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SOME PROPERTIES AND STRUCTURE OF THE CRYSTALLINE CRUST FROM SUPERDEEP DRILLING DATA (SG-3, SG-4, KTB)

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ABSTRACT
Among the programmes aimed at developing a standard model for properties and state of the Earth's crystalline crust, those dealing with drilling the Kola (SG-3), Ural (SG-4) and German (KTB) superdeep boreholes yielded the most interesting results. No marked depth dependence of rock volume density and seismic wave velocities was observed in the sections of SG-3 and SG-4. A new result of the investigations is the discovery of strongly anisotropic rocks in the SG-3, SG-4 and KTB sections. In the massifs of the Kola and German superdeep boreholes such rocks constitute the majority of the drilled sections. The presence of the velocity anisotropy as well as the complex structure of the rocks composing crystalline metamorphosed sequences greatly hamper the interpretation of the results obtained from the seismic survey conducted at the surface.

KEYWORDS: anisotropy, crystalline crust, density, structure, rock properties, superdeep boreholes, velocity

INTRODUCTION

The Russian superdeep borehole drilling programme included drilling of deep and superdeep boreholes in both sedimentary and crystalline rocks (Kozlovsky, 1987). Among the programmes aimed at the study of the properties and state of the Earth's crystalline crust the most interesting results were obtained when drilling the Kola (12261 m), Ural (6010 m) Saatly (8267 m), Krivoi Rog (3600 m) etc. boreholes (Nalivkina and Khakhaev, 1995). Among foreign scientific projects also aimed at the study of the crystalline crust, Gravberg-1 (Sweden) and KTB (Germany) are best known.

The Gravberg-1 superdeep borehole drilled in the Siljan astrobleme in southern Sweden reached a depth of 6.6 km and was terminated due to technical reasons (Boden and Eriksson, 1988). The German superdeep borehole KTB located at the town of Windischeschenbach, Bavaria, reached a depth of 9.1 km (Engezer, 1996). The geographical location and geochronological positions of the massifs in which the above boreholes are located, are given in Figures 1 and 2 (Gorbatsevich, 2006). From the above diagram, the geochronological positions of the massifs intersected by the deep and superdeep boreholes cover the age range from Cenozoic (Saatly borehole) to Early Archaean (Kola Superdeep).

KOLA SUPERDEEP

The Kola Superdeep Borehole (SG-3) is the world's deepest borehole. It was drilled in the northern NW-trending (300-310^{o}) and SW-dipping (30-50^{o}) limb of the Pechenga rift structure, composed of rhythmically alternating volcanic and tuffaceous sedimentary sequences. The borehole intersected the lower Proterozoic complex of the Pechenga Formation and an Archaean granite and metamorphic complex (the middle continental crust).

The Proterozoic complex (9-6842 m) is composed of metavolcanic and metasedimentary rocks in the ratio of 3:1 (Fig. 3). Metabasalts and tuffs are most common, meta-andesites, metatrachyandesites and metapicrites are less common. Metasedimentary rocks are represented by phyllites, siltstones, carbonaceous rocks, sandstones, grits and conglomerates. Intrusive sheets of metagabbro, ultrabasic rocks and dacite porphyrite occur throughout the entire complex.

The drilled part of the Archaean complex (6842-12261 m) is composed of biotite-plagioclase and biotite-amphibole-plagioclase gneisses with high-calcium minerals, gneisses with high-alumina minerals, amphibolites and meta-ultrabasite, pegmatites and granites (Mitrofanov, 1991). In the vertical section of the Archaean complex 10 geological units have been distinguished. They are characterized by various compositions and combinations of constituent rocks, type of regional and dislocation metamorphism, granitization, elements of folding and fracturing.

The age of the crystalline rocks in the SG-3 section is in the range of 1765-2835 Ma. The most ancient rocks are plagiogranitoids from the amphibolite-tonalite-plagiogranite complex (Orlov and Laverov, 1998). The main units (I-IV) of the SG-3 Archaean complex (6842-10144 m) are

