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Abstract

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GEOPHYSICS

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THE VELOCITY OF ELASTIC WAVES IN CRYSTALLINE ROCKS AND ITS DEPENDENCE ON MOISTURE

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The geological interpretation of the velocity section of elastic waves recorded by the methods of seismology and deep seismic sounding is based chiefly on experimental investigations of velocity in rock samples under increasing pressure and at pressures characteristic of the Earth's surface. The latter are distinguished by the simplicity of the measurements, which makes it possible to obtain statistical data on the velocity of elastic waves in rocks of different genetic types, composition, and structure.

At the All-Union Scientific Research Geological Institute, investigations were carried out of the velocity of elastic waves in samples of crystalline rocks from the eastern (Soviet) part of the Baltic Shield and other regions. Velocity measurements were performed on samples with different degrees of liquid saturation. By drying the samples at 100°, hygroscopic and capillary moisture was removed from them. The samples were then saturated with water in a vacuum desiccator, from which air was pumped out to a pressure of 1-2 mm Hg. The maximum saturation of a sample with water was established when it reached constant weight. Additional experiments were carried out by saturating the samples with ESU oil, which, because of its viscosity, filled microcracks and pores at normal pressure. (Saturation of low-porosity rocks with water without pumping out air from them, and with oil under vacuum, is ineffective.) The velocity of longitudinal waves was measured by the transmission method on an IPA seismoscope. The size of the samples averaged $10 \times 8 \times 7$ cm. The root-mean-square value of the relative error in determining the velocity was 1.2%.

As can be seen from the curves in Fig. 1, when rocks are saturated with liquid, a considerable increase in the velocity of longitudinal waves is observed. After maximum saturation of the samples, the velocity remains constant, and the composition of the liquid does not affect the value of the parameter. Saturation of rocks with water takes 3-4 hours, and with oil 10-20 hours.

The results of determining the velocity of longitudinal waves in different rocks in dry (deprived of hygroscopic and capillary moisture), air-dry, and liquid-

Figure 1

Figure 1: Figure 1

saturated samples (Table 1) make it possible to see the following. The velocity values in dry samples of all rocks are the lowest. Close to them are the velocity values in air-dry samples of the same rocks, which are usually measured in studies of crystalline rocks. The velocities of longitudinal waves are significantly higher in samples whose microcracks and pore channels are maximally saturated with liquid (water or oil). The change in the magnitude of the velocity of longitudinal waves in rocks at different moisture contents varies from 0.3 to 2 km/sec. The discrepancies between velocity values in dry and water-saturated rocks amount to (in %): for granites 11-38; schists 22-34; gneisses of different composition 16-35; diorites 9-24; granulites 7-12; gabbros, norites, hyperbasites 1-9. The reduction in the discrepancies of velocity values is caused by a decrease in the microfracturing and porosity of the rocks.

The observed effect of an increase in the velocity of elastic waves when low-porosity rocks are saturated with liquid can be explained by the considerably greater difference in the bulk elasticity of air and of the rock-forming minerals than of the latter in liquid. In this connection, the presence of air in microcracks and pore channels disrupts the elasticity of rocks, whereas filling them with liquid creates favorable conditions for the propagation of longitudinal waves.

For 920 samples of crystalline rocks of different composition and facies of regional metamorphism, selected from boreholes on the Kola Peninsula, a study was made of the velocity of longitudinal waves at maximum saturation of the samples with liquid.

Fig. 1. Velocity of longitudinal waves in rocks—dry (*a*) and saturated with water (*b*) or oil (*c*). 1—granite, 2—diorite, 3—hyperbasite

As can be seen from Fig. 2, which presents the determination data, there is a very compact distribution of points, from which a continuous increase in velocity in rocks is confidently established with increasing basicity (from 5.2-6.3 km/sec in granites and biotite gneisses to 7.1-8.4 km/sec in hyperbasites). In addition, a regular relationship is clearly recorded between the velocity of longitudinal waves in crystalline rocks and their density. The gradient of the averaging curve is constant for rocks of acid and intermediate composition and increases somewhat in basic and ultrabasic rocks. The velocity dispersion at the same density is almost constant for all rocks (0.04-0.05), but is due to different factors. For acid rocks the predominant significance is different microfracturing; for basic and ultrabasic rocks, different velocities in minerals with similar density (for example, in pyroxene and olivine).

