Acta Geodyn. Geomater., Vol. 11, No. 2 (174), 165–174, 2014
DOI: 10.13168/AGG.2013.0059
journal homepage: http://www.irsm.cas.cz/acta

REVIEW

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

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ARTICLE INFO

Article history:
Received 24 April 2013
Accepted 15 August 2013
Available online 26 November 2013

Keywords:
Crystalline crust
Density
Elastic anisotropy
Superdeep borehole

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.

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 metamorphism, which increases the rock density.

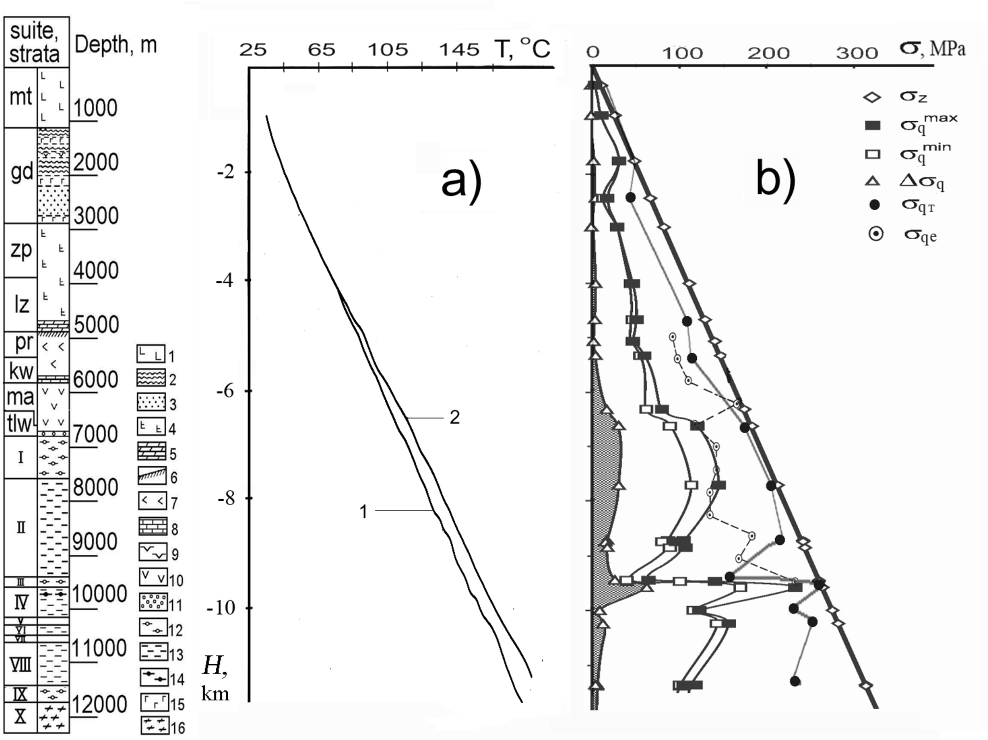

Fig. 1 Depth dependences of the temperature, vertical and horizontal components of the stress field along the Kola superdeep borehole (Kola Superdeep, 1998; Gorbatsevich, Savchenko, 2009).

Distribution of the rocks and structural elements:
1 – augitic metadiabase with pyroxene and picrite porphyrite interbeds; 2 – metaphyllite, metasiltstone with metatuff interbeds; 3 – rhythmically alternating metasandstone with subordinate metasiltstone and metaphyllite; 4 – actinolized metabasalt; 5 – dolomite, arkose metasandstone; 6 – sericitic schist; 7 – metabasalt; 8 – dolomite, polymictic metasandstone; 9 – wehrlite; 10 – metaporphyrite, schist after it; 11 – metasandstone; 12 – biotite-plagioclase-gneiss with high-alumina minerals; 13 - biotite-plagioclase-gneiss with amphibole, epidote, sphene; 14 – magnetite-amphibole schist; 15 – gabbro-diabase; 16 – biotite-plagioclase and sphene-biotite-amphibole-plagioclase gneiss, schist.
mt – Matert, gd – Zhdanov, zp – Zapolyarny, lz – Luchlompolo, pr – Pirttijarvi, kw – Kuvernerinjoki, ma – Majarvi, tlw – Televi Fms.
I – X – units in the Archaean section.
a - temperature measurements: 1 - 02.03.1984; 2 - 13.05.1984.
b - vertical and horizontal components of the stress field: σ_z - calculated vertical, σ_q^{max} and σ_q^{min} - horizontal components of the stress field; $\Delta\sigma_q = \sigma_q^{max} - \sigma_q^{min}$; $\sigma_{q\tau}$ - horizontal component of the stress field with regard for tectonic forces assessed by the method of sample loading; σ_{qe} – horizontal component of the stress field with regard for tectonic forces assessed by the method of sample saturation.

