УДК 550.83.04:550.812:553.078; DOI 10.21455/gr2016.2-2

STRESS-STRAIN STATE AND VARIATIONS IN THE ELASTIC PARAMETERS OF THE HOST GRANITOIDS AT DIFFERENT DEPTHS, THE MO-U ANTEI DEPOSIT, TRANSBAIKAL

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Abstract. The results of petrophysical studies of the host granitoids samples from deep levels of the molybdenum-uranium Antei deposit, the Streltsovskoe ore field (SE Transbaikal), are considered. With the increase in depth, the samples observed demonstrated the decrease in velocity of ultrasonic waves and the reduction of values of the Poisson's ratio and elastic moduli that suggests a sharp decline in the ability of rocks to resist mechanical stress and increase in their fragility and fracture porosity. The degree of disturbance of the crystalline matrix also increases with the depth. The higher values of flow parameters imply conditions that are favorable to the circulation of ore-bearing solutions and ore localization. Accordingly, an increase in quantity and thickness of ore bodies with the depth can be expected. However, the real situation in the deposit is totally different. Both the quantity and the thickness of ore bodies decrease with the depth. Preliminary calculations of the modern normal stresses indicate the change in tectonic regime from tension to compression at deep (>750 m) horizons of the deposit. Thus the instrumental studies of the stress-strain state of the Antei deposit should be conducted and the project on the directional drilling for detection of hidden ore bodies should be developed.

Keywords: granitoids, stress-strain state, uranium deposit, petrophysical parameters, tectonic regime, ultrasound**.**

Introduction

The Antei deposit is located in Transbaikal region near Krasnokamensk situated 460 km south-east of Chita. The extraction of the molybdenum-uranium ore is done by underground method. The Streltsovskoe ore field including the deposit, is located in the caldera of the same name formed in the late Mesozoic. The stockwerk-vein steep ore bodies of the deposit are localized in the late Paleozoic crystalline caldera basement and are controlled by the branches of submeridional faults forming the Central fault zone. The fault that controls the mineralization in the Antei deposit can be traced from the basement to the cover of the late Mesozoic volcanogenic rocks. Seams developed in the hanging wall of the fault represent the main ore-containing gaps that are up-dip limited by the cover bottom [*Laverov et al.*, 2008; *Petrov et al.*, 2009].

For finding new ore bodies and ensuring the safety of mining operations at the deposit the knowledge about the petrophysical features of rocks is necessary. This article focuses mainly on the elastic properties of rocks, that include the velocities of ultrasonic longitudinal (V_P, km/s) and shear (V_S, km/s) waves, dynamic moduli of elasticity (K is the bulk modulus , GPa; G is the shear modulus, GPa; E is the Young modulus, GPa), and the Poisson's ratio μ.

Currently the study and determination of the regularities of ultrasonic wave propagation through anisotropic media (including rocks) is of particular interest. The ultrasonic methods are based on the close relationship of the wave velocity and its damping with physical properties and structure of the medium. These methods are intensively developed due to the possibility of their application to the wide range of tasks, high accuracy of measurements, and relative simplicity of the used equipment [*Yamshchikov*, 1982].

The study of minerals and rocks focuses on the physical anisotropy. After polarizers were introduced in microscope design in the beginning of XIX century, methods of optical polariscopy appeared and took the major place in petrography. Microstructural features of minerals structure allowed the founder of structure crystallography E.S.Fedorov (1853-1919) to create a complete classification of 230 spatial point symmetry groups associated with the anisotropy of optical, dielectric, magnetic, elastic, thermal, and other properties. The most important is the study of anisotropy of elastic properties, since it involves the behavior under load of different natural objects and materials.

If the theory of anisotropy of elastic properties of media is developed in detail in numerous works (see, for example, [*Lekhnitsky,* 1977; *Petrashen*, 1980] and others), the situation with the experimental methods of studying the elastic anisotropy is much worse. The practical use of optical polarization methods is limited, in particular, by the opacity of the rocks. This is what causes the necessity of the ultrasonic methods application.