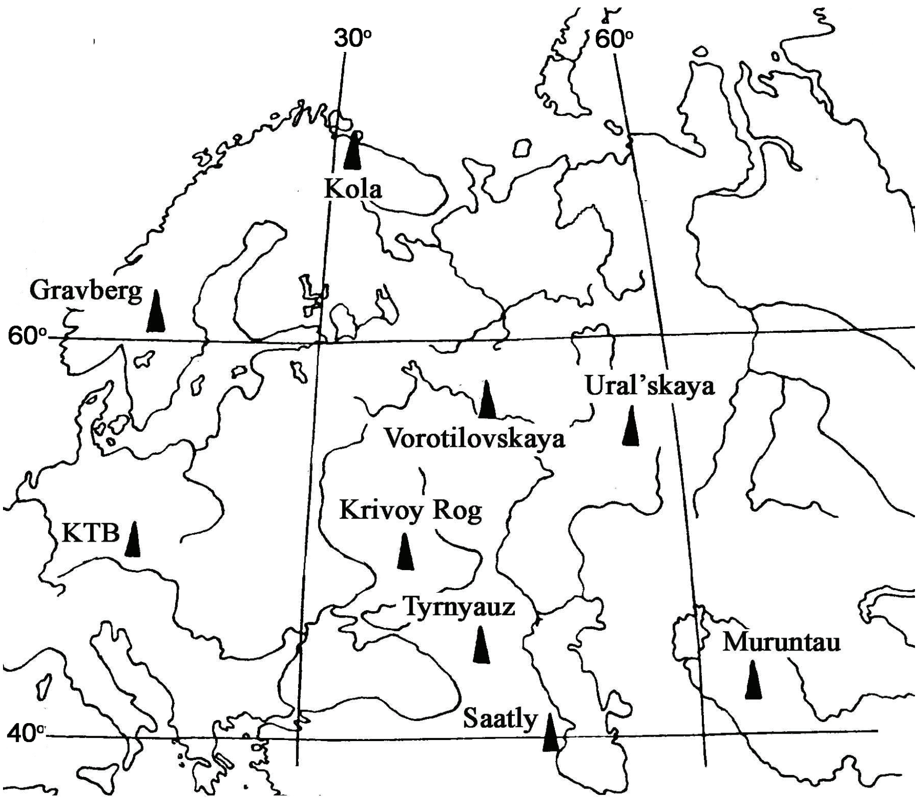

Fig. 1 Geographical location of deep and superdeep research boreholes drilled in the crystalline crust in the European part of the continent.

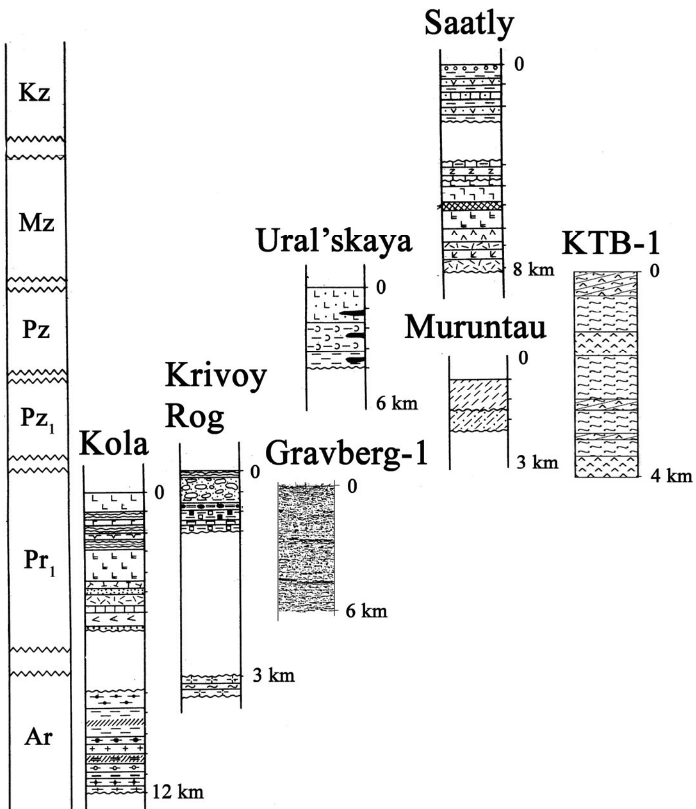

Fig. 2 Geochronological positions of massifs in deep and superdeep research boreholes drilled in the crystalline crust of the European continent.