The depth dependence of rock physical properties is associated with the change in the rock structure, texture, mineral composition and deep PT-conditions. For example, the structure, texture and mineral composition in the SG-3 section is mainly determined by the change of metamorphism facies from prehnite-pumpellyite (0-1400 m) and greenschist (1400-4900 m) to epidote-chlorite (1400-3200 m), epidote-amphibolite (4900-6000 m) and amphibolite (6000-12000 m and deeper). The aim of this work is revealing regularities of changes in density, compression and shear wave velocities, elastic anisotropy within the upper and middle crust by the example of the Archaean rocks cut by the Kola superdeep borehole. To some extent, the work should complement the geophysical section obtained for the SG-3 profile down to a depth of about 25 km.

PT-CONDITIONS IN THE UPPER AND MIDDLE CRUST

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

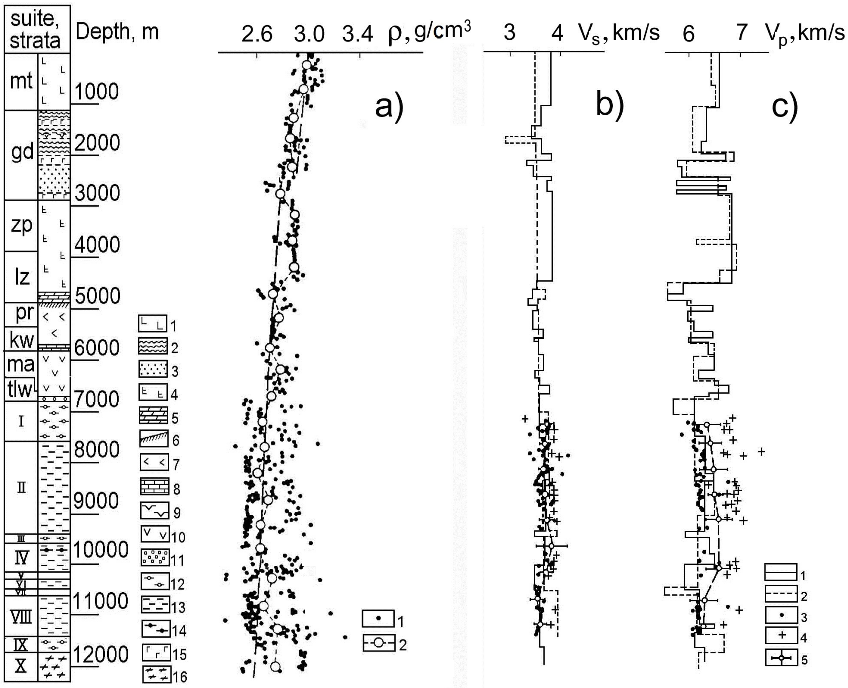

Fig. 2 The distribution of density, shear and compression wave velocities along the SG-3 section. The distribution of rocks and structural elements see in Figure 1.

a – the density ρ 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.

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 σ_q in the Pechenga geoblock is mainly near N-S. The vertical component of the stress field σ_z is usually determined by the weight of the overlying rocks. In assessing the values of horizontal stresses σ_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 ρ, 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) are given (Archaean complex…, 1991). The CM method implies determining V_P and V_S by the specific contribution of the average velocity values in the mineral grains constituting the rock (Belikov et al., 1970). The calculation was done without regard for the effect of microcracks and PT-conditions in the massif.

From the plot, Figure 2a, it follows that in the upper Proterozoic section (H < 6842 m) the scattering of the points relative to the average interval values of ρ_u is not great. Within the 3.0-3.6, 3.9-4.35 and 5.20-5.50 km intervals, according to the relatively constant

Table 1 General characteristics of the core samples from the SG-3 Archaean section.