Theoretical analysis

Analysis of the results of the ultrasonic research gives the possibility to determine the anisotropy of the elastic properties of rocks related to their structural and textural features. Note that the elastic parameters depend not only on the composition and structure of rocks but also on the degree of their deformation, stress state at different depths, and geodynamic conditions of formation.

There is a large amount of instrumental methods for the determination of the stress-strain state of the rocks, among which three classes can be distinguished according to [*Shkuratnik and Nikolenko*, 2012]:

geological methods (analysis of geological and geotectonic features of the massif; estimation of the stress-strain state on the base of visual examination of mines; estimation of the stress-strain state by the core disking);

geomechanical methods (method of the core unloading; method of partial unloading; method of fissure unloading; method of elastic inclusions; method of hydro fracturing; method of the differential pressure; method of overcoring);

geophysical methods (ultrasonic method; gamma method; electrometric method; sound ranging method; methods based on the use of memory effects in rocks and composite materials placed to the massif).

These methods became widespread in our country (for example, in Lovozersky rare-metal deposit, North Ural bauxite deposits, Tashtagol iron-ore deposit, etc.), as well as abroad (underground research laboratory Äspö in Sweden, Grimsel in Switzerland, ONKALO in Finland, White Shell in Canada, etc.).

In the Antei deposit discussed in this work, currently, the work on instrumental estimation of the stress state of the rock massif is started [*Rasskazov et al.,* 2012] and the creation of the numerical model of its stress-strain state is studied [*Kozyrev, Semenova, and Avetisyan*, 2014; *Shchukin et al.*, 2015; *Petrov et al.*, 2015].

Further the data on the stress-strain state of rocks in the Antei deposit will be analyzed compared with their structural and petrophysical characteristics.

Note that up to the present time there is no generally accepted terminology to describe the stress-strain state of the rocks. International Society for Rock Mechanics (*ISRM*) suggested to accept the terminology by *Hudson, Cornet, and Christiansson* [2003], that will be used in this work applied to the Antei deposit stress-strain state (Table).

Terms used to describe the stress-strain state of the rocks according to [*Hudson, Cornet, and Christiansson,* 2003]

Natural stresses	Tensions in the massif before its opening by mine working
Regional stresses	The stress-strain state in relatively large geological space
Stresses of the distant field	The stress-strain state beyond the influence of mining
Tectonic stresses	The stress-strain state caused by the movement of geological mass
Gravitational stresses	The stress-strain state caused by the column of the overlying rocks
Local stresses	The stress-strain state in small geological space
Stresses of the near-field	The stress-strain state in zone of mining influence
Induced stresses	Natural stresses associated with the tunneling activity
Residual stresses	The stress-strain state associated with the previous tectonic activity
Thermostresses	The stress-strain state associated with the temperature influence
Paleostresses	Natural stresses of previous geological eras

Computational model of the rock stress-strain state

The models of the stress-strain state inevitably schematize the characteristics of rocks and their internal structure. In engineering-geological practice the most widespread model considers the medium as homogeneous and isotropic. Such an assumption poorly corresponds to reality but allows using simple analytical models and modeling methods for solving the given tasks. The actual rock massifs are usually inhomogeneous and anisotropic by strain and strength properties due to their mineral composition, breaking-fractured structures, degree of watering and other factors.

Determination of parameters of the modern stress field in different parts of the Earth [*Zoback*, 1992; *Fuchs and Müller*, 2001] showed that horizontal tectonic stresses *T* are 10–40 MPa. In the case of the Antei deposit, *T*=15 MPa was taken for calculations. Generally this value corresponds to main normal stresses measured instrumentally far from the Baikal rift zone (www.world-stress-map.org). Instrumental methods also helped to determine the shear (strike-slip) nature of the modern stress field in regional scale [*Rasskazov et al.*, 2014].

