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Decompaction mechanism of deep crystalline rocks under stress relief

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Abstract

Within a geological massif in a stable geodynamical situation contacts on the grain boundaries in polycrystalline rocks at great depths are continuous and firm. The stress release of those rocks during drilling and excavation to the surface is accompanied by their disintegration (decompaction). The reason for the decompaction is generation of microcracks during stress release due to the difference between the elastic moduli of crystalline grains at their contacts. The mechanism of decompaction may occur not only in polymineral but in polycrystalline rocks as well. The method of decompaction evaluation of deep crystalline rocks under stress relief is presented. According to the calculations the initial manifestation of the decompaction effect in biotite gneisses will occur when they are extracted from the deep range of 0.8–1 km. The first microcracks arise on the grain borders between quartz–biotite and oligoclase–biotite. It is shown that the uplift of gneiss–granite varities of the rocks cut by the Kola superdeep borehole from depths exceeding 13–15 km will be possible in a form of separate mineral grains. Practical importance of the presented method is in an opportunity to evaluate the level of excavated decompaction. The method allow estimating the depth, from which the rock will be extracted only in a sludge form.

Keywords: Crystalline rocks; Stress release; Elastic anistropy; Decompaction; Wave velocity

1. Introduction

Compression stress release of a crystalline rock, for instance in the course of drilling deep boreholes and core recovery, is related to decompaction caused by anisotropy of mechanical properties of mineral grains. The decompaction is accompanied by decrease in compression wave velocity and elasticity modulus and by marked increase of porosity and permeability of rock samples (Gorbatsevich et al., 1997).

Minerals of biotite gneisses, plagioclase granites and amphibolites from the Archean complex that are abundant within the Kola Peninsula, in particular in its north-western part. The main rock forming minerals of these rocks are quartz, plagioclase (oligoclase), microcline, biotite, amphibole (hornblende) and granite (Polkanov, 1935). Elastic anistropy of such minerals as biotite, oligoclase, microline, amphibole is very high (Clark, 1966; Alexandrov and Prodayvoda, 2000).

Rocks of the alkaline intrusion, to which the Khibiny apatite–nepheline deposits have been assigned, should exhibit significant decompaction. Here the main rock forming minerals represented by nepheline, alkaline feldspars (orthoclase and micro-

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cline), alkaline pyroxene (aegirine-diopside) and apatite (in ores) are also anisotropic (Dudkin et al., 1964).

It should be expected that a rapid stress relief of monomineral rock varieties composed of the above minerals will be accompanied by an uneven expansion of every particular grain. When the composition and structure are heterogeneous and crystallophysical axes of the adjacent grains are differently oriented, the stress relief will be accompanied by the emergence of internal strains. Internal strains at the grain borders along the contact planes of polymineral rocks may be much greater due to the greater difference between the elasticity constants of neighbouring minerals. Stress relief of a rock sample, for example, caused by the uplift of a core from a great depth leads to noticeable internal strains and then to damage of contacts and cracking (Gorbatsevich and Medvedev, 1986). Some observations made on Illinois granite indicate that stress relief caused by the core uplift generates microcracks in rocks (Carlson and Wang, 1986). The cracks inferred from laboratory data may not be present in the granites in situ, because the velocity of compressional waves measured in 3-km boreholes exhibits very little variation with depth (Simmons and Nur, 1968).

2. Calculations and analysis

Consider stresses and strains at the contact of two mineral grains, for example, oligoclase and biotite along the planes (010) (Fig. 1a). At a depth of H from the earth surface, in the vicinity of the contact a–a (Fig. 1b) compressing forces $\sigma = \gamma_c H$ will be considered to act, where γ_c is a mean relative density of rocks composing an overlying sequence. It can be calculated by formulae $\gamma_c = \Sigma \gamma_i \cdot h_i / H$, where γ_i is density of every layer of thickness h_i from the surface to the depth H.

The distribution of these forces σ in space may be close to hydrostatic. Such a distribution is registered already at relatively shallow depths (Jaeger, 1972; Gorbatsevich, 1996).

