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PHYSICAL, MECHANICAL AND DEFORMATIONAL PROPERTIES OF METABASALTS, AMPHIBOLITES AND GNEISSES FROM KSDB-3 COMPARED WITH SURFACE ANALOGUES

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ABSTRACT
Physical and mechanical properties were carried out on core samples of metabasalts, amphibolites and gneisses from various depths of the Kola Superdeep borehole (KSDB-3) measured at uniaxial and triaxial loading conditions. The same tests were performed on the samples of their surface analogues. The comparative investigations between values obtained on the core samples from the various depths in the borehole cross section and their surface analogues gave valuable information about changes of these properties as a function of depth. An idea of the stress condition assessment based on laboratory tests was initiated. The results of tests are in some cases affected by the small amount of rock material that we had at our disposal.

KEYWORDS: samples of metabasalts, amphibolites and gneisses, laboratory tests at uniaxial and triaxial loading conditions, physical a mechanical properties

1. INTRODUCTION

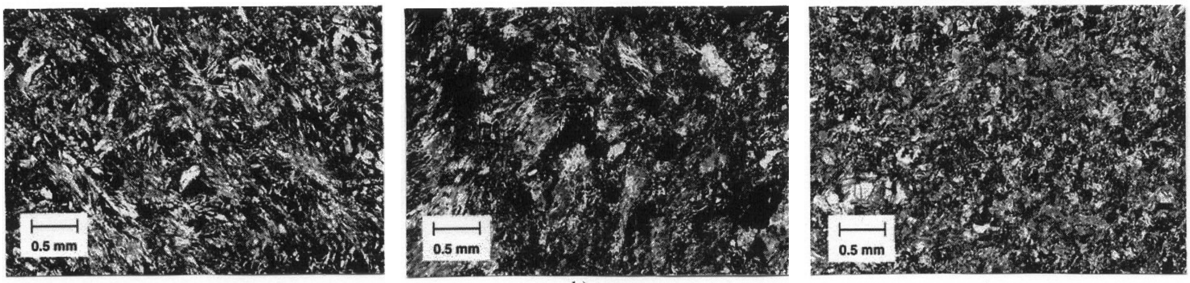
In the frame of the Project IGCP No. 408 „Comparison of composition, structure and physical properties of rocks and minerals in the Kola Superdeep Borehole (KSDB-3) and their homologues on the surface" and INTAS Project No. 0314 „Geodynamics in the cross-section of the Kola Superdeep" we had opportunity to study nine core rock samples recovered from various depths of the deepest borehole of the world, which is located at the Kola Peninsula in the Russia. We had also to disposal samples of their surface analogues collected from outcrops within the Pechenga district.

Experimentally determined physical and mechanical properties of the mentioned core samples from various depths of the Kola Superdeep borehole (KSDB-3) measured at uniaxial and triaxial loading conditions were carried out in our laboratory. The data include grain density, bulk density, porosity, compressive strength, axial, lateral and volumetric strains, deformation modulus, Young's modulus and Poisson ratio. The same tests were carried out on the samples of their surface analogues. In this case, the surface analogues are considered rocks that primarily belonged to the same rock complexes, i.e. rocks formed at the same time in similar geodynamics environment with similar structure and average chemical and normative mineral compositions. The comparative investigations between values obtained on the core samples from the various depths in the borehole cross section and their surface analogues gave valuable information about changes of these properties as a function of depth. Furthermore, they help to increase our understanding the nature of the differences between the properties of similar rocks recovered from different depths and from surface.

Core fragmentation, caused by the drilling method and fracturing during core lifting from great depths to the surface, makes collection of core samples large enough for standard rock mechanics laboratory tests very difficult. Therefore the results of tests are affected by the small amount of rock material that we had at our disposal.