On the basis of data about average mechanism and orientation of axes of the main pressure and tension stresses in area of Krasnokamensk, using the formulas, presented in [Modelirovanie …, 2003], the calculations of main normal stresses were carried out for the shear regime implying

$$\sigma_H=\sigma_1>\sigma_v=\sigma_2>\sigma_h=\sigma_3,$$

where σ_v are vertical stresses; σ_H, σ_h are primary and secondary horizontal stresses; σ_1, σ_2, σ_3 are main normal (maximum, intermediate and minimum) stresses; all stress are measured in MPa.

The analytical solution of the problem on the modern stress-strain state of rocks requires a number of boundary conditions. It was set, that

– rocks are subjected to regional subhorizontal compression and are considered as homogeneous (not fractured) isotropic, elastically deformed massif with horizontal surface;

– tectonic regime is of shear (strike-slip) nature – $\sigma_H=\sigma_1>\sigma_v=\sigma_2>\sigma_h=\sigma_3$;

–stress field due to the tectonic forces is homogeneous for the whole section and horizontal stresses caused by tectonic forces are 15 MPa ;

– the average rock density ρ is 2.7 g/cm^3, the Poisson's ratio μ is 0.25;

– coefficient of lateral resistance $\xi=\mu/(1-\mu)=0.33$;

– pore fluid pressure P_f=0;

– values of tangential stresses τ_c in volume of deformed rocks are taken in the form $\tau_c=[(\sigma_1-\sigma_3)/2]\sin2\varphi\sim5.62\pm0.02$ MPa, where $(\sigma_1-\sigma_3)$ is differential stress; $\varphi=45°$ is angle of internal friction (angle between axes of effective normal and principal normal stresses).

Existing stresses in the massif are calculated according to the following formulas:

$$\sigma_v = \rho gh,\ \sigma_H = \xi\rho gh + T,\ \sigma_h = \xi\rho gh + \mu T,$$

where g is gravity acceleration, m/s^2; h is a distance from the surface, m.

The results of calculations for accepted initial data and boundary conditions are graphically shown in Fig. 1 and are listed in the following table, where the depths (H, m) of the considered horizons are given.

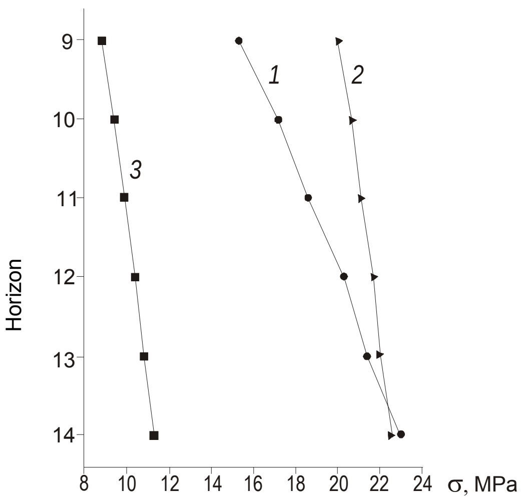

Fig.1. Change in values of normal stresses in the section of the Antei deposit for taken boundary conditions (horizons 9–14), 1 is vertical stresses σ_v; 2 is main horizontal stresses σ_H; 3 is secondary horizontal stresses σ_h

Horizon	H, m	σ_v, MPa	σ_H, MPa	σ_h, MPa
9	568	15.3	20.0	8.8
10	636	17.2	20.7	9.4
11	690	18.6	21.1	9.9
12	750	20.3	21.7	10.4
13	810	21.8	22.2	10.9
14	870	23	22.6	11.3

Taking into account the given data and on conditions that the pore fluid pressure P_f is constant, and differential stress $(\sigma_1-\sigma_3)$ is less than four values of ultimate tensile strength of rocks (Griffiths fracture criterion), at first approximation can be analyzed the nature of changes of modern tectonic stress field in the section of the massif. The Griffiths criterion suggests that the fracture occurs when the infinitesimal extension of the crack will release more elastic energy than it is required for the formation of new surfaces. According to the principle of Griffiths, crack existing in the body will spread in an avalanche if the energy release of the elastic deformation per unit of its length will exceed the work for breaking ties.