When a rock is relieved from the stress σ along the contact plane a–a (Fig. 1b) relative strains of oligoclase ε^p and biotite ε^b grains will be observed. The shearing strain along the grain contact line will be equal to:

$$\varepsilon_c = \varepsilon^p - \varepsilon^b \tag{1}$$

At some limiting value of $\varepsilon_c = |\varepsilon_c|$ along the line a–a the contact breaking should occur.

The elementary theory of elasticity of anisotropic media (Nye, 1964) allows one to determine ε^p, ε^b and $|\varepsilon_c|$ via the tensor components of linear compressibility and acting forces in accordance with the chosen crystallographic reference frame (Fig. 1a).

$$|\varepsilon_c| = \gamma_c H_p(\alpha_i' - \alpha_i''), \tag{2}$$

where H_p is the depth of rocks occurrence, the extraction from which causes the contact failure; α_i', α_i'' are tensor components of linear compressibility of the adjacent grains pair in the directions of the axes $X(i=1)$, $Y(i=2)$, $Z(i=3)$, respectively.

For instance, in granites (massive structure) mutual crystallographic orientation of individual grains may

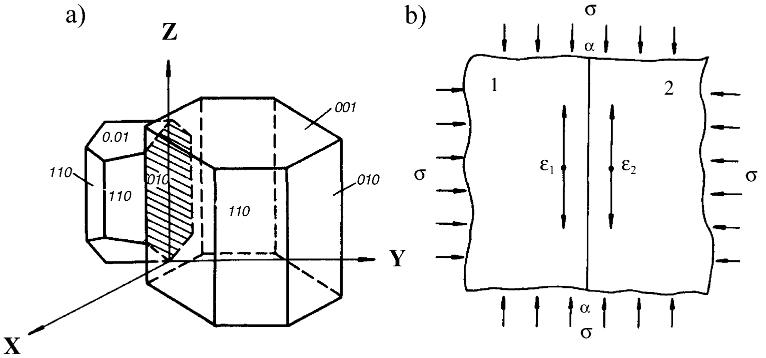

Fig. 1. Mineral grains contact of oligoclase and biotite along the planes (010) (a), diagram of forces applied to the contact (b). 1—oligoclase, 2—biotite.

be of any type, so the calculation of $\alpha_i'-\alpha_i''$ should be done according to the circular substitution of indexes:

$$\begin{array}{lll} \alpha_1'-\alpha_1'' & \alpha_1'-\alpha_2'' & \alpha_1'-\alpha_3'' \\ \alpha_2'-\alpha_1'' & \alpha_2'-\alpha_2'' & \alpha_2'-\alpha_3'' \\ \alpha_3'-\alpha_1'' & \alpha_3'-\alpha_2'' & \alpha_3'-\alpha_3'' \end{array} \qquad (3)$$

For the rocks with persistent linear and stratified structures the directions of crystallographic axes of adjacent grains coincide with high probability. Therefore the calculation of $\alpha_i'-\alpha_i''$, for instance, for amphibolites and biotite gneisses may be done according to the direction of the three main axes:

$$\begin{array}{l} \alpha_1'-\alpha_1'' \\ \alpha_2'-\alpha_2'' \\ \alpha_3'-\alpha_3'' \end{array} \qquad (4)$$

The values of linear compressibility in the direction of axes of crystallographic reference system for every grain are calculated via the components of linear compliance matrix (Nye, 1964):

$$\alpha_1 = S_{11}+S_{12}+S_{13},$$

$$\alpha_2 = S_{12}+S_{22}+S_{23},$$

$$\alpha_3 = S_{13}+S_{23}+S_{33}, \qquad (5)$$

Eq. (5) represents compression–tensile strains under hydrostatic (equilateral) stresses. The values of purely shear strains are disregarded.

The calculated values of $\alpha_i (i=1, 2, 3)$ for the rock forming minerals of some Kola polycrystalline rocks are given in Table 1. Their syngony, mean density γ_c, average elasticity modulus E, lateral strain factor v (Poisson ratio) and compression strength limit $|\sigma_r|$ are presented. Summary components of linear compliance have been calculated by formula (5) using the data of Alexandrov and Prodayvoda (2000), physical properties of minerals have been taken from Clark (1966).

