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ON ELASTIC ANISOTROPY RELATION IN UNLOADED AND LOADED SAMPLES OF CRYSTALLINE ROCKS

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Elastic anisotropy properties of rocks extracted from 40 to 12014 m depth of the Kola Superdeep Borehole(SG-3) were measured on the core samples by the ultrasonic method. The measurements were performed on unloaded samples under atmospheric conditions and in special apparatuses that make possible the temperature and pressure approaching in-situ conditions. In the borehole section down to 4.5 km isotropic and weakly anisotropic rocks dominate. A very important result is verification of high anisotropy of rocks from 6.3-10.2 km. Anisotropy of rock samples from the lower section both in lab and under simulated in situ conditions is very high. However, elastic anisotropy measured on the unloaded samples can greatly differ from that determined for the rocks in situ. A high grade of elastic anisotropy of crystalline rocks from the SG-3 lower section suggests complex palaeogeodynamic history of the massif formation.

For an adequate interpretation of deep seismic sounding data of a crustal section knowledge of the symmetry type and of the grade of elastic anisotropy, besides other parameters, is extremely important. Elastic anisotropy of crystalline rocks is generally considered to be weak [1]. Recent results from superdeep boreholes, however, give hints for significant seismic in-situ anisotropy. Investigation of a great number of core samples from the Kola superdeep borehole (SG-3) revealed high elastic anisotropy [2]. The measurements were performed on the samples in surface conditions (at the normal barometric pressure and room temperature). However, due to decompacting [3] during drilling and core recovery elastic properties change dramatically. Therefore, to determine the contribution of seismic anisotropy to the velocity structure of the crustal section is still an urgent problem. Good results have been obtained [4] when saturating the SG-3 core samples with liquid and applying a uniaxial loads to them.

Below are the results of the study of elastic-anisotropic characteristics on the SG-3 samples in surface conditions and under simulated *in situ* conditions. The maximum PT values at which the measurements were conducted corresponded to 20-35 km depth. For the measurements 25 cubic samples with the edge of 47-60 mm were cut from the core extracted from SG-3. Then by the acousopolarization method [5] the orientation of elastic characteristics in the samples in lab conditions was determined. At the second step the compression and shear wave velocities were measured in the directions conformable with the orientation of the symmetry elements revealed by the acoustopolariscopy method. The values were recorded in accordance with the q-matrix (quasi-matrix) V_{ij}. The compression wave values were used to calculate the anisotropy factor A_P. The index of elastic anisotropy B was determined using the shear wave values and formulae given in [6]. The matrixes determined parameters, indexes B and A_P for some samples are given in the Table.

As the Table suggests, rather low velocities of both compression and shear waves were detected on the samples extracted from great depths (9571-11364.2 m), due to the decompaction effect [3].Such velocities are uncommon for crystalline rock samples taken, for instance, at the earth surface. The values of the factors B and AP also exceed the levels generally detected in the near-surface rocks.

The next steps of the study of elastic properties were performed in the apparatus that make possible PT conditions similar to the in situ pressure and temperature. Part of the samples (№№ 17775S, 18679S, 31115, 35400, 36058, 38098S, 43560, 43726) were tested at confining pressure up to 600 MPa and at temperatures to 600^0 C in a multi-anvil apparatus of Prof. H. Kern in Kiel University, Germany [7].

Another group of samples (№№ 2679p, 11373, 20289, 31136, 43731) were tested in the sell of Prof. N. Christensen at Wisconsin University, USA. The sell is designed for the measurement of wave velocities under an increasing confining pressure of up to 1000 MPa [8]. The *P* and *S* wave velocities of the samples were measured at varying pressure and temperature. Figure 1 exemplifies the resulting pressure dependences of elastic wave velocities.