The velocities of transverse waves in maximally saturated and dry samples are equal or close to one another. The ratio V_p/V_s increases with increasing water saturation from 1.7-1.9 to 2.1-2.5. In this connection, the Poisson's ratio and

Fig. 2. Velocities of longitudinal waves in crystalline rocks and their density at maximum saturation with liquid. Rock composition: 1 –acidic, 2 –intermediate, 3 –basic, 4 –ultrabasic. a –averaged curve, — –the range of dependence of $V_p(\sigma)$ for dry rocks at a pressure of 1000 kgf/cm², — –the same at 2000 kgf/cm² (according to data from ^{1,2,4,5})

Figure 2: Fig. 2. Velocities of longitudinal waves in crystalline rocks and their density at maximum saturation with liquid. Rock composition: 1 –acidic, 2 –intermediate, 3 –basic, 4 –ultrabasic. a –averaged curve, — –the range of dependence of $V_p(\sigma)$ for dry rocks at a pressure of 1000 kgf/cm², — –the same at 2000 kgf/cm² (according to data from ^{1,2,4,5})

Young' s modulus increase in water-saturated rocks.

A comparison of the velocity of longitudinal waves in water-saturated samples with velocity data obtained by seismic sounding and seismic logging (³) shows identical values for rocks of similar composition occurring at depths of 100-1000 m. At the same time, measurement of velocity in samples makes it possible to obtain data with substantially greater differentiation of rocks by composition and structure.

Experimental studies of changes in the velocity of longitudinal waves in crystalline rocks as a function of pressure are, as a rule, carried out on dry (more rarely air-dry) samples. Numerous experiments have established the presence of a high gradient of velocity change in rock samples when pressure is varied from 0 to 1000-2000 kg/cm²; with a further increase in pressure, the gradient of velocity change decreases sharply (^{1, 2, 4, 5}). The strong dependence of the velocity of longitudinal waves in crystalline rocks on water saturation does not permit the use of

velocity values obtained in dry samples, for interpreting velocity sections of the Earth' s crust at depths to which the presence of gravitational and pore waters may be assumed.

The available data make it possible to infer the course of the velocity curve for longitudinal waves in water-saturated samples as pressure increases. The interval of a sharp gradient in the change of velocity at pressures of 0-2000 kgf/cm² (recorded for dry samples) will be absent. At such pressures, apparently, only a very slight increase in velocity occurs. This is confirmed by the curves delimiting the range of velocity values

Fig. 2. Velocities of longitudinal waves in crystalline rocks and their density at maximum saturation with liquid. Rock composition: **1** –acidic, **2** –intermediate, **3** –basic, **4** –ultrabasic. **a** –averaged curve, — –the range of dependences $V_p(\sigma)$ for dry rocks at a pressure of 1000 kgf/cm², — –the same at 2000 kgf/cm² (according to data from ^{1,2,4,5}).

of velocity in dry samples at a pressure of 1000-2000 kgf/cm² (Fig. 2), coinciding

with the boundaries of the range of velocity values for water-saturated samples at normal pressure. At higher pressures, the increase in velocity in water-saturated samples will occur more slowly than in dry ones, owing to the absence of direct contacts between mineral grains. With increasing pressure and temperature, a small in amplitude but sharp increase in velocity should be observed when the content and state of the liquid change.

The materials obtained make it possible to consider that differences in the water regime of different horizons of the Earth's crust should exert a noticeable influence on the propagation velocity of longitudinal and shear waves. In this connection, it is likely that some horizontal seismic boundaries, including the Mohorovičić discontinuity, are caused by a change in the water regime. Thus, a stepwise increase in the velocity of elastic waves with increasing pressure and temperature may occur when water is completely displaced from open microcracks and pore channels; when the walls of closed pores are crushed and water and gas are displaced from them; when water passes into the critical and supercritical states; and, finally, in the event that minerals lose crystallization water.

Table 1

Velocity of longitudinal waves in intrusive and metamorphic rocks, their density and porosity

Characteristics of rocks	Borehole no.	Depth, m	Dry	Air-dry	Saturated with oil	Saturated with water	Density, g/cm ³	Porosity, %
Biotite-amphibole granite			3.76	3.85	5.10	5.10	2.62	—
Biotite-amphibole granite	»		3.20	3.25	5.15	5.10	2.65	—
Biotite-amphibole granite	»		4.20	4.30	5.20	5.20	2.66	—
Migmatite of plagioclone granite	591	314	3.35	3.45	5.45	5.45	2.65	1.1