Minerals as garnet, quartz, aegirine will be deformed similarly in all directions. For instance, for garnet $\alpha_1:\alpha_2:\alpha_3 = 1:1:1$, for quartz $\alpha_1:\alpha_2:\alpha_3 = 1:1:0.746$. Thus, after the relief the level of internal stresses in the above mineral grains will be relatively low. Even significant stresses will not cause their fracturing. Minerals microcline and biotite are highly anisotropic, for them the ratio $\alpha_1:\alpha_2:\alpha_3$ is 1:0.172:0.296 and 0.217:0.217:1.0 accordingly. Anisotropy of amphibole, nepheline and oligoclase is less but marked. In the grains of these minerals under high stresses relief significant internal stresses that cause separation along cleavage planes and fracturing may appear.

The data from Table 1 allowed calculating the values of $\alpha_i'-\alpha_i''$ for each pair of mineral grains by the formulae (3) and (4). The calculation results for the main minerals of biotite gneisses, plagiogranites, amphibolites and banded apatite–nepheline ore are given in Table 2. For the plagiogranites the calculations have been done according to the chart (3) but in Table 2 only maximum values of the difference $\alpha_i'-\alpha_i''$ are presented.

The data given enable to assess relative strains arising at the contact boundaries of individual pairs of

Table 1
Physical properties of some minerals

Mineral	Syngony	γ_c, g/cm^3	$E\cdot10^{-4}$, MPa	v	$\lvert\sigma_r\rvert$, MPa	$\alpha_1\cdot10^6$, 1/MPa	$\alpha_2\cdot10^6$, 1/MPa	$\alpha_3\cdot10^6$, 1/MPa
Quartz	trigonal	2.65	9.0	0.077	2600	9.73	9.73	7.26
Oligoclase	triclinic	2.6	6.5	0.28	1250	8.75	3.75	4.75
Biotite	monoclinic	3.0	6.9	0.27	300	3.68	3.68	16.93
Amphibole (hornblende)	monoclinic	3.1	10.6	0.28	940	6.13	3.72	2.01
Microcline	triclinic	2.6	7.6	0.29	1200	15.21	2.61	4.5
Garnet	cubic	4.2	24.2	0.27	–	2.75	2.75	2.75
Apatite	hexagonal	3.26	11.5	0.25	550	6.64	6.64	3.20
Nepheline	hexagonal	2.63	7.6	0.24	1100	12.26	12.26	5.63
Aegirine	monoclinic	3.56	14.7	0.28	1900[a]	3.23	3.52	2.55

[a] The data according to Handbook (1975).

Table 2
Calculated values of strains on mineral grains contacts $\alpha_1'-\alpha_1''$, $\alpha_2'-\alpha_2''$, $\alpha_3'-\alpha_3''$ ($\alpha \cdot 10^6$, 1/MPa). Calculated values of H_p (km), the excavation from which leads to formation of breaks on the grain boundary

Rocks	Mineral pair	$(\alpha_1' - \alpha_1'')/H_p$	$(\alpha_2' - \alpha_2'')/H_p$	$(\alpha_3' - \alpha_3'')/H_p$
Biotite gneisses (North-western part of the Kola peninsula—NWKP)	quartz–oligoclase	0.98/(13.7–26)	5.98/(7.7–14.8)	2.51/(13.7–26)
	quartz–biotite	6.05/(1.6–3.2)	6.05/(1.6–3.2)	9.67/(1.0–1.9)
	oligoclase–biotite	5.07/(2.0–3.8)	0.07/(13.7–26)	12.18/(0.8–1.6)
	quartz–oligoclase	5.98(1–2)/(7.7–14.8)	5.98(2–2)/(7.7–14.8)	3.51(3–2)/(13–25)
Plagiogranites (NWKP)	quartz–microcline	7.12(1–2)/(5.4–10.4)	7.12(2–2)/(5.4–10.4)	7.95(3–1)/(4.8–9.2)
	oligoclase–microcline	6.46(1–1)/(5.9–11.4)	11.46(2–1)/(3.4–6.4)	10.46(3–1)/(3.6–7.0)
	amphibole–oligoclase	2.62/(8.1–15.6)	0.03/(13.7–26)	2.74/(7.8–15)
Amphibolites (NWKP)	amphibole–biotite	2.45/(4.1–7.9)	0.04/(13.7–26)	14.92/(7.8–15)
	oligoclase–biotite	5.07/(1.8–3.4)	0.07/(13–25)	12.18/(0.75–1.4)
Banded apatite–nepheline ore (Khibiny massif)	apatite–nepheline	5.62/(2–3.8)	5.62/(2–3.8)	2.37/(1.3–2.5)