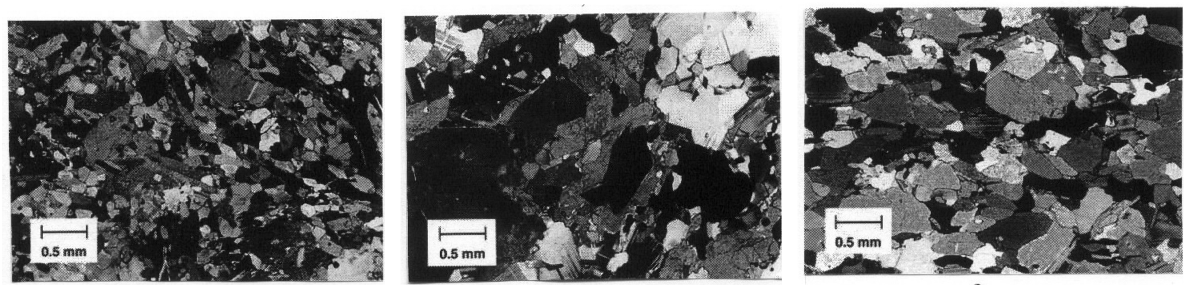
2. ROCK SAMPLES

Studied rocks of core samples can be subdivided into tree groups (Šrein, 2004). First group represents extremely fine-grained basic metavolcanic rocks (metabasalts) from Proterozoic Karelian Complex showing characteristic intergrowths of hornblende and plagioclase grains (Figs. 1 a-c) recovered from depths of 3043 m, 3530 m and 4389 m. Second group is form by amphibolites of Archean Kola-Belomorian Complex characterized by coarser grain than the previous rocks and display compositional layering defined by alteration of plagioclase-rich and hornblende-rich bands (Figs. 2 d-f) recovered from a depth of 7951 m, 8942 m and 9904 m. Third group represents biotite gneisses from depths of 6849 m, 7913 m and 8411 m (Figs. 3 g-j).



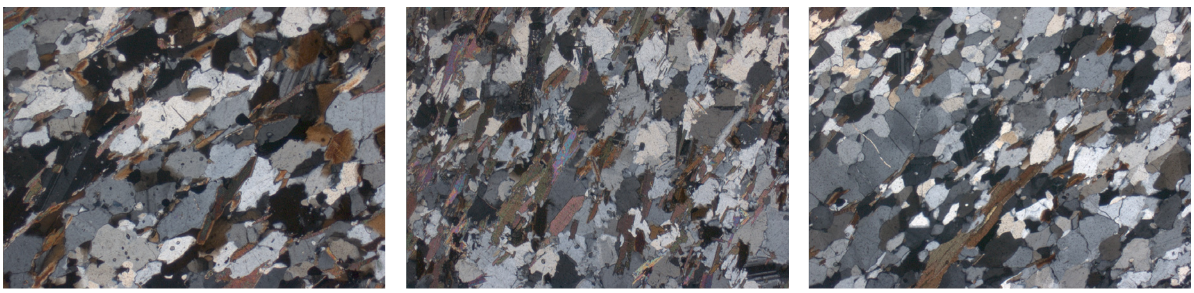
a) b) c)

Fig. 1 Microphotographs illustrating microfabrics of studied core samples of metabasalts: a) sample from depth 3043 m, b) sample from depth 3530 m, c) sample from depth 4389 m



d) e) f)

Fig. 2 Microphotographs illustrating microfabrics of studied core samples of amphibolites: d) sample from depth 7951 m, e) sample from depth 8942 m, f) sample from depth 9904 m



g) h) j)

Fig. 3 Microphotographs illustrating microfabrics of studied core samples of gneisses: g) sample from depth 6849 m, h) sample from depth 7913 m, j) sample from depth 8411m

3. METHODS, INSTRUMENTS AND PROCEDURES

Laboratory tests of the all rock samples were carried out following ”Suggested Methods” of the International Society for Rock Mechanics Commission on Standardization of Laboratory and Field Tests.

The grain density (mass per unit volume) was determined applying the pyknometer method. The bulk density, mass of rock, including solid particles, water and air, contained in a unit volume, was determined on irregular specimens with coated with paraffin wax using the water displacement method based on Archimedes’s law. The porosity, defined as volume of pores to total volume of rock specimen, was determined from formula:

$$n = 1 - (\rho_d / \rho) ,$$

where ρ_d is bulk density of the dry specimen (after drying at 105 °C) and ρ is grain density.

Cylindrical specimens 25 mm in diameter and 50 mm in height were prepared from the rock samples by diamond drilling to carry out unconfined compressive tests and triaxial strength (Lama and Vutukuri, 1978). During tests the specimens were loaded parallel to the cylinder axis, at core specimens corresponding to the direction of the borehole.

Compressive strength σ and axial (ε_A) and lateral (ε_L) strains were measured at uniaxial compression as well as during triaxial loading with 50 MPa and 100 MPa confining pressure.