In our model for shear stress-regime and T=15 MPa, the vertical stresses σ_v increase with the highest rate and become closer to the main horizontal stresses σ_H with depth. As a result at depths more than 810 m (below the horizon 13) the shear regime changes to the normal regime – $\sigma_v > \sigma_H > \sigma_h$. In other words at these depths the shear regime of horizontal compression changes into the geodynamic tension regime with normal displacements along the fault planes.

The nature of the deformation behavior of rocks and kinematic characteristics of ruptures obvoiusly depend on the value of tangential stresses. In our calculations carried out according to [*Jaeger*, *Cook*, 1979], tangential stresses τ_c were taken to be equal to ~5.62±0.02 MPa. It is generally assumed that the level of tangential stresses and consequently the probability of shear dislocations in the fractured systems decrease with the depth due to the increasing lithostatical load. However the theoretical regularities are often not consistent with the real geological situation when with the depth the predisposition of ruptures or their separate segments to shear dislocations increases. Such conditions arise mainly because of the reorientation (virgation) of displacers' planes and change of the angle to the axis of main compression ($\sigma_1=\sigma_H$ for shear tectonic regime). At deep (>750 m) horizons of the Antei deposit in conditions of the right-side shear and orientation of the axis of main horizontal stresses S_H at an angle of 50 to 80° to meridian [*Petrov et al.*, 2009, 2015] the most prone to the shear dislocations are the fault segments and large cracks, that are oriented in E-NE–W-SW and E-SE–W-NW directions.

The results of the analytical solution of the problem of general laws of modern stress-strain state of geological environment of the Antei deposit comes to the following.

1. In conditions of regional subhorizontal compression in the thickness of granite at depths more than 810 m there is a change of shear tectonic regime to the normal one. As a result the probability of normal-shear dislocations increases.

2. The lithostatical load increasing with depth reduces the level of tangential stresses (cleavaged), but in conditions of right-side shear and orientation of the axis S_H at an angle of 50 to 80° to the meridian, E-NE–W-SW and E-SE–W-NW directions of structures are dominant in increase of shear dislocations.

These conclusions require the instrumental confirmation. However the probability of changes in geodynamical regime with depth is high, which is confirmed by the measurements in the underground research laboratories located in granite massifs [*Ask, Stephansson, Cornet*, 2001].

Below are given the results of the petrophysical studies of host granitoids of the Antei deposit that also indicate the change of deformation regime from shear (compression) to normal faulting (tension).

Types of host granitoids of the Antei deposit

Under the granitoids we understand the whole complex of granites of different composition from leucocratic to melanocratic varieties that differ in petrographic composition and textural-structural features as well as in petrophysical parameters. At the Antei deposit, the host rocks are granitoids that underwent the metasomatic and strain transformations of various type and intensity (Fig.2).

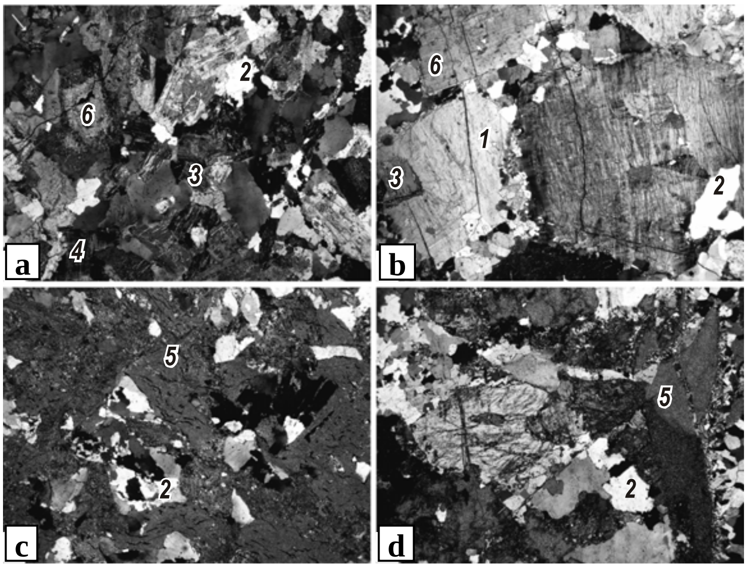

Fig. 2. Types of transformed granitoids of the Antei deposit: (*a*) unaltered biotite granite, (*b*) high-temperature quartz-kalifeldspath metasomatite (kalifeldspathite); (c) cataclastic and brecciated hydromicaceous metasomatite; (*d*) intensive brecciated hydromica with areas of silicification. Photographs of thin sections where by numbers are marked (*1*) feldspar, (*2*) quartz, (*3*) biotite, (*4*) microcline, (*5*) hydromica, (*6*) plagioclase

