DENSITY AND VELOCITY MODEL OF METAMORPHIC ROCK PROPERTIES IN THE UPPER AND MIDDLE CRYSSTALLINE CRUST IN THE KOLA SUPERDEEP BOREHOLE (SG-3) SECTION

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INTRODUCTION

At times geodynamic processes within the upper and middle Earth's crust manifest themselves in the form of sudden movements that lead to earthquakes, tsunamis, landslides etc. The centers of the strongest earthquakes with catastrophic consequences, as a rule, are located within the upper and middle crust (New Catalogue ..., 1977). The manifestation strength of these terrible events depends mainly on the level of tectonic stresses, physical and mechanical properties of rocks, their state and rheology, temperature and its change gradient with depth. The major reserves of minerals used by mankind are concentrated in the Earth’s upper crust, and therefore the knowledge of the properties, structure and stressed state of the Earth becomes very important.

In this context, the fundamental scientific problem is to create a model of the composition, structure, properties, and state of the crystalline crust, reflecting their changes with depth under the influence of PT conditions. The model should reflect the general trends of changing with depth such parameters as composition, degree of metamorphism, density, compression and shear wave velocities, anisotropy, indices of elasticity modulus and lateral strain factor, lithostatic and tectonic stresses. To estimate the composition, structure and properties of the middle and lower crust the following methods are mainly used:

- seismic, electromagnetic sounding of the Earth's crust, gravity measurements of the surface heat flow for assessment of composition of the rocks, concentration of minerals and radioactive elements in the rocks;
- the study of the cores of deep and superdeep wells;
- the study of rocks of high-temperature amphibolite and granulite facies generated in the deep conditions and exposed at the present-day erosional surface as a result of ascending tectonic movements;
- the research of deep-seated xenoliths evacuated from great depths.

The methods of seismic, electromagnetic and other types of sounding are widely used and allow compiling extensively elaborated sections. However, in the crystalline metamorphic rocks detailed information of the most informative seismic sections greatly decreases with depth. As the drilled sections of the Kola (SG-3), Ural (SG-4) and other research wells showed, the relative correspondence between the seismic and actual structure of the massifs is maintained only down to a depth of 4-5 km (Kozlowsky, 1987; Kola Superdeep, 1998; Druzhinin et al., 1999). Drilling deep and superdeep boreholes is very expensive and cannot be used widely.

The composition, structure and properties of the rocks, located within 12-25 km (uncut by SG-3) of the middle crust, can be judged only tentatively according to the published data (Sobolev and Babeyko, 1994; Christensen and Mooney, 1995; International Handbook, 2002). According to the results of seismic studies the transition from the upper to the middle crust is accompanied by an increase of compression wave velocities ($V_p$) from 6.0-6.4 km/s to 6.4 - 6.7 km/s. This may be due to a higher degree of metamorphic transformation, which increases the rock density.

ABSTRACT

Using the experimental and calculated data as the base, a model for a depth dependence of density, compression and shear wave velocities along the Kola superdeep borehole (SG-3) section was developed down to a depth of ~25 km. The variations of the density, compression and shear wave velocities are mainly caused by the changes in the rock mineral composition. The relative reduction in the velocities of compression and shear waves with depth under the influence of increasing pressure and temperature in the range of 5-25 km is about 2 %. The observed increase in seismic velocity with depth may be due to changes in the degree of metamorphic transformation of rocks.
One might suppose that the middle crust in the SG-3 area can be represented by rocks similar in age and composition of the protoliths to the SG-3 Archaean complex but metamorphosed under conditions of high-temperature amphibolite and granulite facies. Such rocks were intersected at the present day erosional surface. They are represented by highly metamorphosed complexes that constitute a substantial part of the Kola-Norwegian block to the north-east and east of the Pechenga rift structure (Vetrin, 2007).

The real changes in the stress state and temperature with depth (PT conditions) in the SG-3 vicinity are well studied, Figure 1 (Kola Superdeep, 1998; Gorbatsevich and Savchenko, 2009). Modern
subhorizontal stresses of the northern Baltic Shield and Pechenga geoblock are determined by the continental plates moving apart in the mid-ocean rift zones of the Atlantic and Arctic Oceans and by the pressure of the African plate on the Eurasian lithospheric plate. The orientation of the maximum compressive stresses $\sigma_q$ in the Pechenga geoblock is mainly near N-S. The vertical component of the stress field $\sigma_z$ is usually determined by the weight of the overlying rocks. In assessing the values of horizontal stresses $\sigma_q$ for an isotropic model we used the methods taking into account the extent of core disking, changes in the acoustic wave velocities in the samples saturated by fluids, the values of the elasticity modulus and Poisson's ratio of rocks. It was found that horizontal tectonic stresses vary from 7 MPa near the surface to 125 MPa at a depth of 11.5 km along the Kola superdeep borehole section. The average ratio of working horizontal stresses (including the value of the lateral pressure arising under the influence of the vertical component, and the tectonic component) to vertical is 0.7-0.8. Sudden changes in the values of the stress horizontal component in depth are caused by structural inhomogeneities and elastic anisotropy of rocks.