Three cycles of loading and unloading of the core samples and one cycle of loading and unloading of surface analogues in the loading process during the uniaxial compression test were applied to calculate deformational properties. After the last cycle, the samples were loaded until failure. The uniaxial compression tests were made in a hydraulic press with a maximal loading force of 300 kN.

The triaxial tests with one cycle of loading and unloading were carried out as for core samples as for surface analogues. In the conventional triaxial tests a hydraulic load frame with a maximal axial compression force of 3000 kN and a triaxial cell with a fluid-confining pressure of up to 150 MPa were used.

Standard tests of compressive strength (without unloading cycles) were carried out for surface analogue samples to obtained information about strength changes due to cycle loading as during uniaxial as triaxial tests.

Axial ε_A and lateral ε_L strains were measured by electric resistance strain gauges during all the tests. In the case of the uniaxial compressive tests, the cross strain gauges were glued half way up opposite sides of the specimens. For the triaxial tests, the special calibrate sensitive elements were used. The lateral strain was measured as a deformation between two opposite points at half height of the lateral area of the test specimen by the semi-ring sensing device made from springy steel strip, upon which the electric resistance gauges are glued. The values of lateral strain were determined on the basis of sensor calibration. Axial strain was measured indirectly according to change in position of the axial piston relative to the stable top part of the cell. As well as in this case the calibrated sensor from springy steel strip with glued gauges were used. The volumetric strain ε_V was calculated from the observed longitudinal and lateral strains as

$$\varepsilon_V = \varepsilon_A - 2\varepsilon_L \, .$$

From the strains measured under the cyclic uniaxial loading values of the deformation modulus E_{def}, the Young's modulus E and the Poisson's ratio ν were determined using the formulae:

$$\mathrm{E}_{def} = \frac{\sigma_{1,3}}{\varepsilon_{A1}}$$

$$\mathrm{E} = \frac{\sigma_{1,3}}{\varepsilon_{Ael}} = \frac{\sigma_{1,3}}{\dfrac{\varepsilon_{A1} + \varepsilon_{A3}}{2} - \varepsilon_{Aper}}$$

$$\nu = \frac{\varepsilon_{Lel}}{\varepsilon_{Ael}} = \frac{\dfrac{\varepsilon_{L1} + \varepsilon_{L3}}{2} - \varepsilon_{Lper}}{\dfrac{\varepsilon_{A1} + \varepsilon_{A3}}{2} - \varepsilon_{Aper}}$$

in which ε_{Ael} and ε_{Lel} are elastic axial and lateral strains, and ε_{Aper} and ε_{Lper} are permanent axial and lateral strains.

4. ASSESSMENT OF MEASURED PHYSICAL AND MECHANICAL PROPERTIES, RESULTS AND DISCUSSION

4.1. GRAIN AND BULK DENSITY

Determined differences between grain density and bulk density of all tested rocks are small as all core samples as their analogues because the rock material is very compact (Table 1). The density values of core samples of metabasalts and amphibolites cover the range of those reported by Orlov and Laverov (1998), which are between 2.95 – 3.14 g/cm^3, and are close to the average of 3.00 g/cm^3 reported by Lobanov et al. (2000). Density of the gneisses is slightly lower, average of 2.75 g/cm^3. The density does not bring any dependence with depth because density values are given especially by mineral composition of rocks.

4.2. POROSITY

The porosity of core samples mostly increases very slowly with depth of core sample recovery (approximately from 1% to 5%), basically as a result of relaxation of the cores during recovery at the surface. This effect cannot be observed on the samples of the surface analogues. The porosity of gneisses is globally slightly high. Porosity of the surface analogues is practically ever mostly lower than porosity of the equivalent core samples (Table 2).

4.3. COMPRESSIVE STRENGTH

4.3.1. UNCONFINED COMPRESSIVE STRENGTH

Marked differences in unconfined compressive strength were found between metabasalt samples of the Karelian Complex and amphibolite samples from the Kola-Belomorian Complex in spite of their very similar modal compositions. The average unconfined compressive strength of the metabasalt samples from the upper part of the borehole is about 50% higher then amphibolite samples (Table 3). It can be caused by the decompaction due to drilling, core retrieval and rapid pressure and temperature release during lifting the core from great depths to the surface and probably partly also by the differences in grain size distribution

Table 1 Grain and bulk densities of metabasalts, amphibolites and gneisses from KSDB-3 compared with surface analogues