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

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%.

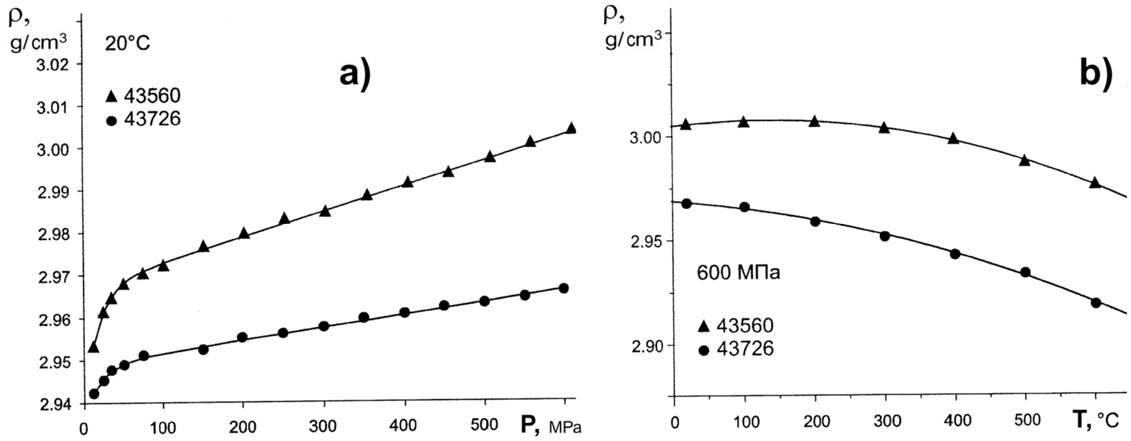

Fig. 3 Example of the changes in the density of the SG-3 core samples according to the applied confining pressure (a) at the constant temperature of 20 °C and according to increasing temperature (b) at the confining pressure of 600 MPa (Golovataya et al., 2006).

values of ρ_u dense homogeneous rocks occur. In the Archaean section the scatter in the density values of rocks occurring in the intervals close in depths, is much higher. Leucocratic (gneisses, granites, migmatites) and melanocratic (amphibolites, schists, metagabbro) rocks differ clearly in the values of ρ. Moreover, this difference, on average, is progressing with depth. On the whole, judging from the density values of ρ in the Archaean section, the frequency of alternating intervals of rocks of different composition is considerably higher than in the Proterozoic section. This conclusion is confirmed by a detailed geological section of the borehole (Kola Superdeep, 1998). The unit values of density, in general, do not go beyond the scope that is typical of modified, metamorphosed and also effusive and intrusive rocks (Reference book..., 1975). The general tendency for the density decrease observed on the plot, Figure 1, can be explained by the samples decompaction during their extraction from a great depth and lithostatic pressures and temperature release (Gorbatsevich, 2003).

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 ρ_0 and the factors *α, β* and *γ* for calculating depth dependences of density for the samples from the SG-3 Archaean section.

Sample No.	ρ_0, g/cm^3	α	$\beta \cdot 10^4$, g/(cm^3·km)	$\gamma \cdot 10^4$, deg.$^{-1}$
31115	3.077(0.002)	1.0043(0.0009)	7.96(0.31)	0.210(0.017)
35400	3.080(0.002)	1.0039(0.0009)	8.12(0.31)	0.210(0.017)
36058	3.083(0.015)	1.0015(0.0085)	32.63(0.82)	0.090(0.028)
38098S	2.705(0.002)	1.0102(0.0015)	29.46(0.28)	0.158(0.018)
43560	2.940(0.003)	1.0093(0.0015)	16.28(0.34)	0.154(0.015)
43726	2.936(0.002)	1.0044(0.0012)	7.97(0.30)	0.210(0.017)

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.

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

the volume density of deep samples with increasing confining pressure (a) and temperature (b). Figure 3a shows that after a sharp increase in the density due to the closure of microcracks at the initial stage (up to 100-200 MPa), the density increases linearly. According to the plots, Fig 3b, the sample density decreases rather monotonically and linearly with increasing temperature.