Figure 2 shows the determined $\rho$, $V_S$ and $V_P$ in the SG-3 section in the depth range from the surface down to 12 km (The lithosphere..., 2005). Investigations were carried out many times by the acoustic log (AL) and vertical seismic profiling (VSP) methods in the Proterozoic and Archaean sections of SG-3 (Kozlovsky, 1987; Lithosphere..., 1987; Lizinsky and Lanev, 1991). The AL method is more detailed than the VSP one.

At the parts of the borehole that are free from complications and have no caverns the data obtained by the AL and VSP methods virtually coincide. For the depth range of 7.2-11.5 km $V_P$ and $V_S$ obtained by the calculation method (CM) used for gneiss-granite rocks; 4 - the calculation method used for amphibole-bearing rocks; 5 - the calculation method, the confidence limits of the average interval values.

Figure 2 The distribution of density, shear and compression wave velocities along the SG-3 section. The distribution of rocks and structural elements see in Figure 1.

a – the density $\rho$ distribution along the section. 1 – the unit values measured on the core samples; 2 – the average interval values.

b – scattering of the unit values of shear wave $V_S$ velocities. c – scattering of the unit values of compression wave $V_P$ velocities.

1 – the method of vertical seismic profiling (VSP); 2 – the method of acoustic logging (AL); 3 – the calculation method (CM) used for gneiss-granite rocks; 4 - the calculation method used for amphibole-bearing rocks; 5 - the calculation method, the confidence limits of the average interval values.
Table 1  General characteristics of the core samples from the SG-3 Archaean section.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Rock name</th>
<th>Depth, m</th>
</tr>
</thead>
<tbody>
<tr>
<td>31115</td>
<td>Plagioclase amphibolite (Hbl-67, Pl-22, Qtz-5, Bt-4)</td>
<td>8718</td>
</tr>
<tr>
<td>35400</td>
<td>Biotitized amphibolite (Hbl-78, Bt-11, Pl-9)</td>
<td>9438</td>
</tr>
<tr>
<td>36058</td>
<td>Biotitized amphibolite (Hbl-63, Pl-16, Bt-12)</td>
<td>9571</td>
</tr>
<tr>
<td>38098S</td>
<td>Garnet-biotite- plagioclase gneiss (Pl-80, Bt-13, Grt-5)</td>
<td>10238.3</td>
</tr>
<tr>
<td>43560</td>
<td>Garnet-clinopyroxene amphibolite (Hbl-74, Qtz-12, Cpx-7, Grt-4)</td>
<td>11353.5</td>
</tr>
<tr>
<td>43726</td>
<td>Plagioclase amphibolite (Pl-55, Hbl-38, Qtz-5)</td>
<td>11383</td>
</tr>
</tbody>
</table>

Note: Mineral symbols as in (Kretz, 1983). Mineral contents are given in %.
In each rock the content of accessory minerals - Aln, Ap, Cal, Grt, Op, Sil, and Zrn, - in various combinations is 2-3%.

Fig. 3  Example of the changes in the density of the SG-3 core samples according to the applied confining pressure (a) at the constant temperature of 20 °C and according to increasing temperature (b) at the confining pressure of 600 MPa (Golovataya et al., 2006).

DENSITY AND VELOCITY CALCULATIONS
To determine the depth dependence of density several samples from the SG-3 Archaean core were tested. Rock samples of amphibolite facies were selected from the bottom (8718-11383 m depth) of SG-3, Table 1. The samples were in the form of a cube with the edge 43 mm long.

The tests were performed in a multi-anvil pressure (to 600 MPa) and temperature (to 600 °C) apparatus by Prof. H. Kern at the University of Kiel, Germany (Kern et al., 1997). At increasing confining pressure applied to the sample its volume and elastic characteristics (compression and shear wave velocities) changed in three mutually perpendicular directions. At the second stage elastic characteristics of the samples were measured at the constant pressure of 600 MPa increasing room temperature to 600 °C.