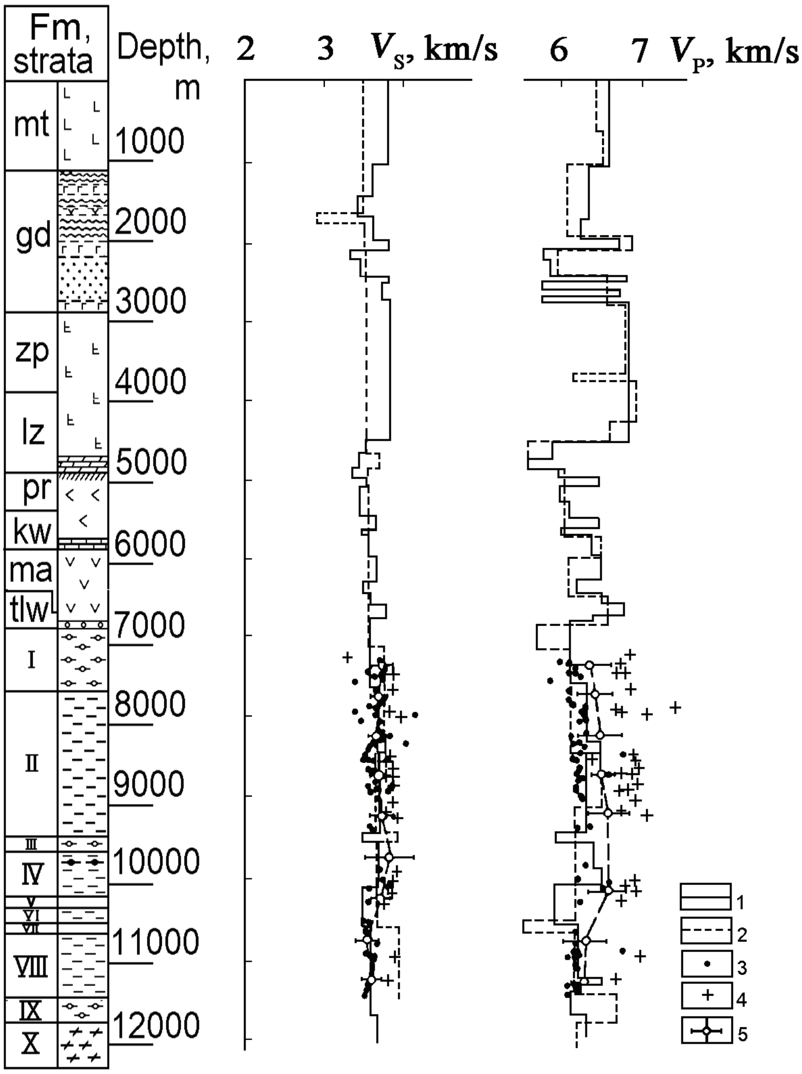

Fig. 3 Geological column and velocity section along the SG-3 hole (Sharov, 1997). mt – Matert Fm, gd – Zdanov Fm, zp – Zapolyarny Fm, lz – Luchlompolo Fm, pr – Pirttijarvi Fm, kw – Kuvernerinjoki Fm, ma – Majarvi Fm, tlw – Televi Fm. I – X – Archaean units in the section.
Geophysical methods:
1 – vertical seismic profiling (VSP); 2 – acoustic logging (AL);
3 – calculation method (CM) by mineral composition for rocks of granitic-gneiss composition; 4 – calculations for amphibole-bearing rocks;
5 – confidence limits for averages along the intervals.

composed of gneisses (56%), the thickness of the units ranging from 0.1 m to 70 m. Their average thickness is about 16 m. Amphibolite accounts for 21%; the average thickness of its layers is 12 m. The average thickness of migmatite (13% of the volume) reaches 21 m. Granite accounts for 7% with an average thickness of ~ 9 m.

The distribution of thickness is similar for gneisses, migmatites and amphibolites. This is most likely related to the formation mechanism of these rocks, i.e. rhythmicity of sedimentation periods and volcanic activity and metamorphic episodes that these rocks have undergone. On the whole, this analysis shows that the geodynamic history of the Kola Superdeep Borehole Archaean section reflects frequent changes in the formation stages of rock that differ in their geological nature.

On the whole, the average velocity of compression waves (V_P) in the Archaean rocks from the SG-3 section determined by the acoustic logging, VSP and calculation methods, is V_P = 6.2 km/s, that of shear waves is V_S = 3.6 km/s, Figure 3. The first velocity boundary is registered at a depth of ~ 1.1 km.

By the points of marked changes in the V_P and V_S values, an interval of 1.7-2.1 km with copper-nickel mineralization stands out. The 2.7-4.6 km interval of

