.04	39.86	0.03	0.02	0.01	0.03	–	0.05	82.18
Olivine*	40.49	0.01	0.02	6.78	0.15	52.07	0.10	0.01	0.01	0.06	0.37	0.04	100.11
Serpentine**	42.63	0.01	0.31	2.39	0.01	40.79	0.09	0.02	0.02	0.09	0.12	0.07	86.55
“Clinochlore”**	30.13	0.03	17.74	1.97	0.02	34.72	0.05	0.56	0.02	0.10	0.10	2.20	87.64

Olivine in starting dunite is indicated by an asterisk; minerals formed in dunite at P_{H_2O} = 300 MPa and 600°C are indicated by two asterisks. The concentrations of H_2O in serpentinite, serpentine, and “clinochlore” estimated approximately by the difference 100 – Σ are 17, 13, and 12 wt %, respectively.

[6, 7]; V_P in rock was measured by the method of impulse scanning (with an ultrasonic frequency of 2 MHz) in combination with the echo–impulse method. A cylindrical sample with a diameter of 8 mm and height of 5 mm and acoustic lines connected to its edges was loaded into the platinum reactor filled with water. The heater was located outside the reactor (Fig. 1).

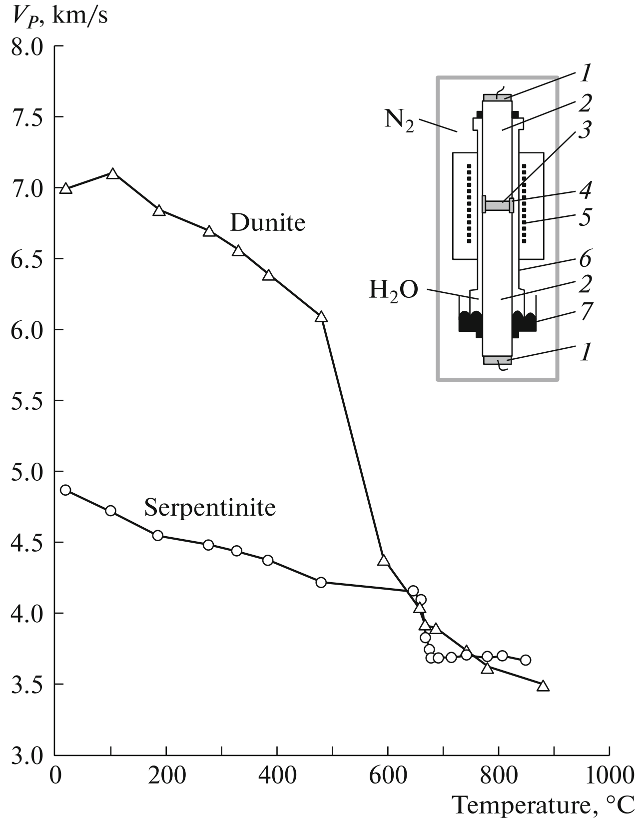

Fig. 1. Dependence of V_P on temperature in dunite and serpentenite at a water pressure of 300 MPa and in a temperature range from 20 to 850°C. The inset shows the apparatus for measurement of V_P: (*1*) piezoelectric element; (*2*) acoustic line; (*3*) sample; (*4*) nut fixing acoustic lines to the sample; (*5*) heater with thermocouples; (*6*) reactor; (*7*) mercury seal transmitting nitrogen pressure in a high-pressure vessel on water inside the reactor.

Piezoelectric elements were fixed on cool edges of acoustic lines. The total pressure in the apparatus was produced by nitrogen. Separation of the water filling the reactor from the nitrogen controlling the pressure was carried out using a mercury seal. The duration of measurement at each temperature was 30 min. The temperature was maintained with an accuracy of ±5°C. The errors in pressure and longitudinal wave velocities were 1 and 5%, respectively. The results obtained are reported in Table 2 and on the *VP*–*T* graph (Fig. 1).