Part of the dependences ρ vs P within the pressures of 200-600 MPa and temperatures of 50-600 ^{o}C was approximated by the linear function:

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

The initial values of ρ_0 and the factors *α, β* and *γ* 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 ρ 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 ρ, 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 ρ 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

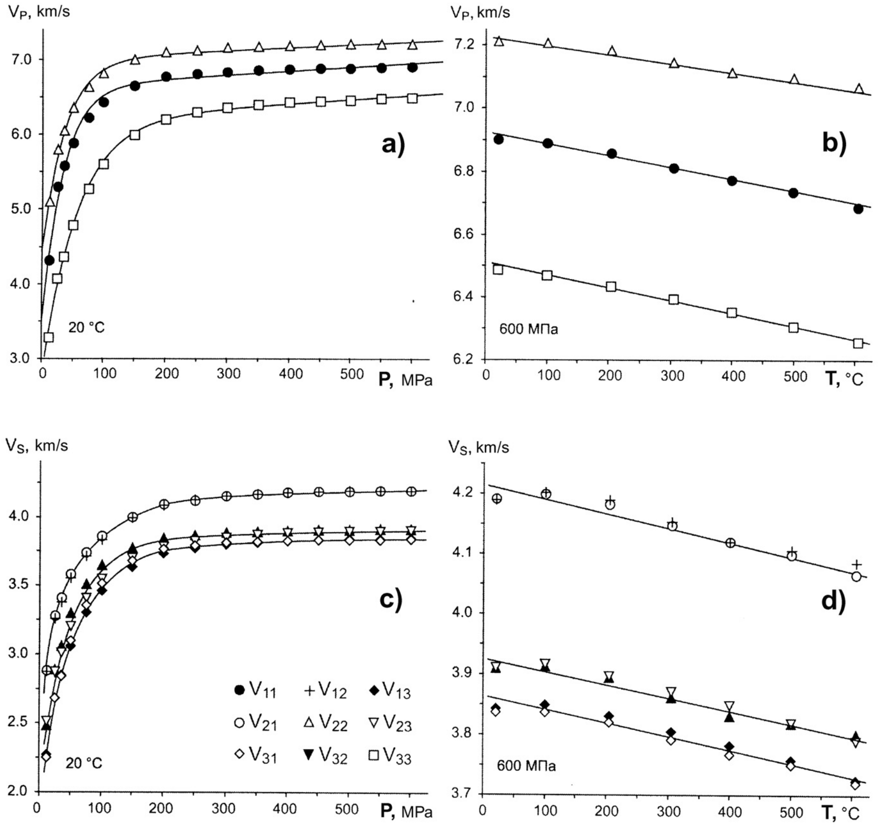

Fig. 4 Changes in the compression V_P (a, b) and shear V_S (c, d) wave velocities in sample 31115 according to the confining pressure (a, c) and temperature (b, d) (Golovataya et al., 2006).

Table 4 The values of V_0^P, V_0^S and factors α_p, α_s, β_p, β_s γ_p, γ_s for calculating compression and shear wave velocities as a function of deep PT-conditions for the samples from the SG-3 Archaean section.

Sample No.	V_0^P, km/s	V_0^S, km/s	α_P	α_S	$\beta_P \cdot 10^4$, km/s^{-1},·MPa^{-1}	$\beta_s \cdot 10^4$, km/s^{-1}, MPa^{-1}	$\gamma_P \cdot 10^4$, km/s^{-1}· deg.$^{-1}$	$\gamma_s \cdot 10^4$, km/s^{-1}· deg.$^{-1}$
31115	3.60(0.11)	2.24(0.05)	1.83(0.06)	1.73(0.04)	5.1(1.4)	2.31(0.68)	3.29(0.01)	2.1(0.3)
35400	4.11(0.11)	2.37(0.05)	1.54(0.04)	1.44(0.03)	8.2(1.4)	3.59(0.68)	2.0(0.3)	3.2(0.3)
36058	4.28(0.08)	2.39(0.04)	1.52(0.03)	1.44(0.02)	5.94(0.85)	2.86(0.41)	1.6(0.7)	2.5(0.5)
38098S	3.21(0.07)	1.80(0.05)	1.85(0.04)	1.74(0.05)	7.27(0.96)	5.57(0.64)	2.6(0.3)	1.7(0.2)
43560	3.12(0.15)	2.12(0.04)	2.11(0.10)	1.88(0.04)	6.4(1.9)	1.44(0.65)	1.95(0.05)	0.94(0.8)
43726	3.68(0.20)	2.50(0.07)	1.74(0.09)	1.57(0.05)	10.0(2.7)	3.3(1.1)	3.0(0.2)	1.7(0.2)