Groups	Depth (m)	Grain density (g/cm^3)		Bulk density (g/cm^3)	
		Core sample	Analogue	Core sample	Analogue
Metabasalts	3043	2.97	2.98	2.92	2.94
	3530	3.03	3.05	3.00	3.02
	4389	3.14	2.94	3.07	2.90
Average values		3.05	2.99	3.00	2.95
Amphibolites	7951	2.98	3.09	2.90	3.03
	8942	3.12	3.09	3.02	3.04
	9904	3.13	3.10	3.02	3.04
Average values		3.08	3.09	2.98	3.04
Gneisses	6849	2.74	2.75	2.74	2.71
	7913	2.76	2.82	2.76	2.76
	8411	2.76	2.84	2.76	2.75
Average values		2.75	2.80	2.75	2.74

Table 2 Porosity of metabasalts, amphibolites and gneisses from KSDB-3 compared with surface analogues

Groups	Depth (m)	Porosity (%)	
		Core sample	Analogue
Metabasalts	3043	1.67	1.28
	3530	0.99	1.05
	4389	2.23	1.13
Average values		1.63	1.15
Amphibolites	7951	2.68	1.94
	8942	3.21	1.62
	9904	3.51	1.94
Average values		3.13	1.83
Gneisses	6849	3.19	1.67
	7913	2.06	2.09
	8411	4.89	3.27
Average values		3.38	2.34

Table 3 Unconfined compressive strength of metabasalts, amphibolites and gneisses from KSDB-3 compared with surface analogues

Groups	Depth (m)	Unconfined compressive strength (Mpa)	
		Core sample	Analogue
Metabasalts	3043	207.0	243.1
	3530	292.3	344.8
	4389	272.3	-
Average values		257.2	294.0
Amphibolites	7951	164.8	275.4
	8942	155.3	270.3
	9904	186.3	203.7
Average values		168.8	249.8
Gneisses	6849	111.8	183.9
	7913	99.4	213.3
	8411	168.5	93.9
Average values		126.6	163.7

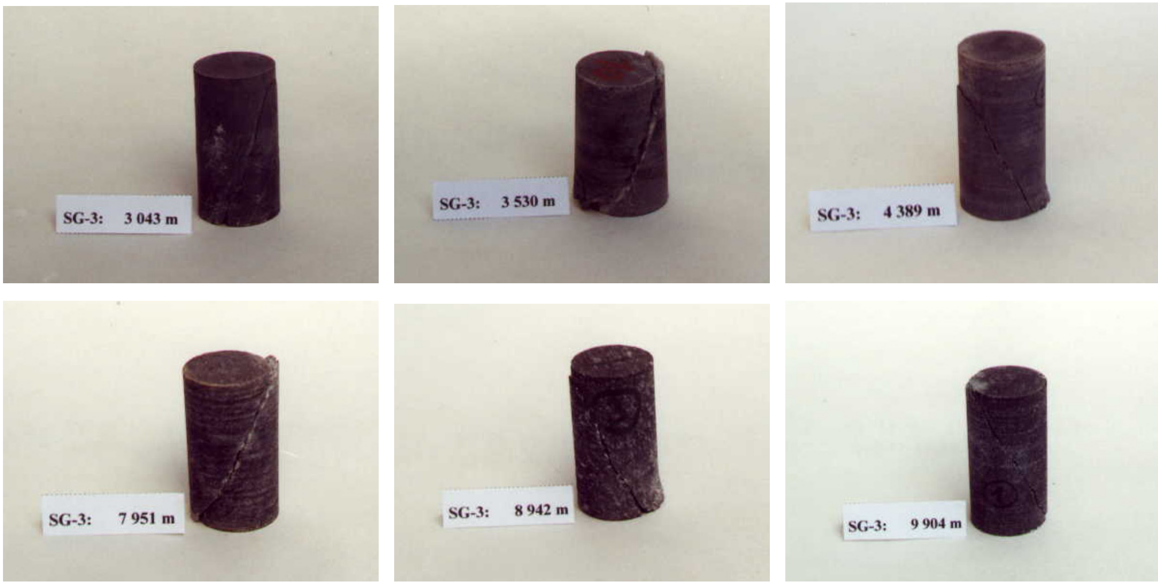


Fig. 4 Disturbed core specimens after unconfined compressive test

Table 4 Triaxial strength of metabasalts, amphibolites and gneisses from KSDB-3 compared with surface analogues