Variations in the sample density at increasing pressure and temperature were calculated from the changes of the sample volume, its mass being constant (Kern et al., 1997). Figure 3 presents the changes in
Table 2 The values of $\rho_0$ and the factors $\alpha$, $\beta$ and $\gamma$ for calculating depth dependences of density for the samples from the SG-3 Archaean section.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>$\rho_0$, g/cm$^3$</th>
<th>$\alpha$</th>
<th>$\beta \times 10^4$, g/(cm$^3 \cdot$km)</th>
<th>$\gamma \times 10^4$, deg.$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>31115</td>
<td>3.077(0.002)</td>
<td>1.0043(0.0009)</td>
<td>7.96(0.31)</td>
<td>0.210(0.017)</td>
</tr>
<tr>
<td>35400</td>
<td>3.080(0.002)</td>
<td>1.0039(0.0009)</td>
<td>8.12(0.31)</td>
<td>0.210(0.017)</td>
</tr>
<tr>
<td>36058</td>
<td>3.083(0.015)</td>
<td>1.0015(0.0085)</td>
<td>32.63(0.82)</td>
<td>0.090(0.028)</td>
</tr>
<tr>
<td>38098S</td>
<td>2.705(0.002)</td>
<td>1.0102(0.0015)</td>
<td>16.28(0.34)</td>
<td>0.154(0.015)</td>
</tr>
<tr>
<td>43560</td>
<td>2.940(0.003)</td>
<td>1.0093(0.0015)</td>
<td>7.97(0.30)</td>
<td>0.210(0.017)</td>
</tr>
<tr>
<td>43726</td>
<td>2.936(0.002)</td>
<td>1.0044(0.0012)</td>
<td>7.97(0.30)</td>
<td>0.210(0.017)</td>
</tr>
</tbody>
</table>

Note. The confidence limits of the values calculated by the least squares method are given in brackets.

Table 3 Depth dependence of density (g/cm$^3$) for the samples from the SG-3 Archaean section.

<table>
<thead>
<tr>
<th>Depth, km</th>
<th>Sample No.</th>
<th>31115</th>
<th>35400</th>
<th>36058</th>
<th>38098S</th>
<th>43560</th>
<th>43726</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td>3.09</td>
<td>3.09</td>
<td>3.09</td>
<td>2.73</td>
<td>2.97</td>
<td>2.95</td>
<td>2.99±0.14</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>3.09</td>
<td>3.09</td>
<td>3.10</td>
<td>2.74</td>
<td>2.97</td>
<td>2.95</td>
<td>2.99±0.14</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>3.09</td>
<td>3.09</td>
<td>3.12</td>
<td>2.76</td>
<td>2.98</td>
<td>2.95</td>
<td>3.00±0.13</td>
</tr>
<tr>
<td>15</td>
<td></td>
<td>3.09</td>
<td>3.09</td>
<td>3.13</td>
<td>2.77</td>
<td>2.98</td>
<td>2.95</td>
<td>3.00±0.13</td>
</tr>
<tr>
<td>20</td>
<td></td>
<td>3.09</td>
<td>3.09</td>
<td>3.15</td>
<td>2.78</td>
<td>2.99</td>
<td>2.95</td>
<td>3.01±0.13</td>
</tr>
<tr>
<td>25</td>
<td></td>
<td>3.09</td>
<td>3.09</td>
<td>3.16</td>
<td>2.79</td>
<td>2.99</td>
<td>2.95</td>
<td>3.01±0.13</td>
</tr>
</tbody>
</table>

Part of the dependences $\rho$ vs $P$ within the pressures of 200-600 MPa and temperatures of 50-600 °C was approximated by the linear function:

$$\rho(P,t)=\left[\alpha \cdot \rho_0 + \beta \cdot P \right] \left[1 - \gamma (t - 20) \right]$$

(1)

The initial values of $\rho_0$ and the factors $\alpha$, $\beta$ and $\gamma$ for the samples mentioned in Table 1 are given in Table 2 (Golovataya et al., 2006).

Using the data from Table 2 we calculated the rock density with regard for PT-conditions from the surface down to a depth of ~25 km. It was assumed that the entire section consists of rocks listed in Table 1. The calculation results are presented in Table 3.

