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# THE RELATIONSHIP BETWEEN GNEISSES FROM THE KOLA SUPERDEEP BOREHOLE AND THEIR SURFACE ANALOGUES

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**ABSTRACT**

Modal composition and grain-size characteristics, physical and mechanical properties of three samples of Archean gneisses of the Kola series from the depths of 6.8 to 8.4 km of the Kola Superdeep Borehole (KSDB-3) and two collections of their surface analogues were analysed. On the basis of a comparison of the petrographic characteristics of the borehole samples and analogues, it was found that not all analogues are equivalents of corresponding core samples completely. Mechanical properties of core samples are affected by depth of the core sample position in the borehole. This work forms part of the research in the frame of the INTAS Project No.314 "Geodynamics in the cross-section of the Kola superdeep".

**KEYWORDS:** Kola superdeep borehole, gneisses, surface analogues

## 1. INTRODUCTION

The basic petrographic characteristics, physical and mechanical properties of three samples of Archean gneisses of the Kola series from depths of 6.8 to 8.4 km of the Kola Superdeep Borehole (KSDB-3) and two collections of their surface analogues collected from outcrops within the Pechenga district were tested (Orlov and Laverov, 1998; Lobanov et al., 2000). The first collection of three surface analogues was selected by the Geological Institute RAS Apatity and the second by the Institute of Geology of Ore Deposits, Petrography, Mineralogy and Geochemistry RAS Moscow. The aim of our study was to find differences in rock properties of samples from the KSDB-3 borehole and both collections of surface analogues.

On the assumption that rocks from surface are analogues of tested gneisses from the KSDB-3 (the same modal composition and grain-size characteristics), the differences in the other physical and deformation properties between core samples and analogues arose due to P-T conditions in the deep borehole.

The results of tests of physical and mechanical properties are partly affected by the small amount of rock material which we had at our disposal.

## 2. METHODS

Petrographic research and documentation were made on microscope LEICA; modal composition and grain-size characteristics, particle and bulk density, total porosity, unconfined compressive strength, modulus of deformation, Young´s modulus and Poisson´s ratio were determined on all the available samples in the laboratory of the Institute of Rock Structure and Mechanics AS CR Prague.

## 3. TESTED SAMPLES

Table 1 presents the catalogue of selected samples from the three borehole cores and two groups of their surface analogues.

**Table 1** Signification of the tested samples.

| Rocks | Depth (m) of core samples | Catalogue numbers | | |
|---|---|---|---|---|
| | | Core sample | Surface analogue GI Apatity | Surface analogue IGEM Moscow |
| Biotite gneiss | 6849 | 22515 | 1-02 | PL-360 |
| Muscovite–biotite gneiss | 7913 | 26609 | 2-02 | PL-366 |
| Biotite gneiss | 8411 | 28938 | 4-02 | PL-367 |