Methods of research

Studies were carried out at horizons 9–14 of the Antei deposit, located at the depths ~568, 636, 690, 750, 810 and 870 m from the surface (see table in Fig. 1). The sets of oriented samples of host granitoids were selected at the each horizon. The laboratory measurements were conducted on cubic samples with sides not less than 50 mm. Samples were marked by the coordinate axes *X*, *Y* and *Z* in the left Cartesian coordinate system (Fig. 3).

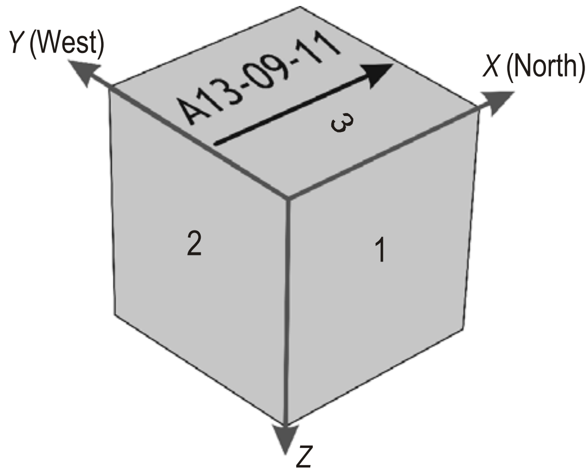

Fig. 3. Sample for the ultrasonic measurements. Black arrow on the top side is plotted during the selection of the sample and marks the North direction; numbers next to the arrow is the sample number. 1, 2, 3 are planes of sonic test.

Velocities of elastic waves were measured for each direction (*X*, *Y, Z*) using the complex, consisting of generator-receiver of ultrasonic waves *Panametrics PR*5072 (USA) and a pair of radiators of *P*- and *S*-waves with eigenfrequency of 1 MHz. All measurements were conducted on the samples in two states – air-dry and water-saturated. Drying of the samples was carried out in the drying cabinet at the temperature of 80 °C and lasted for three hours. Water saturation of the sample was achieved by immersion in a bath for 6-7 days with a consecutive pouring of water. Note that considering the peculiarities of the structure of fracture-pore space of the granitoids such method of saturation is optimal for them [*Petrov and Nasimov*, 2014]. Moreover, the open fracture and porosity of all samples did not exceed 1 %.

The elastic waves velocities measured in the water-saturated state correspond more to their velocities in the massif than velocities in dry samples as the fracture systems that occurred during the collection work and the following technology processing of the samples are filled with water. Due to the low porosity the influence of water on the velocity values of both *P*- and *S*- waves is insignificant.

Involving data about the density of the samples according to formulas, presented in [*Burmistrov et al.*, 2009], we calculated the bulk *K* modulus, shear modulus *G*, Young modulus *E*, and the Poisson's ratio μ:

$$K = \rho(V_P^2 - 4/3V_S^2),\ G = \rho V_S^2\ ,$$

$$E = \rho V_S^2(3V_P^2 - 4V_S^2)/2(V_P^2 - V_S^2) = [(G/2)(3V_P^2 - 4V_S^2)]/(V_P^2 - V_S^2),$$

$$\mu = (V_P^2 - 2V_S^2)/2(V_P^2 - V_S^2).$$

In these formulas ρ is the density of the samples, g/cm^3; V_P is the velocity of the longitudinal waves, km/s; V_S is the velocity of shear waves, km/s; the Young modulus E was calculated under adiabatic conditions.