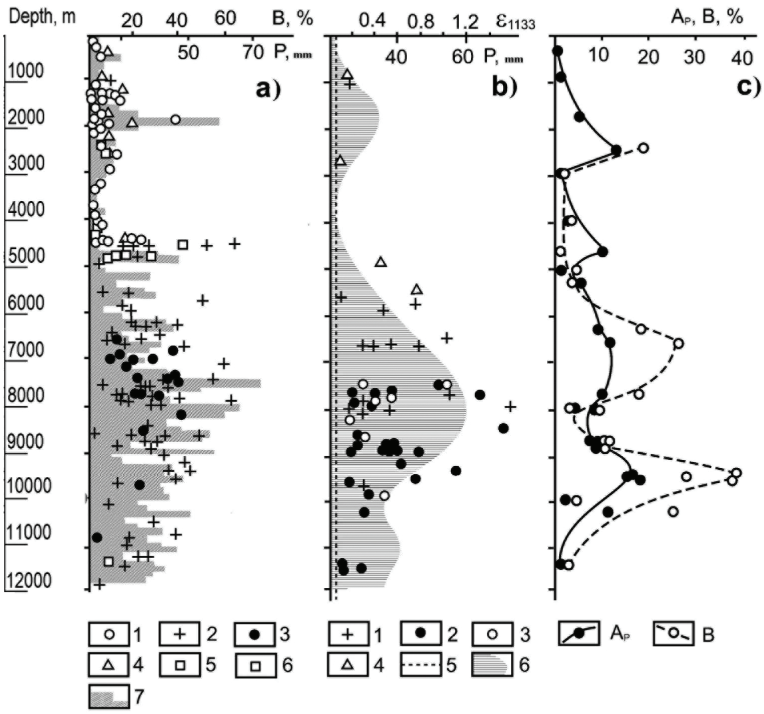

Fig. 4 Distribution of unit values of index *B*, elastic anisotropy factors ε_{1133} and A_P of rock samples along the SG-3 section (Gorbatsevich et al., 2002).
a – index *B*. 1 – metadiabase, peridotite; 2 – amphibolite, schist; 3 – gneiss, granite, migmatite; 4 – phyllite, tuff; 5 – metasandstone, metasiltstone; 6 –porphyry; 7 – average interval lateral dimension of the borehole.
b – factor ε_{1133}. 1 – schist; 2 – amphibolite; 3 – biotite gneiss, granite; 4 – phyllite; 5 – boundary line ε_{1133} = 0.05*;* 6 – envelope for the caverns of the greatest size *P*.
The data (a, b) have been obtained when measuring samples in lab conditions. c – factor A_P and index *B* (given in %). The data (c) determined under *in situ* conditions.

the section with most stable composition of rocks is characterized by rather high velocity homogeneity (V_P ≈6.7 km/s, V_S ≈3.8 km/s). The vertical velocity section allows a boundary between the Proterozoic and Archaean complexes (6842 m) to be identified. At a depth of ~9.5 km an interlayer (~150 m thick) of low velocity rocks is observed. The same interlayer was registered at a depth of 10.2-10.7 km. At other parts of the section the velocity gradient is rather low or the changes in V_P, and V_S occur nonsynchronously.

From the obtained velocity section (Fig. 3), it may be inferred that the difference in the data derived by the VSP, acoustic logging and calculation methods is not great. The calculation method of determining V_P and V_S by the rock mineral composition leads to results close to the real ones inherent in the massif. On the whole, the velocities of compression and shear waves calculated by the mineral composition can be used when interpreting the results of geophysical survey. But it can be done only with certainly isotropic or weakly anisotropic massifs, since the calculation method allows only average velocities of elastic waves in a rock to be obtained.

It follows from an analysis of the SG-3 vertical velocity section, that the velocities of compression waves are more sensitive to changes in rock composition than those of shear waves. Accordingly, the V_P velocities can be more useful for distinguishing boundaries between rocks with various composition. This property of compression waves can also be applied when distinguishing dislocations with a break in continuity, decompaction zone boundaries filled, for instance, by fluids. At the same time, the use of shear waves, especially the VSP polarization method, is quite effective for distinguishing highly anisotropic areas in the massif under study.

The parameters of elastic anisotropy measured on the samples both in lab and PT conditions adequate to those *in situ*, allow the Kola Superdeep Borehole section to be divided into two parts (Fig. 4). In the upper section down to a depth of 4.43 km isotropic and weakly anisotropic rocks prevail. Below 4.43 km