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

$$V(P,t)=\left[\alpha_p \cdot V_0+\beta_0 \cdot P\right]\cdot\left[1-\gamma_p\left(t-20\right)\right] \quad (2)$$

$$V(\mathrm{S},t)=\left[\alpha_s \cdot V_0+\beta s \cdot P\right]\cdot\left[1-\gamma_s\left(t-20\right)\right] \quad (3)$$

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 α_p, β_p, γ_p, α_s, β_s, γ_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

Table 5 Depth dependences of compression wave velocities (km/s) for the samples from the SG-3 Archaean section.

Depths, km	Sample No.						Average
	31115	35400	36058	38098S	43560	43726	
0	6.58	6.33	6.51	5.94	6.58	6.40	6.39±0.24
5	6.53	6.37	6.51	5.95	6.60	6.43	6.40±0.23
10	6.42	6.38	6.51	5.92	6.58	6.41	6.37±0.23
15	6.31	6.39	6.51	5.89	6.56	6.38	6.34±0.24
20	6.20	6.39	6.51	5.86	6.54	6.35	6.31±0.25
25	6.08	6.39	6.51	5.82	6.52	6.31	6.27±0.27

Table 6 Depth dependences of shear wave velocities (km/s) for the samples from the SG-3 Archaean section.

Depth, km	Sample No.						Average
	31115	35400	36058	38098S	43560	43726	
0	3.88	3.41	3.44	3.13	3.99	3.92	3.63±0.35
5	3.86	3.40	3.43	3.18	3.98	3.93	3.63±0.33
10	3.82	3.36	3.40	3.21	3.97	3.92	3.61±0.33
15	3.79	3.32	3.37	3.24	3.96	3.91	3.60±0.32
20	3.76	3.27	3.34	3.28	3.95	3.90	3.58±0.32
25	3.72	3.22	3.30	3.30	3.94	3.89	3.56±0.32

down to a depth of 25 km. The calculation results are given in Tables 5 and 6.

The obtained results allow us to see that the changes in the V_P velocity for the rocks listed in Table. 1, are confined to 5.82-6.58 km/s (Table 5). On average, from a depth of about 5 km there is a tendency for a decrease in the V_P values. This behaviour is explained by a stronger gradient of the velocity decrease with increasing temperature rather than by the influence of the pressure rise with increasing depth. Previously, such a trend was mentioned by Christensen and Mooney (1995). The average value of V_P at depths of 5-25 km changes slightly, from 6.40 to 6.27 km/s, which is 2.1 %. Shear waves also show a decrease in velocity with depth (Table 6). The range of changes for the rock samples is 3.13-3.93 km/s, Table 1. The average value of V_S decreases from 3.63 km/s (5 km) to 3.56 km/s (25 km). The relative change is 2.0 %.

The calculated data (Tables 3, 5 and 6) together with experimental results presented in Figure 2 are shown in Fig. 5. As one can see the velocity section V_P obtained by experimental methods in the SG-3 section, agrees well with the calculated data for the range of 10-25 km. The variations of the V_P values in the range of the Archaean section (6.84-12.0 km) are close to the same variations in the depth range of 10-25 km (The lithosphere..., 2005). The average values of the compression wave velocities in the range of 0-25 km are 6.2-6.3 km/s.

The velocity section of V_S 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).