mineral grains. For instance, at the quartz–oligoclase boundary (biotite gneisses, plagiogranites) the maximum strains will be in the contact planes parallel to the axis Y (Fig. 1a). Thus, when the principle crystallophysical axes of the main minerals are oriented conformably, biotite gneisses should experience the greatest strains in the directions perpendicular to foliation. At the contact between biotite and amphibole (amphibolites) the maximum strains should be observed in the axis Z direction and their values should be six times higher than those in the contact between quartz and oligoclase (along the same axis). The strains at the contacts between oligoclase and biotite (axes Z–Z) in amphibolites and between oligoclase and microcline are significant when the axes Y (oligoclase) and X (microcline) as well the axes Z (oligoclase) and X (microcline) are directed conformably. The strain mean values in the contacts are typical of the apatite–nepheline pair of minerals.

The data from Tables 1 and 2 and the expression (2) allow one to assess the depth H_p from which the core extraction will be accompanied by decompaction caused by the contact failure at the boundaries of mineral grains. From Eq. (2) follows:

$$H_p = |\varepsilon| / (\alpha_i' - \alpha_i'')\gamma_c, \tag{6}$$

where $|\varepsilon|$ is the contact shear strength of the mineral grain pair.

In accordance with the known relation for brittle failure processes (Kartashov et al., 1979)

$$|\varepsilon_c| = |\sigma_s| / G \tag{7}$$

where $|\sigma_s|$ is shear strength in the mineral grain contact, G is a shear modulus.

Determination of the values of $|\sigma_s|$ is accompanied by significant experimental difficulties, so it is hard to find these values for the above mineral pairs in literature. An assessment of the value of H_p can be made indirectly according to the value of compression strength $|\sigma_r|$, taking into account that as a result of a large volume of rock tests the following correspondence has been set up (Il'nitskaya et al., 1969):

$$|\sigma_s| = (0.25 - 0.48)|\sigma_r|. \tag{8}$$

The value of the shear modulus can be also calculated by the value of elasticity modulus E and lateral strain factor v (Nye, 1964):

$$G = 0.5E(1 + v). \tag{9}$$

With regard to the expressions (7)–(9), the formula (6) will be

$$H_p = \frac{2K(1 + v)|\sigma_r|}{E\gamma_c(\alpha_i' - \alpha_i'')}, \tag{10}$$

where $K = 0.25–0.48$ is a factor taking into consideration the relation (8).

Calculation results for H_p by the formula (10) are given in Table 2. The value of mean density γ_c from the formula (10) should be average for the overlying rock unit under consideration. The weighted average value of $\gamma_c = 2.7$ g/cm^3 for the whole granitoid complex of the north–west part of the Kola Peninsula and for the Khibiny massif rocks the average $\gamma_c = 2.68$ g/cm^3 (Tyuremnov et al., 1982).

The calculations of H_p have been done using the principle of a weak link. For instance, when analysing the failure process of the contact between quartz and biotite it was believed that the failure would be realized by biotite, since it represents a medium with lower strength characteristics. Accordingly, when calculating H_p for this contact the values of biotite physical characteristics were substituted into the formula (10) (Table 1).

3. Discussion

Summarizing the results presented in Table 2, it should be noted that core recovery and extraction of crystalline rocks, such as biotite gneisses, plagiogranites, amphibolites, apatite ores, etc., from mine deep horizons will be accompanied by the effect of their inner decompaction. First of all the mentioned effect is expressed in discontinuity in the individual contacts of mineral grains.