With increasing temperature above 150–200°C under water pressure, the longitudinal wave velocities gradually decrease; a strong decrease (ΔV_P = 3 km/s) is observed in the range of 400–800°C. At ~650–750°C, V_P in dunite reaches the values that were measured in serpentinite (4.0–3.7 km/s) under the same conditions. V_P in serpentinite at low temperatures is much lower (by ~2 km/s) than that in dunite. The increase in T up to 600°C is accompanied by a gradual decrease in V_P, but then, in a relatively narrow range of 640–680 °C, a remarkable decrease in V_P by ~0.4 km/s is observed. With a further increase in T up to 850°C, the longitudinal wave velocity remains almost constant.

Quench runs under the same parameters (P_{H_2O}, T, and duration) as those in runs on V_P measurement were carried out in order to study changes in structure and mineralogical composition of dunite during experiments. The samples produced by quenching were studied under microscope and on a Cameca SX100 electron microprobe. In the temperature range of strongly decreasing V_P, dunite undergoes relatively small structural changes (Fig. 2). With increasing temperature, the boundaries between olivine grains (“microfractures”) expand and interstitials are filled with newly formed serpentine crystals (Table 1). In addition to serpentine, another hydrous mineral containing ~12 wt % H_2O, with the composition close to clinochlore (Table 1) is observed in the samples synthesized at $T > 600$°C. Thus, the strong decrease in V_P in dunite within the range of 400–800°C is most likely explained by penetration of water into rock along the mineral grain boundaries and by relatively rapid formation of hydrous minerals (mostly serpentine with the elastic wave velocities significantly lower than those in olivine) as a result of interaction with olivine. We should emphasize that a strong decrease in V_P is observed, even if serpentinization covers a very small volume of dunite (mostly along the olivine grain boundaries), i.e., the relatively small portion of water exhausted for the formation of hydrous minerals and filling of interstitials between crystals is sufficient to cause such an effect in olivine-bearing rocks. The significantly less pronounced (in comparison with the olivine sample) jumplike decrease in V_P in serpentinite at $T > 640$°C is most likely explained by phase reactions with the formation of talc [8, 9] and related changes in the sample structure.

DISCUSSION OF RESULTS

The experimental studies allowed us to make a discovery that is important for solution of the problem of the physicochemical nature of waveguides in the upper mantle. It is shown experimentally that at a high depth (100–120 km), partial or complete serpentinization of olivine-rich mantle rocks in the presence of water is accompanied by a strong decrease in V_P. The experimental data available show that serpentine and other high-pressure hydrous phases with similar compositions in the $MgO–SiO_2–H_2O$ system, which formed after olivine in the presence of water, may be stable up to 8 GPa (up to a depth of ~260 km) and 1100 °C [8–11]. Wadsleyite, an olivine modification with low elastic wave velocities in comparison with those of olivine, becomes a hydrated phase at higher mantle pressures in the presence of water [12]. Thus, the effect of serpentinization or formation of such hydrous minerals as a result of interaction of hydrous fluids with olivine may be given for explanation of the nature of the low-velocity zones at significantly higher depths (~100 km and more) characterized by the appropriate $P–T$ conditions.

Table 2. Primary wave velocities (V_P) in dunite and serpentinite at a water pressure of 300 MPa in the temperature range from 20 to 880°C

T, °C	V_P, km/s	
	dunite	serpentinite
20	7.00	4.86
102	7.11	4.72
187	6.84	4.54
277	6.70	4.48
330	6.56	4.43
385	6.39	4.37
480	6.10	4.22
590	4.38	–
648	–	4.15
658	4.05	4.09
668	3.89	3.83
677	–	3.74
680	–	3.68
686	3.92	–
690	–	3.68
715	–	3.68
743	3.73	3.70
780	3.62	3.68
808	–	3.70
850	–	3.66
880	3.46	–

The heterogeneity of the wave velocity in the upper mantle was previously explained by variability in the temperature regime, because tectonically active