Groups	Depth (m)	Confining pressure 50 MPa		Confining pressure 100 MPa	
		Core sample	Analogue	Core sample	Analogue
Metabasalts	3043	409.9	520.2	608.7	665.4
	3530	596.3	504.6	838.5	706.4
	4389	393.4	409.4	697.7	512.6
Average values		466.5	478.1	715.0	628.1
Amphibolites	7951	376.8	612.0	585.9	810.2
	8942	517.6	571.9	691.5	830.9
	9904	436.8	443.1	683.2	592.6
Average values		443.7	542.3	653.5	744.6

(Figs.1 and 2) and by the spatial arrangement of main rock-forming minerals of both suites of rock samples, even the contrast of grain size of both complexes is not so expressive (Trčková et al., 2002). This assumption is confirmed by the results obtained on the analogue samples, which average values of the unconfined compressive strengths are greater then those of the parallel core samples and there are close to compressive strength values of the core samples of metabasalts from upper part of the borehole. Unconfined compressive strength values of core samples from the upper and lower parts of the borehole yield similar results as those mentioned by (Komarov et al., 2000). These values Komarov determined on the basis of comparison and correlation analysis of the results obtained by laboratory measurements of strength properties of the rock samples from the borehole and those of seismoacoustic borehole investigations.

Unconfined compressive strength of gneiss is at large lower then unconfined compressive strength of metabasalt and amphibolite samples. The average values of the unconfined compressive strength measured on the core samples are rather lower then on the parallel surface analogue samples (Gorbatsevich et al., 2004).

4.3.2. TRIAXIAL STRENGTH

Triaxial strength tests with one cycle of loading and unloading were carried out for core samples of metabasalts and amphibolites and their surface analogues on the specimens of the same size as unconfined compressive tests (Table 4). The assumption of decompaction during lifting the core from great depths to the surface is just, because the confining pressure applied on the core samples during the triaxial tests yields to recompaction and partial closure of possible joints and pores. Therefore, the

Table 5 Young´s modulus and modulus of deformation of metabasalts, amphibolites and gneisses from KSDB-3 compared with surface analogues

Groups	Depth (m)	Young´s modulus (GPa)		Modulus of deformation (GPa)	
		Core sample	Analogue	Core sample	Analogue
Metabasalts	3043	-	73.1	-	63.1
	3530	110.4	102.8	104.7	102.1
	4389	106.7	65.1	98.6	56.5
Average values		108.6	80.3	101.6	73.9
Amphibolites	7951	53.0	92.2	46.9	83.9
	8942	59.9	95.7	39.9	89.3
	9904	70.7	102.0	61.6	99.0
Average values		61.2	96.6	49.5	90.7
Gneisses	6849	40.2	80.7	32.0	77.1
	7913	36.0	95.7	26.0	89.0
	8411	48.0	89.1	43.3	77.8
Average values		41.4	88.5	33.8	81.3

Table 6 Poisson´s ratio of metabasalts, amphibolites and gneisses from KSDB-3 compared with surface analogues

Groups	Depth (m)	Poisson´s ratio	
		Core sample	Analogue
Metabasalts	3043	-	0.23
	3530	0.20	0.29
	4389	0.33	0.23
Average values		0.26	0.25
Amphibolites	7951	0.14	0.28
	8942	0.20	0.23
	9904	0.16	0.24
Average values		0.17	0.25
Gneisses	6849	0.28	0.27
	7913	0.33	0.29
	8411	0.21	0.25
Average values		0.27	0.27

differences of the values of the triaxial strength of the core samples are not so strong between Karelian Complex and Kola-Belomorian Complex, and there are close to values of triaxial strength of their surface analogues (Živor and Trčková, 2004). Owing to insufficient amount of gneiss samples (as core samples as surface analogues), triaxial test could not be made for these samples.

4.4. DEFORMATIONAL CHARACTERISTICS

Deformational characteristics (modulus of deformation, Young's modulus and Poisson's ratio), calculated from axial and lateral strains measured during the uniaxial compressive tests, bring, as well as unconfined compressive strength, dependence with depths of recovering of the core sample (Table 5). The values of deformation and Young´s moduli of core samples obtained from upper part of the borehole are considerably higher then the ones from lower part of the borehole. Differences between values of both moduli determined for core samples and their analogues are small for metabasalt samples of the Karelian Complex and for as amphibolite as gneiss samples from the Kola-Belomorian Complex are very significant and attain until double values for analogues. This phenomenon is caused by higher axial strain of core samples, which are roughly twice higher and it can be attributed namely by the decompaction of core samples from the lower part of the borehole during lifting.