Analysing the results obtained one can notice that the range of the density values within the depths of 0-25 km is 2.73-3.16 g/cm$^3$. These variations are mainly explained by the changes in the rock mineral composition. There is a weak trend of increasing density with increasing pressure and temperature. Judging by the average values of $\rho$ for the entire set of samples, the changes resulting from the combined influence of pressure and temperature are 0.6 % for the whole range of 0-25 km. This trend can be explained by the fact that if an increase in pressure leads to an increase in $\rho$, an increase in temperature reduces its value (see Fig. 3, formula 1). Reflected in the range of 10-25 km in Figure 2 the trend of a slight density increase with depth shows that in the SG-3 lower section, from a depth of ~ 5 km, the values of $\rho$ measured in atmospheric conditions are significantly affected by the decompaction effect (Goryainov et al., 1992; Gorbatsevich, 2003).

The changes in velocities of compression and shear waves with increasing pressure and temperature are similar in nature to the changes registered for the density, Figure 2. As an example, Figure 4 shows the changes in the compression $V_p$ and shear $V_s$ wave velocities as a function of the PT-conditions. The velocities were measured in three mutually perpendicular directions in cubic sample № 31115; the depth of extraction is 8718 m.

With increasing confining pressure up to ~200 MPa, a rapid non-linear growth of elastic wave velocities was fixed for all samples (both core samples taken at considerable depths and surface rocks) (Kern and Popp, 2000). The nature of dependencies is about the same for compression and shear waves. At this stage of loading microcracks close at the borders and within mineral grains. Then the growth of $V_p$ and $V_s$ becomes nearly linear since the rock crystalline basis becomes deformed. With increasing temperature a linear decrease in $V_p$ and $V_s$ is observed, Figure 4.

Similar to the procedure applied to the density indices, by formulas...
Fig. 4 Changes in the compression $V_P$ (a, b) and shear $V_S$ (c, d) wave velocities in sample 31115 according to the confining pressure (a, c) and temperature (b, d) (Golovataya et al., 2006).

Table 4 The values of $V_0^P$, $V_0^S$ and factors $\alpha_p$, $\beta_p$, $\gamma_p$, $\beta_s$, $\gamma_s$ for calculating compression and shear wave velocities as a function of deep PT-conditions for the samples from the SG-3 Archaean section.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>$V_0^P$, km/s</th>
<th>$V_0^S$, km/s</th>
<th>$\alpha_p$</th>
<th>$\alpha_S$</th>
<th>$\beta_p \cdot 10^4$, km/s$^2$, MPa$^{-1}$</th>
<th>$\beta_s \cdot 10^4$, km/s$^2$, MPa$^{-1}$</th>
<th>$\gamma_p \cdot 10^4$, km/s$^1$, deg.$^{-1}$</th>
<th>$\gamma_s \cdot 10^4$, km/s$^1$, deg.$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>31115</td>
<td>3.60(0.11)</td>
<td>2.24(0.05)</td>
<td>1.83(0.06)</td>
<td>1.73(0.04)</td>
<td>5.1(1.4)</td>
<td>2.31(0.68)</td>
<td>3.29(0.01)</td>
<td>2.1(0.3)</td>
</tr>
<tr>
<td>35400</td>
<td>4.11(0.11)</td>
<td>2.37(0.05)</td>
<td>1.54(0.04)</td>
<td>1.44(0.03)</td>
<td>8.2(1.4)</td>
<td>3.59(0.68)</td>
<td>2.0(0.3)</td>
<td>3.2(0.3)</td>
</tr>
<tr>
<td>36058</td>
<td>4.28(0.08)</td>
<td>2.39(0.04)</td>
<td>1.52(0.03)</td>
<td>1.44(0.02)</td>
<td>5.94(0.85)</td>
<td>2.86(0.41)</td>
<td>1.6(0.7)</td>
<td>2.5(0.5)</td>
</tr>
<tr>
<td>38098S</td>
<td>3.21(0.07)</td>
<td>1.80(0.05)</td>
<td>1.85(0.04)</td>
<td>1.74(0.05)</td>
<td>7.27(0.96)</td>
<td>5.57(0.64)</td>
<td>2.6(0.3)</td>
<td>1.7(0.2)</td>
</tr>
<tr>
<td>43560</td>
<td>3.12(0.15)</td>
<td>2.12(0.04)</td>
<td>2.11(0.10)</td>
<td>1.88(0.04)</td>
<td>6.4(1.9)</td>
<td>1.44(0.65)</td>
<td>1.95(0.05)</td>
<td>0.94(0.8)</td>
</tr>
<tr>
<td>43726</td>
<td>3.68(0.20)</td>
<td>2.50(0.07)</td>
<td>1.74(0.09)</td>
<td>1.57(0.05)</td>
<td>10(2.7)</td>
<td>3.3(1.1)</td>
<td>3.0(0.2)</td>
<td>1.7(0.2)</td>
</tr>
</tbody>
</table>

Note. The confidence limits of the values calculated by the least squares method are given in brackets.