Table. Acoustic characteristics of some samples

Sample No.	Depth H, m	Rock	Velocity q-matrix, V_{ij}, km/sec.	Indexes B_1, B_2, and B_3	Factor A_P, % (lab conditions)
11373	2965.4	Actinolitized metadolerite	6.46 3.67 3.75 3.62 6.38 3.75 3.82 3.71 6.61	−2.2 −3.5 2.9	2.5
36058	9571	Biotitized amphibolite	1.69 1.43 1.72 1.95 3.31 2.57 2.37 2.59 4.36	−18 −27 −8.9	61
38098S	10238.3	Garnet-biotite-plagioclase gneiss	1.15 1.17 1.20 1.52 2.88 1.81 1.34 1.70 2.15	−2.5 −17 −24	59
43731	11364.2	Clinopyroxene hornblende amphibolite	2.84 2.00 1.74 1.90 3.34 1.83 1.76 1.87 2.11	14 3.8 −6.1	32

The resulting pressure dependences of V_p allowed calculation of the anisotropy factor A_P for P waves referring to *in situ* conditions. This factor was calculated as a deviator of the V_{ii} values in q-matrix by the formula [6].

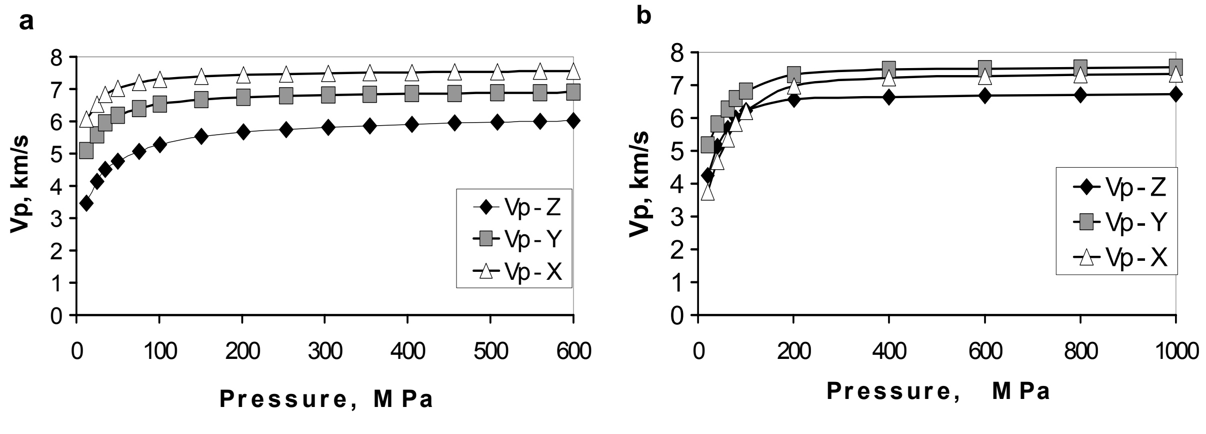

Fig. 1. Compression wave velocities as a function of confining pressure in three mutually perpendicular directions in cube samples № 36058 (a) and № 31136 (b).

In order to compare the P and S wave velocities calculated from the mineral composition and measured under the normal and relevant PT conditions, the in situ pressure at a given depth was found as the weight of overlying rocks. This pressure was set approximately equal to $\sigma_Z = \rho H$, where ρ is the average density of the overlying rocks and H is the depth. Earlier such estimates were made in [9]. An estimate σ_Z (in MPa) ≈ 28.1·H (in km) was obtained for SG-3 section. This conclusion is corroborated by the analysis of V_{ij} q-matrixes, Table, since the V_p values along the q-matrixes diagonal greatly differ.

Combining the results of experimental determination of the B factor and coefficient A_p, the SG-3 section can be subdivided into two parts with respect to the anisotropy. The first part, down to

4.43 km, is characterized by weakly anisotropic or quasi-isotropic rocks. Marked elastic anisotropy is observed only in a depth interval of 1.7-1.9 km, where Cu-Ni ore was found [10].