The values of the Poisson's ratio of the analogue samples are similar each other but the values of the Poisson's ratio of the core samples have a greater sparsity in consequence of the various degree of the failure due to drilling method and decompaction (Table 6).

5. IDEA OF THE STRESS CONDITIONS ASSESSMENT, RESULTS AND DISCUSSION

In the Kola region, the values of the stress conditions were carried out on the basis of numerical modelling based on the information on geological structure and physical-mechanical properties of the rock (Savchenko and Kozyrev, 2000). In publication of Turchaninov et. al. (1978) and Kozlovsky (1984) is mentioned that in the vicinity of KSDB-3 area horizontal stress do not exceed 0.7 of the vertical ones. The changes of horizontal stresses were calculated also in Gorbatsevich (1996). An attempt to determine initial geostatic stress state expressed by the coefficient of lateral pressure in various depths of the borehole vicinity experimentally by comparison of changes of unconfined compressive strength and deformation and Young´s moduli of core samples from KSDB-3 and their surface analogues on the bases of the laboratory tests was performed.

This is idea of the experiment (Trčková and Živor, 2004). In our consideration we suppose, that change of physical and mechanical properties of core samples from various depths of KSDB-3 arrived especially in consequence of fracturing during core lifting to the surface by rapid pressure and temperature release (Kern, Popp, 2000). On the other hand, the surface analogues did not be set up to this effect. From the laboratory tests of the core samples recovered from various depths of the Kola Superdeep, unconfined compressive strength $\boldsymbol{\sigma}$, modulus of deformation $\boldsymbol{E_{def}}$, Young´s modulus $\boldsymbol{E}$ are known. Also temperature $\boldsymbol{t}$ in the depths $\boldsymbol{H}$, from which the core samples were recovered, is known. The temperature changes were measured in the Scientific and Industrial Centre "Kola Superdeep" in Zapolyarny during borehole drilling. On the basis of known density of the overlaying rocks and the depth of borehole core deposition vertical stress in the place of borehole core recovering can be determined.

To demonstrate conditions, which affected on the rocks in the various depths of the borehole, the analogues were exposed to the PT conditions during test. Three specimens of the each analogue sample was be sequential placed in the triaxial cell on the temperature identical to the temperature in the borehole and on the vertical loading given by the weight of the overlaying rocks in the borehole depth, in which corresponding core sample was situated. Confining pressure in the triaxial cell was chosen to $^1/_3$ of vertical stress for first specimen, $^2/_3$ of vertical stress for second specimen and equal to vertical stress for third specimen. These loading conditions were affected at the longest time, at least several hours or days.

After specimen extraction from triaxial cell, the specimen was cooled off and thereupon unconfined compressive strength, modulus of deformation and Young´s modulus were determined under normal laboratory temperature, just as these properties of the corresponding core sample were carried out.

The tested properties depend on the depth and stress conditions, which affected to the rock sample. If our consideration would be faultless, these properties would be changed commensurate with confining pressure that affected on the analogue specimens during the loading test. We obtain three different values for three values of confining pressure. By interpolation among values, it is possible to find the same value as was determined nearly for the core sample and for this value to assign corresponding confining pressure. The confining pressure determined by this manner corresponds to horizontal stress in the depth of borehole core position. It is possible to obtained changes of the horizontal stress as a function of depths on the basis of the tests of several core samples recovered from various depths of the Kola Superdeep borehole and their surface analogues.

Consistent with idea of experiment, specimens of the surface analogues were tested. Results of tests are recorded in Table 7.

The specimens exposed in advance to the PT conditions, did not completely confirmed our assumption. It can be caused by disintegration phenomenon (Gorbatsevich, 2003). Over a long geologic time (millions years) polycrystalline rocks at comparatively great depths were at the isostatic state under great geostatic pressure and contacts among their mineral grains were continuous and firm. During quick release from geostatic pressure by extraction of a borehole core to the surface, mineral grains expanded in accordance with their constants of elasticity. Deformations occurring in an anisotropic mineral grain resulted in the fracture of the previously firm intergrain contacts and the rice of very thin microcracks that extend may be compared with the grain size. In the samples of surface analogues, the equilibrium among mineral grains was under surface PT-conditions. This equilibrium was upset by application of high PT-conditions, but many microcracks did not arise. When high PT-conditions were removed, the equilibrium among mineral grains was re-established.