Using the data from Tables 4 and 5 and formulae (2) and (3) we calculated the changes in the values of $V_P$ (a, b) and $V_S$ with regard for the changes in the PT-conditions along the SG-3 section. The calculations were made for the rock samples listed in Table 1 in the range of PT-conditions from the Earth’s surface down to a depth of ~25 km.

$$V(P,t) = [(\alpha_p \cdot V_0 + \beta_p \cdot P) \cdot [1 - \gamma_p (t - 20)]$$  \hspace{1cm} (2)

$$V(S,t) = [(\alpha_s \cdot V_0 + \beta_s \cdot P) \cdot [1 - \gamma_s (t - 20)]$$  \hspace{1cm} (3)

we calculated dependences of $V_P$ and $V_S$ for the rock samples listed in Table 1 within the PT-conditions from the Earth’s surface down to a depth of ~25 km. The initial values of $V_0^P$ and $V_0^S$ and the factors $\alpha_p$, $\beta_p$, $\gamma_p$, $\alpha_s$, $\beta_s$, $\gamma_s$ have been taken from (Golovataya et al., 2006), see Tables 4 and 5.

Using the data from Tables 4 and 5 and formulae (2) and (3) we calculated the changes in the values of $V_P$ (a, b) and $V_S$ with regard for the changes in the PT-conditions along the SG-3 section. The calculations were made for the rock samples listed in Table 1 in the range of PT-conditions from the Earth’s surface down to a depth of ~25 km.
Table 5 Depth dependences of compression wave velocities (km/s) for the samples from the SG-3 Archaean section.

<table>
<thead>
<tr>
<th>Depth, km</th>
<th>Sample No.</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>31115</td>
<td>6.58</td>
</tr>
<tr>
<td>5</td>
<td>35400</td>
<td>6.33</td>
</tr>
<tr>
<td>10</td>
<td>36058</td>
<td>6.51</td>
</tr>
<tr>
<td>15</td>
<td>38098S</td>
<td>5.94</td>
</tr>
<tr>
<td>20</td>
<td>43560</td>
<td>6.58</td>
</tr>
<tr>
<td>25</td>
<td>43726</td>
<td>6.40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.39±0.24</td>
</tr>
</tbody>
</table>

The velocity section of $V_p$ calculated for the interval of 10-25 km also agrees well with the data obtained by the AL, VSP and CM methods (The lithosphere..., 2005). The average value of the shear wave velocities in the ranges of 0-12 km and 10-25 km is 3.6 km/s. It can be noted that the $V_p$ and $V_S$ calculated by the CM method are close to those calculated with regard for the PT-conditions, so this method can be used for a known mineral composition of the rock to estimate these values at relatively great depths.

**DISCUSSION**

The data in Tables 1 and 3 allow us to see that the mineral composition has a greater impact on the value of the rock density than the change in the deep PT-conditions within the middle crust. Analysing the previously published data (Christensen and Mooney, 1995; Emmermann R. and Lauterjung, 1997; International Handbook, 2002; Gorbatsevich, 2008), it can be noted that density does not show any regular relation with depth but reflects variations in the rock mineral composition. This conclusion is supported by observations of changes in the magnetic susceptibility, which changes like density. It was noted that density variations are due to a larger or smaller amount of siderophile elements in the rock. In general, for all the crystalline crust the average density is 2.83 g/cm$^3$ (Christensen and Mooney, 1995). The density of rocks in the SG-3 section is slightly higher (average 3.00 g/cm$^3$) due to the higher content of mafic minerals, such as amphibole. It should be expected that at greater depths (25 km and deeper), there is an increase in the content of heavy minerals such as garnet and pyroxene (Gorbatsevich et al., 2012).
Fig. 6 The distribution of density $\rho$ (a), shear $V_s$ (b) and compression $V_p$ (c) wave velocities along the SG-3 section (experimental data) and within the middle crust (calculation). The distribution of rocks and structural elements in the depth range of 0-12km see in Figure 1. For the 10-25 km interval (see section (с)): 1 – the simulation of the depth dependences of $\rho$, $V_p$ and $V_s$ in sample 31115; 2 – the same in sample 35400; 3 – the same in sample 36058; 4 - the same in sample 38098S; 5 – the same in sample 43560; 6 – the same in sample 43726.