Dependences of the average values of V_P, V_S, K, G, E and μ in the rock massif on depth are presented in Fig.4. The moduli of elasticity are calculated for the water-saturated sample because in this case they are closer to the moduli values in massif. Presented values are calculated as an arithmetic average for each sample in three directions and then averaged for all investigated samples.

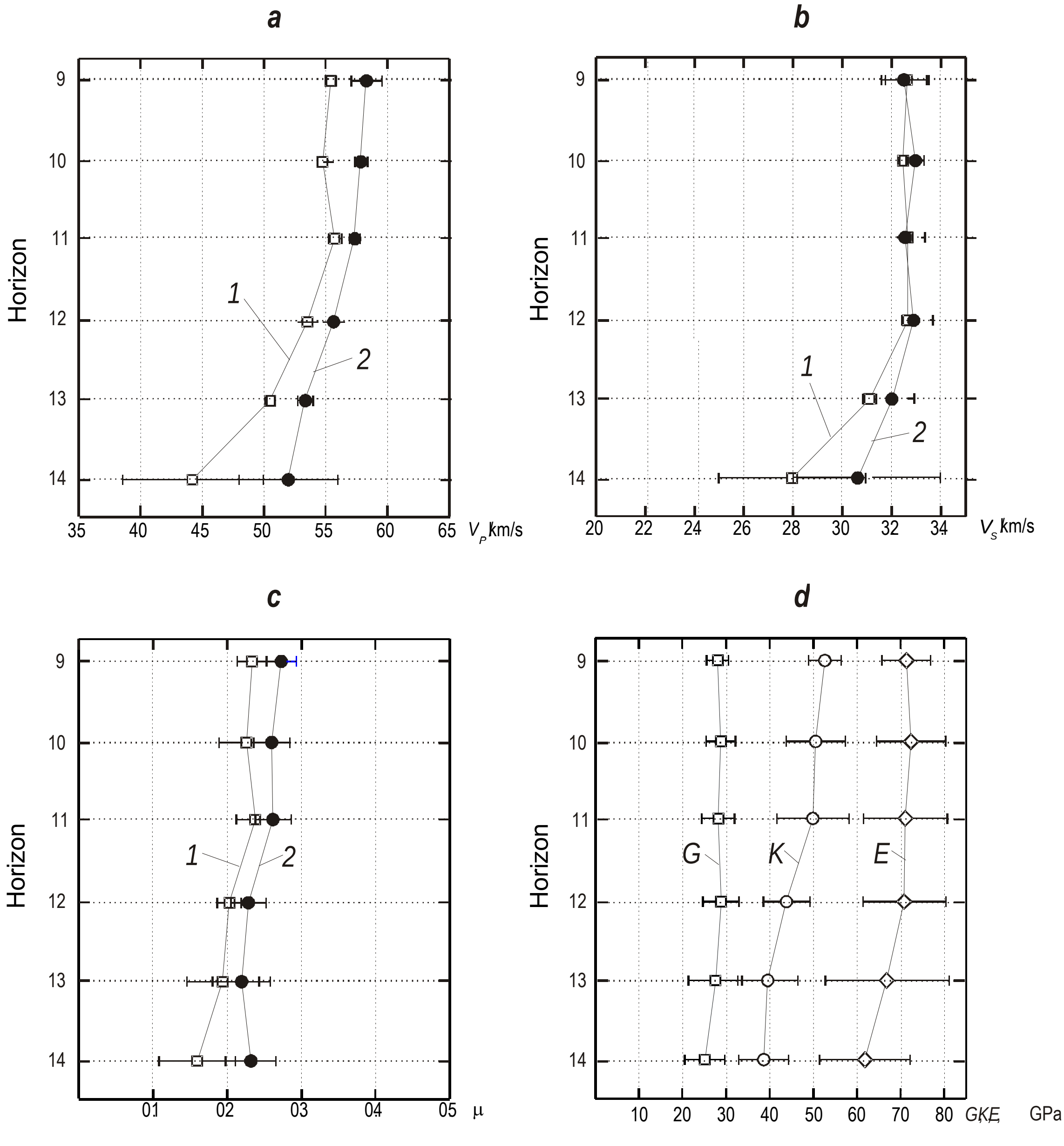

Fig. 4. Mean values of (a) V_P and (b) V_S, (c) the Poisson's ratio μ and (d) elasticity modules G, K, E at different depths. In *a–c*: *1* is the dry condition of the sample, *2* is a water-saturated condition. Horizontal segments show the standard deviations of the determined values.