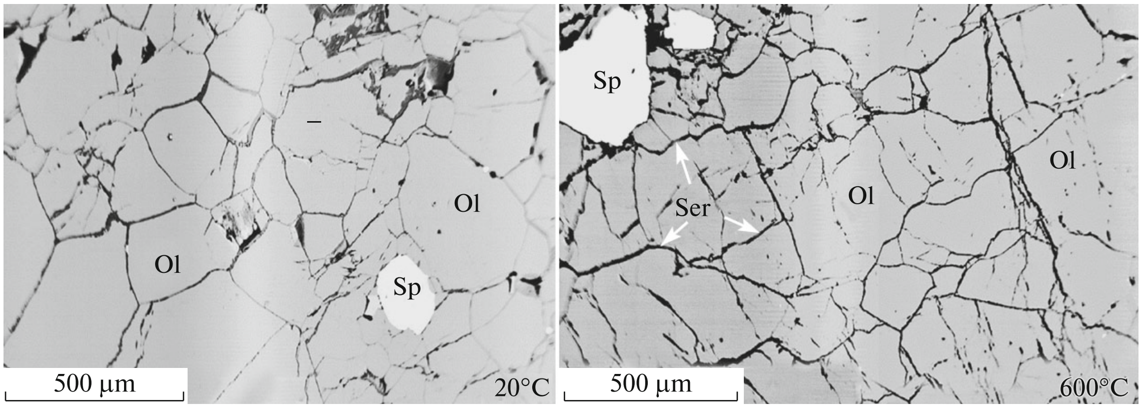

Fig. 2. Change of the dunite texture with increasing temperature at a water pressure of 300 MPa (photos of quench samples after runs at 20 and 600°C). Ol, olivine; Ser, serpentine; Sp, spinel. With increasing temperature ($T > 400$°C), the boundary zones ("microfractures") between olivine crystals expand and mostly filled with serpentine formed as a result of interaction between olivine and water.

regions with a high heat flow are usually characterized by low velocities. The same correlation was suggested for variations in the wave velocities with depth, and the low-velocity zones distinguished in many regions at a depth of 150–300 km were interpreted as zones of probable partial melting. At the same time, estimates of temperature variation with depth for the Siberian Craton [13] show that under the platform conditions with a heat flow of ~30–50 mW/m^2, at a depth of ~100 km, the temperature should not exceed 600°C; i.e., we can hardly expect partially molten ultrabasic material in this area.

As a whole, the results of our experiments indicate the important role of the processes of transformation of mantle materials under the influence of deep hydrous fluids in the formation of upper mantle layering. This is true not only for the layer with the low wave velocity at a depth of 100 km, but most likely for reflecting boundaries at greater depths as well. The probable nature of mantle fluids is discussed in many publications, in which the different processes of their introduction into the upper mantle are considered and various estimates of their possible concentration in mantle material are given. For example, it is shown that the concentration of water in subduction zones may reach high values (up to 10–15 wt %) at depths of 200–300 km [14]. It is also assumed that water may come to the zones of serpentinization (or in a more general case, to the zones of hydration of mantle material) together with fluids formed upon the deep degassing of the Earth [15].

Thus, it has been shown experimentally that the longitudinal wave velocity in dunite at a water pressure of 300 MPa and in the temperature range of 400–800°C decreases significantly (by ~2.5 km/s) due to penetration of water into rock with the formation of serpentine along the mineral grain boundaries upon the interaction of water with olivine.

A strong decrease in V_{P} is observed in dunite, if only a small volume of rock is involved in serpentinization. Small amounts of water are necessary to cause the remarkable effect of V_{P} decrease.

According to the experimental data available, serpentine and other high-pressure phases with a similar composition are stable in the wide P–T area typical of the upper mantle. It is suggested that the formation of such phases in olivine-rich mantle rocks may produce low-velocity zones in the upper mantle at a depth of ~100 km or greater.

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