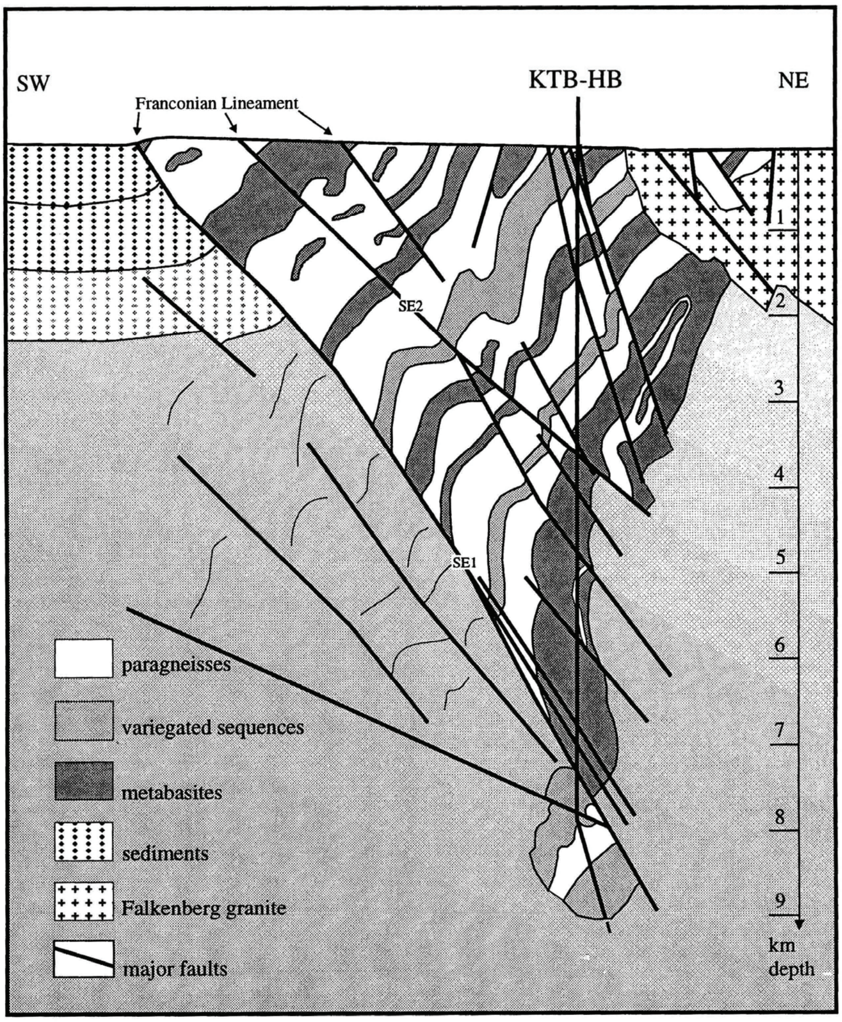

Fig. 5 Geological profile of Zone Erbendorf-Vohenstrauss (ZEV) that cuts the German superdeep borehole KTB (Emmermann and Lauterjung, 1997).

strongly anisotropic rocks mainly of orthorhombic symmetry displaying the effect of linear acoustic anisotropic absorption occur (Gorbatsevich, 1995). The radical difference in the degree of rock anisotropy along with the influence of velocity gradients and temperature may be the reason for seismic reflections. It is remarkable that this depth mark coincides with the inclined seismic boundary interpreted previously as a contact between the Proterozoic and Archaean complexes. To our mind, the boundary at a depth of 4.43 km is tectonic and does not coincide with the lithological boundary between the third volcanic and the third tuffaceous-sedimentary sequences.

A very important result of the investigations is corroboration, by simulating in situ conditions, of high anisotropy in the rocks occurring in the 6.3–10.2 km depth range. In these rocks, anisotropy factors (A_P) determined by compression waves were ~8-18%, and those (B) determined by shear waves ~11-38% (Gorbatsevich et al., 2002). The anisotropy characteristics (Fig. 4) are rather high and greatly exceed the values at which this property may be disregarded (Sharov et al., 2005).

GERMAN SUPERDEEP

The German superdeep borehole (KTB) section is the second most studied section. The borehole was drilled in the crystalline basement of the Bohemian massif in the south of Germany (Emmermann and Lauterjung, 1997). It is located in the tectonometamorphic massif of Zone Erbendorf-Vohenstrauss (ZEV). This massif is considered to be a shear zone formed 330-400 million years ago. The KTB pilot hole reached a depth of 4000 m. Drilling of the main hole was terminated in 1994 at a depth of 9101 m at 265 ^{0}C at the well bottom (Engezer, 1996).

The seismic section that passed through the KTB main hole points to a steeply dipping nature of the structural units in the borehole section. A profile passing through the ZEV zone and KTB was compiled on the basis of the obtained seismic and geological information (Fig. 5). The main rocks composing the

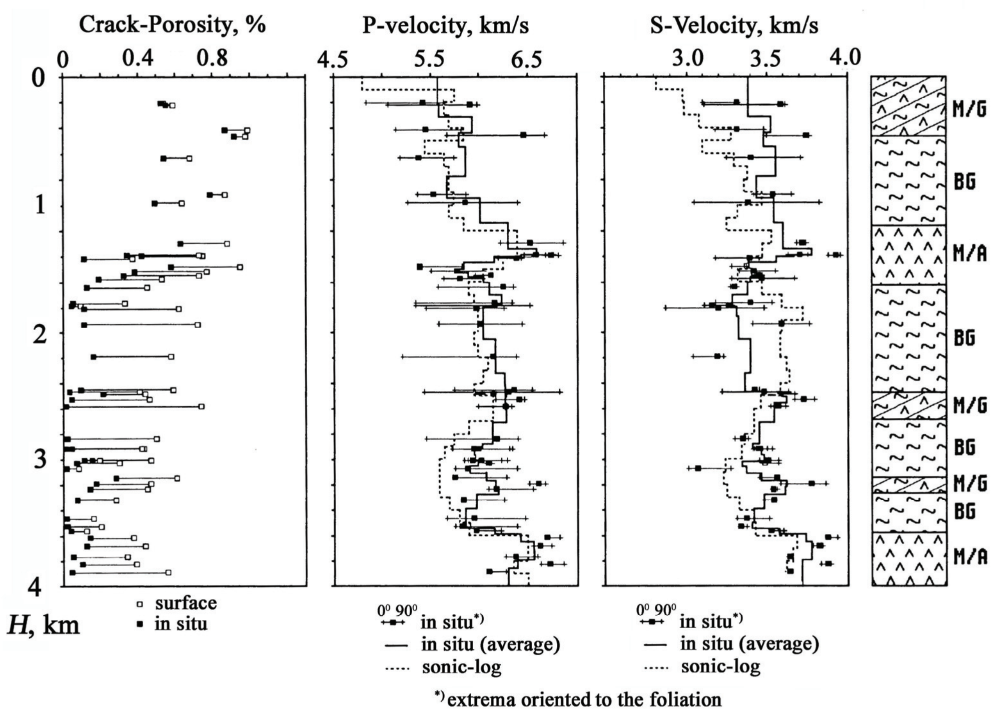

Fig. 6 Porosity, compression and shear wave velocities along the KTB section down to a depth of 4 km (Kern et al, 1991). Compression and shear wave velocities have been measured on the samples along and across schistosity under corresponding PT-parameters (solid lines). The results of acoustic logging are shown as dotted lines. M/G – interbedding of paragneiss and amphibolite, BG – biotite gneiss, M/A – alternation of metagabbro and amphibolite.