Some increase (a rather weak one) in the rock volume will be observed. The volumetric measurements made on the KTB borehole samples suggest this conclusion (Berckhemer et al., 1997). The effect of decompaction under strain relief should manifest itself in an increase of porosity and permeability of rocks, decrease of elastic wave velocities in the rocks, elasticity and deformability values. The decompaction should be more pronounced in finer-grained rocks including greater number of minerals in equal summary volumes. The decompaction degree increases proportionally to the extraction depth H. The initial manifestation of the decompaction effect (Table 2) in biotite gneisses will occur when they are extracted from the depth range of 0.8–1 km on the grain border between quartz–biotite and oligoclase–biotite. For instance, the extraction of gneisses enriched with biotite from depths exceeding 13–15 km should be accompanied by discontinuity, cohesion break and disintegration of the rock as a whole (Gorbatsevich et al., 1997).

A comparatively great decompaction should be expected in plagiogranites. In Table 2 the calculations of H_p for plagiogranites for the "weakest" combinations of crystallophysical axes (in brackets) of the adjacent grains. According to the calculations from the depth of 4–6 km the plagiogranite decompaction is most pronounced. This conclusion is supported by experimental results of longitudinal velocity (V_p) measurements on core samples excavated from the Kola superdeep borehole (Gorbatsevich et al., 1997). In this work a distribution of the V_p measured on the core in laboratory conditions is presented. The measurements have been done on the samples, excavated from the depth of 12 km up to the earth surface. The points on the plot V_p vs. H are limited by two straight lines coming apart with depth. If near the earth surface the values of V_p are in the range from 6.2 to 6.75 km/c, then for the samples excavated from the depth of 12 km the values of V_p vary from 0.6 to 3.75 km/c.

Greater depth dependence of V_p is mainly characteristic of leucocratic varieties of rocks. Measurement results for the V_p values in such varieties excavated from the Kola superdeep borehole (KSDB-3) are presented in Fig. 2.

The results of more than 260 measurements (Fig. 2) show the distinct tendency for a decrease of mean V_p values and a regular shift in internal confidence limits of mean V_p in the given sample with a depth increase. This tendency is not evidently connected with varying strata or rock types depicted in the lithological column.

By the least-squares method a linear dependence of mean $V_p = 3.955 - 0.22H$, km/s, was calculated, where H-km is real in the range from 6.9 to 12.0 km. This dependence allows forecasting the depths at which the extraction of granitoids to the surface will be accompanied by their complete disintegration. Fig. 2 shows that extraction of gneiss–granite varieties of rocks from the depths exceeding 13–15 km will be possible in a form of separate grains. The obtained dependence is reliable for specific geologic, geostatic, temperature conditions in the Kola SD-3 section.

Amphibolites composed mainly of amphibole (hornblende) and feldspars (oligoclase) should be subjected to decompaction to a relatively small degree (Table 2). Mica in a rock promotes decompaction in the samples extracted from relatively shallow horizons (0.9–6.0 km). For the rocks from the north–west part of Kola Peninsula presented in Table 2 the degree of decompaction is an indicator of mica content in the rocks.

The greatest decompaction should be on the grain border of the apatite–nepheline mineral pair (Table 2).