Let us consider each parameter in detail. The V_P values (Fig. 4 *a*) at horizons 9–11 are almost constant and equal to ~5.5 km/s in the dry state and ~5.7 km/s in the water-saturated state. The difference between velocities measured in dry and water-saturated states is minimal at horizon 11, where it is equal to ~0.1 km/s (in other cases – ~0.2 km/s), and is maximal at horizon 14. At horizons 12 and 13 velocities of longitudinal waves sharply reduce reaching at horizon 14 the value of 5.4 km/s in dry state and 5.2 km/s in water-saturated state (Fig. 4 *a*).

Shear wave velocities display the similar behavior (Fig. 4 b). The sharp reduce in velocities begins from horizon 13. If average V_S values are 3.26 km/s in dry state and 3.27 km/s in water-saturated state at horizons 9–12, these values are 3.11 km/s and 3.2 km/s, respectively, below horizon 13. For the samples in dry and water-saturated states, the minimum differences in velocities V_S are marked at horizon 11, maximum, at horizon 14. Thus, at horizons 12–14 the decrease in both velocities V_P and V_S is observed, which indicates that at these depths, the granitoids begin to lose their integrity and the fracturing and porosity of rocks increases.

For the Poisson's ratio μ (Fig. 4 c) the following regularity is noted. At horizons 9–11, as in case with velocities of longitudinal waves, the values of μ remain approximately in the same range both in the dry state (~0.23) and in water-saturated (~0.26) state, but starting from horizon 12, they sharply decrease. As a result at horizon 14 the values of μ reach 0.16 in dry state and 0.22 in saturated state, which means that below horizon 12, the fragility of host granitoids of the deposit increases.

Consider the dynamic moduli of elasticity (Fig. 4 d). Whereas the shear modulus *G* displays approximately the same values (~28 GPa) at each horizon, the bulk modulus *K* and the Young modulus *E* actually repeat the behavior of velocities of longitudinal waves (Fig. 4 *a*) and coefficient μ (Fig. 4 c). At horizons 9–11, the values of these two moduli are approximately constant: $K\approx51$ GPa, $E\approx71.4$ GPa, and below the horizon 12 their values noticeably decrease. At horizon 14, *K* values fall to 39 GPa and *E* values, to 62 GPa (Fig. 4 d).

This behavior indicates a sharp decrease in the rock ability to resist the mechanical influence with depth. In addition the rocks become more brittle, fractured and porous. Such situation creates favorable conditions for circulation of ore-bearing solutions. Due to this the quantity and capacity of ore bodies with depth should increase. However, we can analyze only the modern state of host rocks. Reconstruction of paleotectonic conditions and paleofiltering environment of hydrothermal mineralization at the Antei deposit require special consideration in which the obtained petrophysical data can form the informational basis for construction.

Calculations of modern main normal stresses in the massif cross-section show that at deep (>750 m) horizons of the deposit (horizon 12 and below), the tectonic regime can change from the right-lateral strike-slip faulting to normal regime [*Minaev et al.*, 2013]. So far, these calculations are not supported experimentally, but they correspond to the main trends observed in underground research laboratories located in granite massifs, for example, in the underground laboratory Äspö (Sweden) (Fig. 5).

In accordance with changes in values σ_H, σ_h, and σ_v, the horizons with different tectonic regime can be distinguished. The calculations of stresses are carried out using the formulas given above with ρg=0.026 MPa/m; actual values of σ_H, σ_h and σ_v are determined by the hydraulic fracturing.