According to the determined velocities of V_P and V_S in deep and superdeep wells (Kola SG-3, Ural SG-4, German KTB) compression and shear

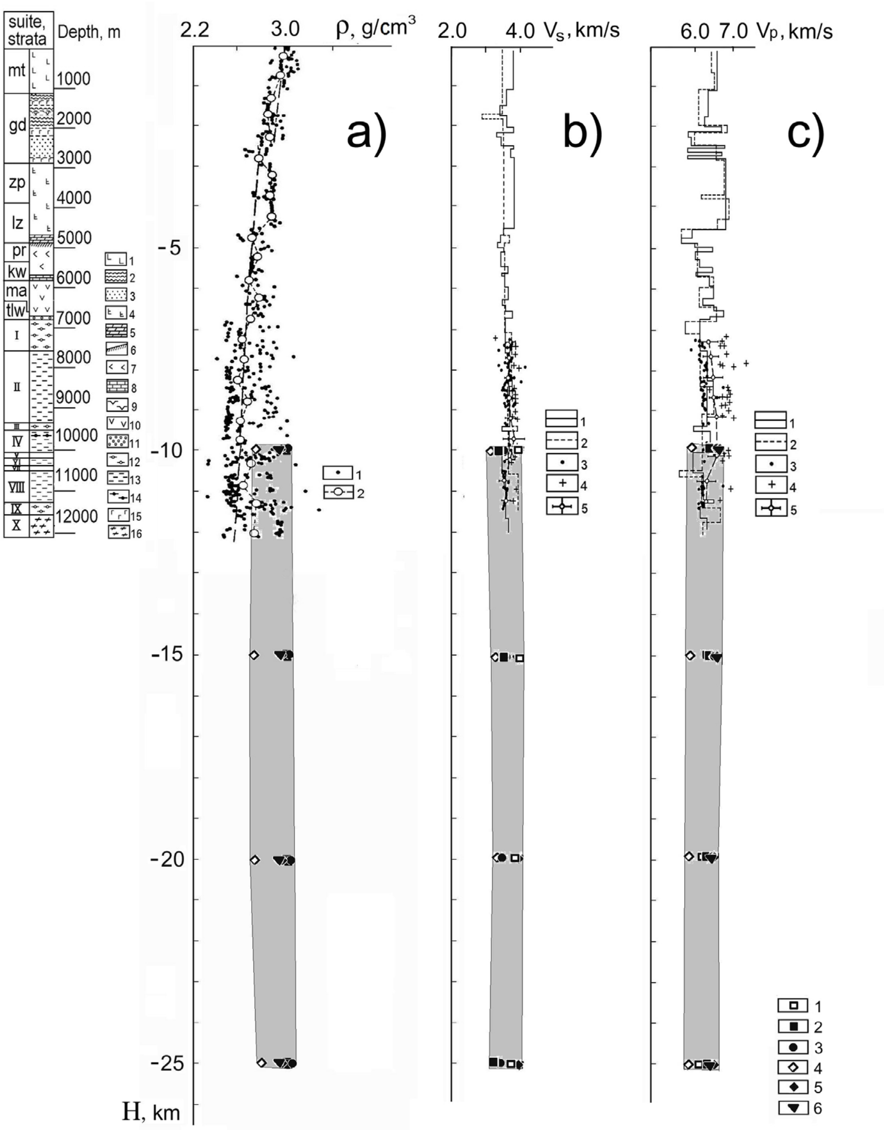

Fig. 6 The distribution of density ρ (a), shear V_S (b) and compression V_P (c) wave velocities along the SG-3 section (experimental data) and within the middle crust (calculation). The distribution of rocks and structural elements in the depth range of 0-12km see in Figure 1.

For the 10-25 km interval (see section (c)): 1 – the simulation of the depth dependences of ρ, 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; Gorbatsevich, 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 (Gorbatsevich 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 Mooney, 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 %. It should be considered that investigations of the SG-3 Archaean section (6842-12261 m) revealed the presence of velocity anisotropy of a high degree both for compression and shear waves. This means that the real velocity values in some directions in some layers can differ greatly from the above variations. Another reason for the change of seismic velocities in the crystalline crust with depth is crystalline restructuring of rocks owing to long-term metamorphic transformations of some minerals into others.

ACKNOWLEDGEMENTS

The author wishes to express his gratitude to Prof. H. Kern and Dr. T. Popp for the useful data. The work was done on the topics of projects №№ 07-05-00100-a, 10-05-00082, 13-05-00125 supported by the Russian Foundation for Basic Research.

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