massif in the profile zone are paragneiss, metabasite, and their interbedding, granite and metasedimentary rocks. The rocks underwent two metamorphic cycles that resulted in strongly anisotropic schistose rocks.

By the accepted drilling technique, bulk selection of core from the KTB borehole was performed down to a depth of 4 km. Figure 6 gives the measured porosity, compression and shear wave velocities in the KTB section from the surface down to a depth of 4 km. The porosity, shear and compression wave velocities were measured in the lab and in simulated *in situ* conditions (Kern et al., 1991).

As follows from Fig. 6, the sample porosity becomes much less under simulated PT-conditions of the massif. In our opinion, this is related to the disintegration effect that is manifested during the release of samples from deep lithostatic stresses (Gorbatsevich, 2003). This conclusion is corroborated by a general tendency for porosity decrease with depth. According to the measurements on samples and sonic logging, the V_P velocities in the massif range from 5.6 to 6.6 km/s, those of V_S – from 3.3 to 3.8 km/s.

The study of the rock samples from the KTB 4.1–7.1 km depth interval showed that they are all elastic anisotropic and belong to orthorhombic symmetry type. The pattern of change in anisotropy factors with depth is the same for compression and shear waves. The linear acoustic anisotropic absorption (LAAA) effect was registered in virtually all samples. (Kovalevsky et al., 2004). The manifestation of this effect is most likely related to the preferred orientation of mineral grains and the formation of microcracks during drilling, core retrieval and lithostatic stress release.

Numerous seismic and petrophysical investigations conducted in the pilot and main boreholes together with a set of geophysical investigations performed at the surface, revealed that fracturing, sheeted zones and faults can greatly influence the variations of the characteristics obtained. The effect of lithologic boundaries is less pronounced and it is not always possible to distinguish them (Emmerman and Lauterjung, 1997).

URAL SUPERDEEP

The Ural superdeep borehole (SG-4) was drilled in the western limb of the Tagil megasynclinorium with the aim of comprehensive study of the Palaeozoic section of the Ural typical eugeosynclinal

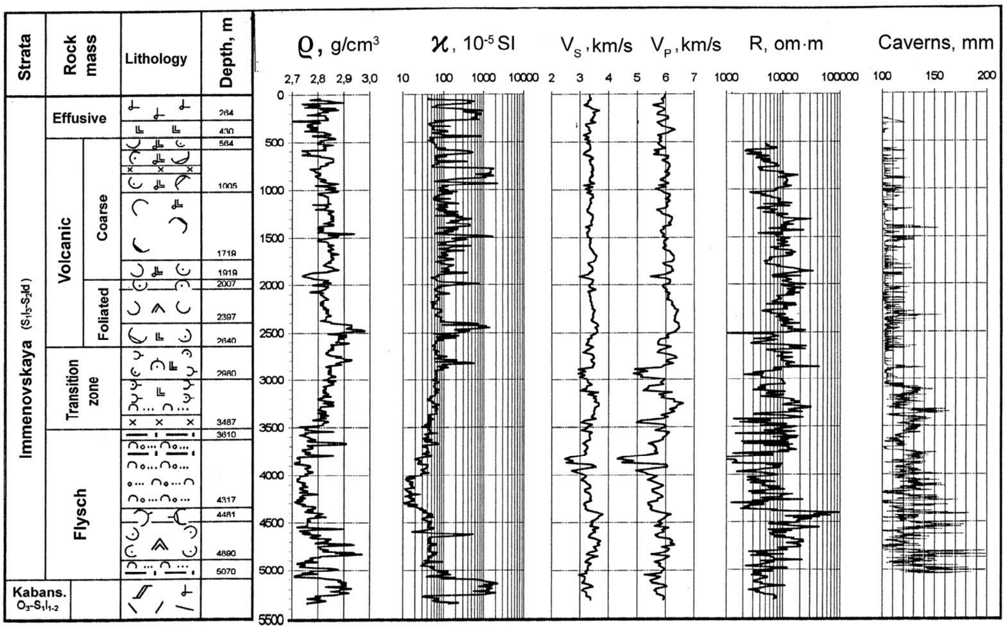

Fig. 7 Geological column and petrophysical properties of rocks from the Ural superdeep borehole section (Druzhinin et al., 1999).

zone. The borehole penetrated rocks of the Silurian Immenov Fm dated at 400-440 Ma. In the interval down to a depth of 5.5 km a uniform sequence of volcanoclastic basic and intermediate rocks has been cut. It is composed of coarse tephroid and tuff of pyroxene-plagiophyre basalt and andesite-basalt, whose pyroclastic material mainly belongs to plagiophyre andesite.