Results of hydraulic tests (hydraulic fracturing method) in boreholes show that the thrust regime dominates approximately to the depth of 250 m, and below it is replaced by the shear regime. Further, approximately from the depth of 510 m the regime change reversely to the thrust that remains at least to the depth of ~750 m [*Ask, Stephansson, and Cornet,* 2001].

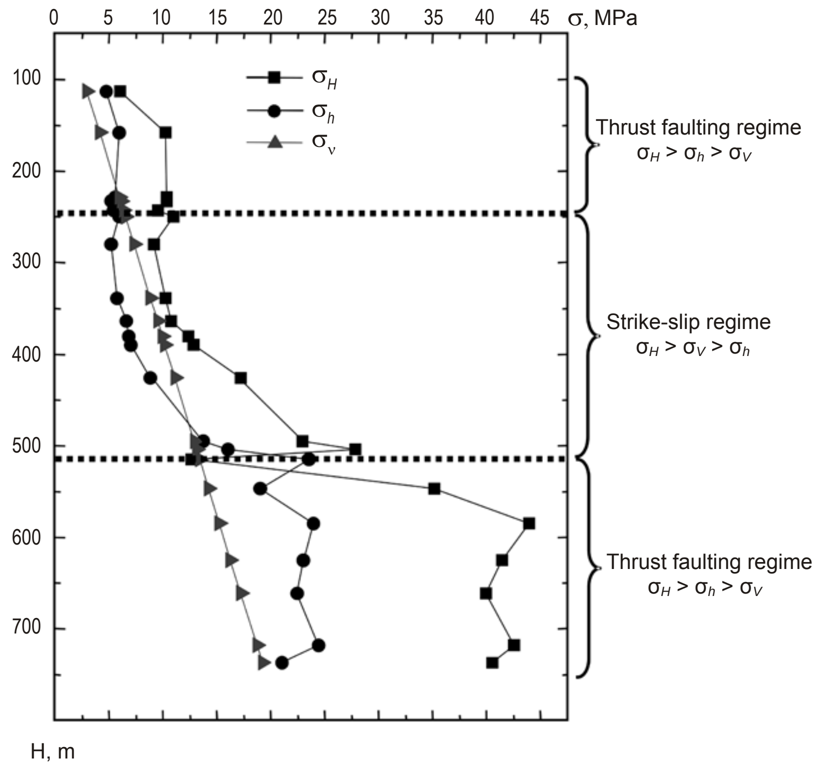

Fig. 5. Depth changes in main normal stresses in the granite cross-section in the underground research laboratory Äspö (using data from [*Ask*, 2003])

Note that although each geological situation is unique, the granite massifs of the Äspö laboratory and the Antei deposit are mainly similar in structure and properties of rock [*Laverov et al.*, 2008].

Conclusions

The results of studies on the samples, selected from different horizons of the Antei deposit show that starting from the depths of 750 m, the velocity of ultrasonic waves, the Poisson's ratio, and the elastic moduli decrease. This is the evidence that rocks become more brittle, fractured and porous, resulting in a sharp decline in their ability to resist the mechanical influence.

In case of high values of filtration parameters, the conditions favorable for the circulation of ore-bearing solutions should be created. However reconstruction of paleotectonic conditions and paleofiltering environment of hydrothermal mineralization at the Antei deposit require special consideration. The obtained petrophysical data can form the informational basis for the reconstruction.

Preliminary calculations of modern main normal stresses in the massif cross-section show that at deep horizons of the deposit (>750 m, horizon 12 and below) the tectonic shear regime is replaced by the normal one. These calculations are not supported by instrumental data, but generally correspond with the trends, observed in European underground research laboratories located in granite massifs.

The obtained data indicate the necessity of the instrumental studies of the stress-strain state of the Antei deposit and the project on the directional drilling for detection of ore bodies that were probably displaced in the result of tectonic activity, should be developed.

Acknowledgements

When writing the article the authors were constantly referring to the materials of untimely deceased R.M. Nasimov, our friend, good companion and a great specialist.

The work is partly supported by the Program I.4П for basic research of the RAS Presidium and by the Russian Foundation for Basic Research, project no. 15-05-01369_a.

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