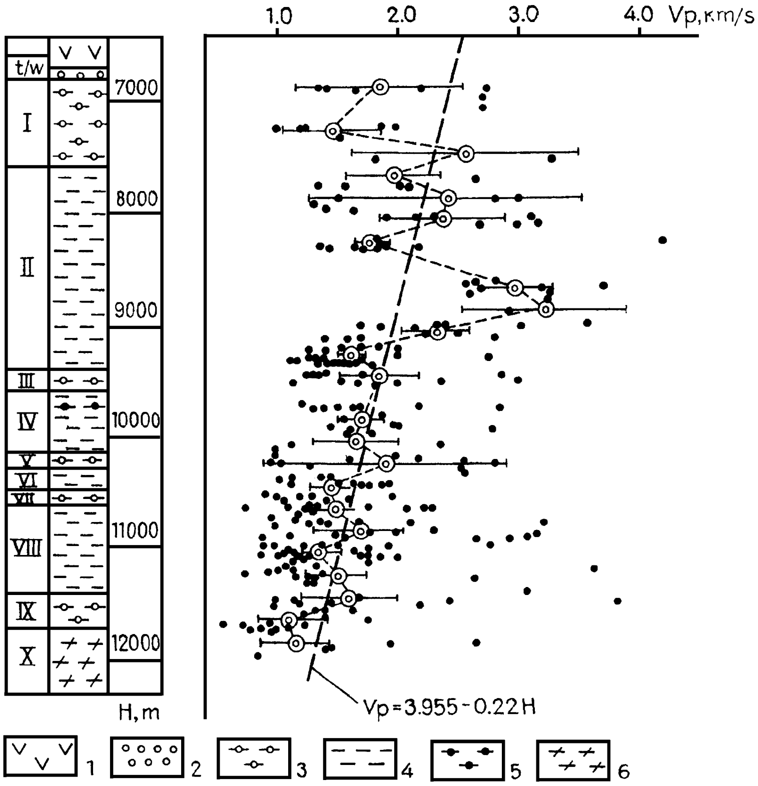

Fig. 2. Results of measurements of longitudinal velocity (V_p) values on gneiss–granite samples of SD-3 core, excavated from the depths of 6905–12,050 m. I–X—strata of Archean section. 1—metadiabases, porphirites, schists; 2—metadiabases; 3—biotite–plagioclase gneisses with high alumina minerals; 4—biotite–plagioclase gneisses with amphibole, epidote, sphene; 5—magnetite–amphibole schists; 6—biotite–plagioclase and sphene–biotite–amphibole–plagioclase gneisses, schists.

The calculations show that the extraction of the core of a banded apatite–nepheline ore from the depth exceeding 3 km will be accompanied by complete mechanical separation of apatite and nepheline grains.

The above method for calculating decompaction is simplified to some extent. It does not take into account real geological conditions, specific stress-strained state of a rock mass, spatial variability of their composition, texture and structure, heterogeneity, tectonic and fractured structures, relief. The impact of the earth interior temperature has not been taken into consideration.

Heating rocks is accompanied by their decompaction (Kern and Wenk, 1990; Christensen and Mooney, 1995). The level of decompaction, caused by temperature, is much less, than that caused by decompression. For example, heating rock samples, excavated from the Kola superdeep to 200 °C, decreases the V_p in them only by ~ 1–3% (Kern et al., 2001). It should be noted that the excavation of rock samples from deep and superdeep boreholes is accompanied by their cooling. Cooling may also cause microcracks in defect-free material (Tvergaard and Hutchinson, 1988). But in polycrystalline rocks some increase in V_p may occur and thus an increase of sample continuity might be expected on cooling. The process of cooling acts in the direction opposite to that of decompression. This conclusion can be drawn from the review of Fig. 2 data and results of the laboratory experiments (Kern et al., 2001).

Since the impact of the earth interior temperature becomes conspicuous from a depth of 8–10 km, the obtained values for the range of 10–20 km should be taken as estimation ones. At the same time when hard polymineral rocks are relieved from geostatic stresses, physical reality of the decompaction effect is rather clear. The known experimental results, obtained during examination of the core from super-deep boreholes, support the availability of this effect (Gorbatsevich et al., 1997; Orlov and Laverov, 1998).

4. Conclusion

The above method for calculation of decompaction mechanism allows foreseeing some effects observed in deep crystalline rocks under stress relief. One of those effects is generation of microcracks in rocks during drilling and uplift to the surface. This process is accompanied by the velocity decrease in the core. The initial manifestation of decompaction in biotite gneisses will occur when they are extracted from the depth range of 0.8–1 km on the grain border between quartz–biotite and oligoclase–biotite. The effect of rock decompaction sets principal limits on extraction of polycrystalline rocks in a solid form from great depths. For example, extraction of gneiss–granite varieties of rocks from the depths exceeding 13–15 km will be possible in a form of separate mineral grains. The calculations show that the extraction of the core of a banded apatite–nepheline ore from the depth exceeding 3 km will be accompanied by complete mechanical separation of apatite and nepheline grains. Hence, the above evaluations suggest that ores, for instance, apatite–nepheline ores, can be extracted from relatively moderate depths using the mechanism of decompaction.

In practice, the decompaction mechanism may be used in the following way. First, one should drill a borehole (or mine) down to the calculated depth of complete rock decompaction. Then, after applying atmospheric pressure to the borehole bottom one can excavate rock material in a form of grains. Thus, the decompaction mechanism can provide the basis for developing new techniques enabling to involve some solid mineral resources situated at depths and requiring an application of unmanned production techniques.

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