The geological column and petrophysical properties of rocks are given in Fig. 7. From the surface to a depth of 0.43 km, basalt and andesite-basalt lavas occur. Psephytic andesite-basaltic pumice tuff is located in the interval of 0.43-1.34 km and coarse andesite-basaltic tuff occurs in the interval of 1.34-1.92 km. From 1.92 km to a depth of 3.0 km, coarse leucoandesitic basaltic, andesitic and basaltic tuffs occur. Below 3.0 km, tuff sandstone and tephroid occur. Accordingly, the boundaries between the units are at 430, 1344.6, 1921 and 3001 m. Within the units, there are interlayers with quartz-carbonaceous veinlets and sulphide penetrated by a large number of healed fissures and other structural and textural peculiarities.

Below the transitional unit at a depth of 3.5-5.1 km, a flyschoid unit is located. By isotopic composition of rock-forming and ore elements (oxygen, carbon, sulphur and lead) one might suppose a homogenous high-temperature deep rock source that is typical of basalts (Zagruzina et al., 1989), which, in turn, should cause a similarity of physical properties of the rocks penetrated along the borehole section.

On the whole, this is corroborated by the data from petrophysical investigations (Fig. 7). Analysing the Figure, one may note that the rock density ρ varies mainly in the range of 2.71 to 2.95 g/sm^3. This index, as well as that for the SG-3 section (Gorbatsevich, 1995), does not show any regular correlation with sampling depth, but reflects variations in the rock mineral composition.

The same conclusion can be drawn from the variation in magnetic susceptibility χ with depth, which behaves like density. Thus, density varies in relation to the presence of siderophile elements.

The velocities of compression V_P and shear V_S waves do not show any dependence vs depth. The velocity of compression waves in the section is 4.5-6.4 km/s, that of shear waves - 2.5-3.7 km/s. Electric resistivity R of rocks showed much greater variation than other characteristics. The dimension (diameter) of the borehole that results from cavern formation showed clear depth dependence.

In the Ural and Kola borehole sections, at depths in the contact zones between rocks of various composition and genesis, elevated and high anisotropy of rocks accompanied by borehole cavernosity is observed.

Examples of large changes in rock properties within such zones are given in Figure 8. The Figure presents acoustopolarigrams of cubic rock samples taken within homogenous parts of the SG-4 section and from zones of heterogeneous rock composition (Gorbatsevich, 1995). Acoustopolarigrams with a shape close to circular were registered within homogenous areas. Acoustopolarigrams of samples from heterogeneous zones are four-petal figures which suggest strong elastic anisotropy of rocks. This is corroborated by a high anisotropy index B. The

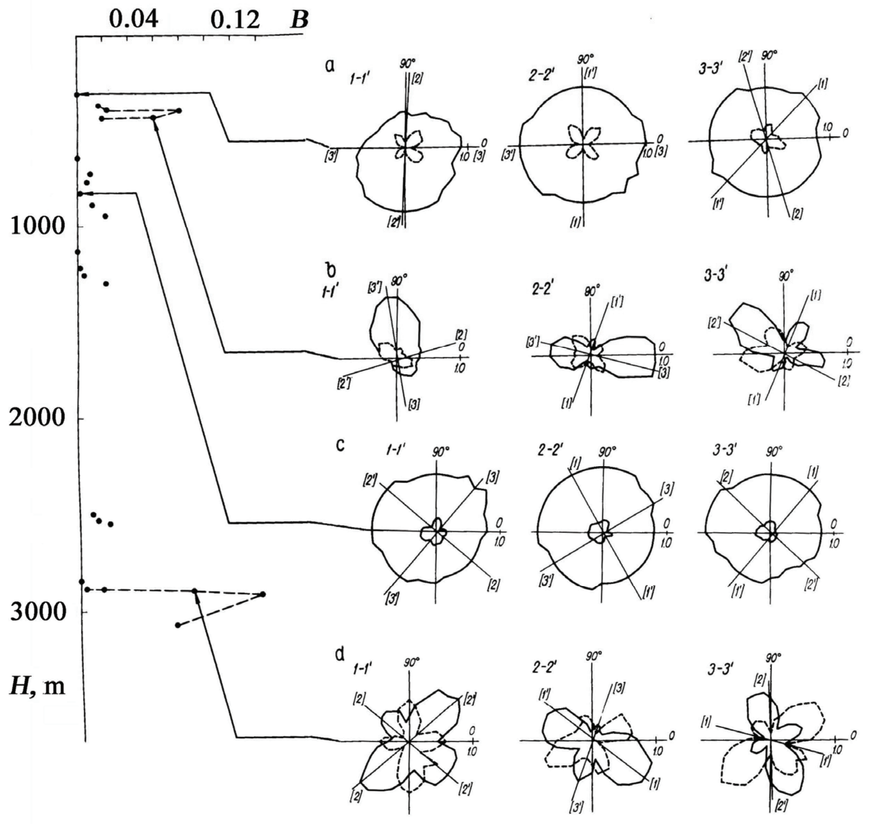

Fig. 8 Elastic anisotropy factor *B* and acoustopolarigrams of rock samples taken from homogenous and heterogeneous areas of the SG-4 section.

majority of acoustopolarigrams are extended along one of the anisotropy axes. This fact suggests manifestation of the linear acoustic anisotropic effect.