wave velocities do not show any dependence on the depth of the rock occurrence. The compression wave velocity in the section is 4.5-6.4 km/s, the shear wave velocity – 2.5-3.7 km/s (Emmermann R. and Lauterjung, 1997; Smithson et al., 2000; Trčková et al., 2002; Gorbatschev, 2008). But the regional seismic investigations by the DSS, RM, RCM, CDP etc. methods most often show an increase in the wave velocity with depth (Christensen and Mooney, 1995; International Handbook, 2002; The lithosphere ..., 2005). Calculation data obtained for a wide range of rocks of various geneses are independent of PT conditions or show a slight decrease in their values with depth.

The previous estimate of compression and shear wave velocities for the depths of 25-40 km yielded $V_p= 6.7$-6.5 km/s and $V_s = 3.8$-3.7 km/s. These values are due to the growth of the higher-velocity minerals pyroxene and garnet in the rocks (Gorbatschev et al., 2012). Thus, the gradient of the seismic velocity increase in the crystalline crust should be explained not by increasing the PT-conditions with depth but by restructuring of rocks. This restructuring is going on for a long time as a result of metamorphic transformation of some minerals, for instance, plagioclase and amphibole into pyroxene and garnet.

Parameters of elastic anisotropy of rocks deserve special consideration. This is indicated by the
difference in the values of velocity $V_P$ and $V_S$, measured in different directions in the cubic sample, Figure 4. Unfortunately, a limited number of samples shown in Table 1 does not permit a reasoned analysis of the property. However, there is a relatively large body of published data for the samples taken from SG-3. (Gorbatsevich, 1995; Kern and Popp, 2000; Kern et al., 2001; Nikitin et al., 2001; The lithosphere..., 2005). In the SG-3 Archaean section anisotropy, as the variability of $V_P$ and $V_S$ in different directions, is very significant. The major intervals of occurrence of highly anisotropic rocks are at depths of 5.75-7.0 and 7.4-8.65 km. These data are supported by the results of the VSP determinations performed in the vicinity of SG-3 (Digranes et al., 1996). Among the rocks with significant anisotropy (amphibolites) the predominant type of elastic symmetry is rhombic (Gorbatsevich, 2009; Nikitin et al., 2001). Below 8.65 km down to a depth of 12 km rock anisotropy decreases. The calculations of the $V_P$ range of changes within the depths of 5-25 km (5.82-6.60 km/s) with the average of 6.27-6.40 km/s allow the anisotropy factor variations to be estimated from 4 % to 9 %, Table 5. Similarly, for $V_S$ (the range of 3.13-3.93 km/s, the average of 3.56-3.63 km/s), these variations make up 9-15 %, Table 6. However, it can be assumed that in the range of 12-25 km a decrease in the rock anisotropy with depth will be observed due to replacement of highly anisotropic minerals (plagioclase, amphibole) by low anisotropic ones (pyroxene, garnet) (Christensen and Monnoy, 1995). This is indicated by the determined level of elastic anisotropy in the rocks of the lower crust (Gorbatsevich et al., 2012). The importance of the study of elastic anisotropy is confirmed by the fact that this feature affects the deviation of the well in the course of drilling and makes it difficult to interpret the results of geophysical constructions.

**CONCLUSION**

The obtained dependences of density and velocities of compression and shear waves down to a depth of ~25 km in the SG-3 section are reliable to a certain degree provided that the mineral composition of rocks is the same as that recorded within the SG-3 Archaean section (6842-12261 m). According to the above results, the density variations within the depths of 0-25 km are 2.7-3.2 g/cm$^3$. These variations are mainly explained by the changes in the mineral composition of rocks. A weak trend of increasing density with increasing PT-conditions is observed. The range of changes in the compression wave velocity in the rocks of this depth interval is 5.8-6.6 km/s. From a depth of about 5 km there is a tendency for a decrease in the $V_P$ value. This change pattern can be explained by a stronger influence of the temperature increase with depth than by the influence of the pressure increase with depth. The shear wave velocity also decreases with depth. The variations of its change for biotite-plagioclase amphibolite rocks are 3.1-3.9 km/s. The relative decrease in the velocity of compression and shear waves in the range of 5-25 km is about 2 %.

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