Characteristics of rocks	Borehole no.	Depth, m	Dry	Air- dry	Saturated with oil	Saturated with water	Density, g/cm ³	Porosity, %
Migmatite 591 of pla- giomi- cro- cline gran- ite	591	327	3.65	3.75	5.50	5.55	2.67	1.6
Migmatite 591 of pla- giomi- cro- cline gran- ite	591	341	3.50	3.60	5.60	5.60	2.65	1.8
Migmatite 591 of pla- giomi- cro- cline gran- ite	591	344	4.00	4.10	5.70	5.65	2.64	1.1
Migmatite 519 of pla- giomi- cro- cline gran- ite	519	41	4.30	4.40	5.80	5.75	2.63	0.6
Migmatite 519 of pla- giomi- cro- cline gran- ite	519	195	4.10	4.20	5.80	5.80	2.64	0.6

Characteristics of rocks	Borehole no.	Depth, m	Dry	Air-dry	Saturated with oil	Saturated with water	Density, g/cm ³	Porosity, %
Biotite-microcline granite	900	12*	5.25	5.30	5.95	5.90	2.62	—
Biotite-microcline granite	425	135*	5.35	5.35	6.00	6.00	2.62	—
Biotite-microcline granite	425	270*	5.30	5.40	6.25	6.30	2.62	—
Nepheline syenite	559	490	3.95	4.10	5.30	5.40	2.68	0.8
Nepheline syenite	559	732	4.45	4.60	5.65	5.70	2.67	0.7
Syenite	541	503	5.20	5.45	6.35	6.45	2.74	1.1
Amphibole biotite gneiss	710	400	3.50	3.65	5.50	5.50	2.68	0.9
Amphibole biotite gneiss	440	527	4.75	4.85	5.80	5.90	2.75	0.3
Amphibole biotite gneiss	440	592	4.95	5.10	5.85	5.90	2.72	0.4
Kyanite-garnet-biotite gneiss	138	115	5.00	5.20	6.00	6.00	2.72	0.9
Kyanite-garnet-biotite gneiss	10	332	4.00	4.15	5.55	5.45	2.79	0.7
Kyanite-garnet-biotite gneiss	10	343	4.55	4.65	5.80	5.75	2.74	0.4

Characteristics of rocks	Borehole no.	Depth, m	Dry	Air-dry	Saturated with oil	Saturated with water	Density, g/cm ³	Porosity, %
Kyanite-garnet-biotite gneiss	10	464	4.30	4.35	5.80	5.80	2.76	0.4
Kyanite-garnet-biotite gneiss	10	198	4.20	4.30	5.95	5.90	2.76	0.5
Granulite-plagioclase	233	295	4.60	4.90	5.45	5.45	2.83	0.4
Granulite-plagioclase	233	297	5.25	5.35	5.80	5.85	2.86	0.2
Granulite-plagioclase	233	297	5.60	5.60	6.00	6.00	2.84	0.3
Hypersthene gneiss-diorite	358	180	4.55	4.65	5.90	5.95	2.79	1.2
Hypersthene gneiss-diorite	358	121	5.20	5.30	6.20	6.20	2.79	0.6
Hypersthene gneiss-diorite	358	181	5.30	5.30	6.20	6.20	2.80	0.7
Hypersthene gneiss-diorite	358	360	5.85	5.90	6.40	6.40	2.81	0.6
Hypersthene diorite		360	5.70	5.70	6.65	6.60	2.86	0.6
Gabbro-norite	1226	890	6.15	6.15	6.70	6.70	2.93	0.2
Norite	767	249	6.40	6.40	6.80	6.75	3.16	0.2
Norite	767	288	6.50	6.50	6.75	6.85	3.16	0.3
Norite	767	275	6.65	6.65	6.95	6.95	3.14	0.2
Norite	767	267	6.75	6.80	7.10	7.10	3.16	0.2
Norite	767	235	7.00	7.00	7.10	7.10	3.16	0.2
Pyroxenite	188	223	7.10	7.10	7.75	7.70	3.22	0.2
Pyroxenite	188	224	7.55	7.60	—	8.10	3.29	—
Pyroxenite	188	563	7.65	7.70	8.90	8.15	3.32	0.2
Pyroxenite	188	563	8.10	8.15	—	8.40	3.33	—

* Samples from intrusions of Kazakhstan; the rest are from the Baltic Shield.

A more detailed study of the questions considered will, in turn, shed light on the highly important problem of the occurrence and state of water in the Earth's crust.

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