The distribution of anisotropy parameters A_P and B along the hole section under *in situ* conditions shows that, similar to the A_P and B values obtained in lab conditions significant anisotropy is observed in rocks that occur below 5 km depth. The parameters A_P and B correlate well. In anisotropic *in situ* rocks represented by samples 20289, 31115, 31136, 35400, 36058 and 38098S the coefficient A_p varies from ~ 8% to 18%,and the factor B from ~11% to 38%. The anisotropy characteristics are very high and substantially exceed the level below which the rock is considered quasi-isotropic.

The tests showed that some rocks retain their high elastic anisotropy under high PT conditions. There are some samples whose anisotropy decreases by more than an order of magnitude under applied pressure. On average, the P wave anisotropy coefficient appreciably decreases with increasing pressure, particularly in an initial interval (up to 100 MPa).

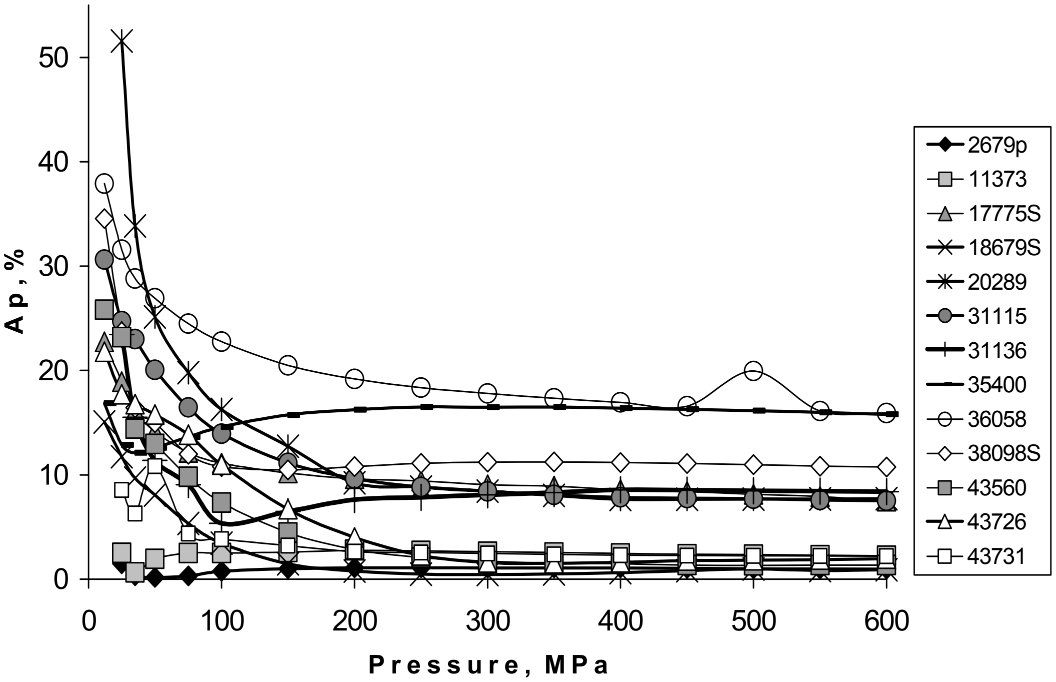

Fig. 2. Dependence of the anisotropy factor V_p vs pressure for 13 samples extracted from the depths of 926.8 to 11718 m.

As a whole, the study of unloaded and loaded samples of the SG-3 core showed substantial distinctions in their elastic properties. The confining pressure release during the core drilling and recovery from a great depth contributes to formation of a large number of microcracks which radically change the rock elastic properties. Herewith, the effect of the microcracks on the anisotropy parameters is greater as that of the sample mineral composition. An application of confining pressure to the sample closes the majority of microcracks and the elastic anisotropy parameters start to depend on the lattice preferred orientation.

It is very important that our results based on the simulation of *in situ* conditions corroborated the high anisotropy of rocks at depths of 6.3 to 10.2 km. In these rocks, the coefficient A_p varies from ~ 8% to 18%, and the factor B, from ~11% to 38%. These values are much greater than the level below which the anisotropy of rocks can be ignored. Judging from these values, in the course of the lower massif formation frequent palaeogeodynamic movements occurred with application of substantial palaeotectonic forces.

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