From a depth of 2867 m the results of measurements and determinations indicate the presence of a zone within which rock properties differ radically from those of overlying rocks (Fig. 8). From this depth, elastic anisotropy determined by compression and shear waves rises sharply.

Among rocks with marked anisotropy, rhombic symmetry prevails. This suggests that the rock was formed under geostatic and tectonic stresses. Judging from our measurements, the direction of the tectonic stress component is close to subhorizontal (Gorbatsevich, 1995). From a depth of 2867 m within the zone of cavern formation, a close correlation between rock elastic anisotropy and borehole lateral dimension (caverns) has been found. Judging from the lateral dimension values presented in Figure 7, borehole cavernosity increases down to a depth of 5 km. This allows one to conclude that high elastic anisotropy of the rocks from the Ural borehole will affect the interpretation of geophysical research results from a depth of about 3 km.

CONCLUSIONS

In this paper we have not used results obtained for other deep boreholes. They can be less suitable for description of a typical section of the crystalline crust. For instance, Gravbeg-1 (Sweden) and Vorotilov (Russia) boreholes were drilled within astroblemes, i.e. in massifs disturbed by external influence. The properties of rocks from the Saatly, Muruntau and Krivoi Rog borehole sections have been studied in less detail as compared with those from SG-3, SG-4 and KTB.

The wealth of accumulated geological, mineralogical, geophysical, petrophysical information, the results of the study of rock samples extracted from depth and taken at the surface from outcrops have been analysed and generalized both by Russian and international scientists within the international programmes IGCP-408 and INTAS-01-0314. The results of investigations revealed the presence of highly anisotropic rocks in the sections of deep and superdeep boreholes. The characteristics of velocity anisotropy are rather high and greatly exceed the value at which this property can be ignored (Sharov et al., 2005).

The analysis of structural and textural features of rocks comprising the crystalline massifs under consideration indicated the presence of two characteristic blocks in their geological-geophysical sections. One of them is mainly composed of homogenous, as a rule, volcanic rocks having one or several close stages of formation. In this block, isotropic or weakly anisotropic rocks dominate. Within the second block, the consequences of intense deformation, a high degree of recrystallization and rock anisotropy, interbedding of rocks are observed. Crystalline-schistose structures dominate. These structures are typical of highly deformed and metamorphosed sedimentary, volcanic and igneous rocks that experienced dislocation metamorphism under inequilateral pressure (stress). Such structures are typical of the lower SG-3 and SG-4 sections and virtually of the entire KTB section.

From the obtained vertical velocity sections of the crystalline massifs, it may be inferred that the difference in velocity characteristics determined by VSP, acoustic logging and simulated PT-conditions of the massif is slight. Virtually no depth dependence of velocity determined by these methods has been observed at SG-3 and SG-4. Compression wave velocities are 4.5-6.4 km/s, those of shear waves are 2.5-3.7 km/s. The calculation method for determining compression and shear wave velocities by mineral composition allows results close to real ones to be obtained, at least to a depth of 15-20 km. The rock density is mainly determined by mineral composition.

It follows from an analysis of petrographical determinations that compression wave velocities are more sensitive to compositional variations than those of shear waves. Accordingly, compression waves can be more useful for distinguishing the boundaries between rocks with different composition, fault dislocations, the boundaries between the decompaction zones filled, for instance, with fluids. At the same time, the use of shear waves, especially the VSP polarization method, is quite effective for distinguishing strongly anisotropic areas of the massif under study.

A new result of the investigations is the discovery of highly anisotropic rocks in the SG-3, SG-4 and KTB sections. For instance, in the massifs of the Kola and German superdeep boreholes such rocks dominate in the drilled sections. The presence of velocity anisotropy, as well as the complex structure of the rocks comprising crystalline metamorphosed units, greatly hampers interpretation of the results of seismic investigations conducted at the Earth's surface.

In conclusion it should be noted that deep and superdeep boreholes drilled in crystalline metamorphosed massifs are the only tool suitable for checking information obtained at the surface by various seismic methods, such as the reflection method, earthquake reflection method, CDP, refraction method, DSS etc. Scientific programmes for drilling deep and superdeep boreholes are also necessary for the development of algorithms for processing the results of geophysical investigations in structurally complex anisotropic massifs.

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