6. CONCLUSION

Determined grain and bulk densities did not bring any dependence with depth because there depend especially on the mineral composition of the tested rock samples. Porosity of the surface analogues was detected lower than porosity of the equivalent core samples. Marked differences in strength properties were found between metabasalt core samples from the Karelian Complex and amphibolite core samples from the Kola-Belomorian Complex in spite of grain size contrast of both complexes was not so expressive. The phenomenon was not found on the surface analogue samples of these rocks. The great differences in strength properties were also found between core samples of amphibolite and gneiss samples and their surface analogues, smaller at samples of metabasalts from upper part of the

Table 7 Changes of the properties of surface analogues of metabasalts, amphibolites and gneisses from KSDB-3 at the PT-condition

Core samples from depth (m)	Unconfined compressive strength of core sample (MPa)	PT-conditions			Unconfined compressive strength of analogue (MPa)	Modulus of deformation (GPa)	Young´s modulus (GPa)
		Temperature (°C)	Vertical stress (MPa)	Confining pressure (MPa)			
3043	207.0	20	0	0	243.1	63.1	73.1
		45	89.5	30	249.3	78.7	81.3
				60	266.0	73.6	79.0
				90	281.8	89.2	90.1
3530	292.3	20	0	0	344.8	102.2	102.9
		52	103.8	40	365.8	108.2	108.8
				70	383.9	104.6	105.2
				110	374.6	112.4	112.9
4389	272.3	20	0	0	153.8	56.5	65.1
		67	129.1	40	205.5	65.5	68.8
				80			
				120			
6849	111.8	20	0	0	183.9	77.1	80.7
		112	201.5	40	187.7	73.5	75.4
				80	163.8	68.4	72.5
				120	174.9	64.1	67.2
7913	99.4	20	0	0	213.3	89.0	95.7
		128	232.8	40	225.9	83.1	80.6
				80	207.6	70.6	74.0
				120	225.8	81.1	82.1
7951	164.8	20	0	0	275.4	83.9	92.2
		130	233.9	40	289.2	134.9	136.9
				80	343.6	151.3	157.2
				120	315.0	158.3	157.6
8411	168.5	20	0	0	93.9	77.8	89.1
		138	247.4	40			
				80	112.6	94.0	96.0
				120	139.8	75.1	76.9
8942	155.3	20	0	0	270.3	89.3	95.7
		146	263.1	80			
				120	284.0	144.7	150.4
				140	288.5	102.9	102.5
9904	186.3	20	0	0	203.7	99.0	102.0
		161	291.4	100	279.6	147.8	145.5
				120	182.4	132.0	131.7
				140			

borehole and surface analogues. These differences were especially caused by decompaction during lifting the core from great depths to the surface. The deformational characteristics obtained for the core samples recovered from the Karelian and Kola-Belomorian Complexes brought the similar relations as strength properties. Small differences between values of both moduli of core samples and their analogues were obtained for metabasalt samples of the Karelian Complex, and very significant for as amphibolite as gneiss samples from the Kola-Belomorian Complex.

The problem of mechanical properties determination of rocks from the borehole was insufficient quantity of rocks material for the tests. Due to core fragmentation, caused by the drilling method and fracturing during core lifting to the surface it was very difficult to make rock samples collection large enough for standard laboratory tests. More rock material was of surface analogues, but not enough to obtain statistically workable collection of the results. In spite of this problem, the notable results were achieved.

The properties of the tested rocks, especially their high strength and small porosity, are important parameters when discussing amphibolites as possible host rocks for underground deposit of dangerous wastes.

Our work was fragment of large research and complex studies of core samples from the Kola Superdeep Borehole and analogues from surface which was performed by many researchers as in many laboratories as in situ.

The mutual comparison of our results together with results other research teams deal with studies of the core samples from the various depths of the borehole and their surface analogues can bring valuable information about changes of physical parameters of rocks and stress state in vertical sections of the borehole and have a principal importance for characterizing the processes developed in upper part of the continental crust.

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