**Table 2** Modal composition (%) of all tested samples.

| Minerals | Biotite Gneiss (depth 6849 m) | | | Muscovite-biotite Gneiss (depth 7913 m) | | | Biotite Gneiss (depth 8411 m) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Core sample 22215 | Surface analogue 1-02 | Surface analogue PL-360 | Core sample 26609 | Surface analogue 2-02 | Surface analogue PL-366 | Core sample 28938 | Surface analogue 4-02 | Surface analogue PL-367 |
| hornblende | - | 5 | - | 2 | 2 | 4 | ac$^{1)}$ | ac$^{1)}$ | ac$^{1)}$ |
| epidote | ac$^{1)}$ | ac$^{1)}$ | - | 0.5 | ac$^{1)}$ | 1.5 | - | - | - |
| chlorite | 0.5 | 0.5 | 2 | 0.5 | 2.5 | ac$^{1)}$ | 0.5 | 0.5 | 2 |
| plagioclase | 54 | 69 | 39.5 | 45.5 | 63 | 44 | 50 | 47 | 42.5 |
| quartz | 25 | 15 | 27 | 25 | 22 | 29 | 42.5 | 35 | 22.5 |
| rutile | ac$^{1)}$ | ac$^{1)}$ | 0.5 | ac$^{1)}$ | ac$^{1)}$ | ac$^{1)}$ | ac$^{1)}$ | ac$^{1)}$ | ac$^{1)}$ |
| apatite | 0.5 | 0.5 | 1 | 1 | 0.3 | 0.5 | 0.5 | 0.5 | 0.5 |
| titanite | ac$^{1)}$ | ac$^{1)}$ | 1 | 1.5 | 1 | 0.5 | 0.5 | 0.5 | 0.5 |
| biotite | 16 | 5 | 2 | 18 | 5 | 14 | 4 | 13 | 20 |
| sillimanite | ac$^{1)}$ | ac$^{1)}$ | 4 | - | - | - | - | - | - |
| muscovite | 2 | - | 2 | 7 | 0.5 | 3 | 1 | 3 | 6 |
| garnet | - | - | - | ac$^{1)}$ | ac$^{1)}$ | 3 | ac$^{1)}$ | ac$^{1)}$ | 5 |
| ore minerals | 2 | 5 | - | ac$^{1)}$ | 3 | ac$^{1)}$ | 1 | 0.5 | 0.5 |
| zircon | ac$^{1)}$ | ac$^{1)}$ | - | 0.5 | 0.7 | 0.5 | ac$^{1)}$ | ac$^{1)}$ | ac$^{1)}$ |
| clinozoisite | - | - | - | 1.5 | - | - | - | - | - |
| sekaninaite | - | - | - | - | - | - | - | 0.5 | - |

$^{1)}$ accessory mineral

## 4. MINERALOGICAL COMPOSITION AND ANALYSIS OF MICROSTRUCTURES

Basic petrographic characteristics of core samples and both groups of surface analogues are summarized in Table 2.

A quantitative analysis of microstructures (grain size distribution) was carried out using an image measurement system on thin sections. Microphotographs illustrating microfabrics of studied rocks are presented (Figs. 1 and 2).

### *4.1. BOREHOLE SAMPLE FROM DEPTH OF 6849 M AND SURFACE ANALOGUE SAMPLES (Fig. 1)*

#### **Core sample No. 22515 - Biotite gneiss (Fig. 1a)**

The rock, of fresh appearance, with lepidogranoblastic texture and parallel structure consists mainly of feldspar (54 %), quartz (25 %) and biotite (16 %), subordinate muscovite (2 %) and an opaque mineral (2 %) and sporadic accessory garnet. Biotite lamellae ranging from 0.1 to 1.3 mm in size are intensely pleochroic and have light to dark brown color. Feldspar is represented by both plagioclase as well as potassium feldspar. Hypidiomorphic plagioclase grains between 0.2 and 0.8 mm in size on average (sporadically can grow up to 1.4 mm) are equal to oligoclase and have albite-like lamellae pattern. Potassium feldspar occurs sporadically. Quartz grains between 0.1 and 0.4 mm in size are interlocked with plagioclase or enclosed by it respectively. Both feldspar and quartz grains are seen to be elongate parallel to the foliation. Muscovite is usually 0.1 to 0.25 mm in size on average, but sporadically may reach 1 mm. An opaque mineral forms grains up to 0.3 mm in size.

#### **Analogue sample 1-02 – Amphibole-biotite gneiss (Fig. 1b)**

Amphibole-biotite gneiss appears with a nematolepidoblastic to granoblastic texture and non-laminated crystalline structure. It consists mainly of feldspar (69 %) and quartz (15 %) and subordinate amphibole (5 %), biotite (5 %) and opaque mineral (5 %). Unaltered albite-like laminated feldspar grains 0.3-3.5 mm in size correspond to oligoclase or oligoclae-andesine respectively. Potassium feldspar is minor. Quartz, grains 0.1-0.4 mm in size of sub-oval shapie, has a slightly wavy extinction. They are interlocked with plagioclase. Dark green, intensively pleochroic (lightly green-yellowish to dark green or black-green) amphibole grains 0.1-0.6 mm in size have extinction angle $\gamma/c$ = 13-20° corresponding to common amphibole. Dark brown, intensely pleochroic (light brown-yellowish to black-brownish) biotite forms grains 0.1-0.5 mm in size. An opaque mineral, replacing dark minerals, appears as grains 0.1-0.3 mm in size. Garnet is included as accessory (one grain in thin section is 0.5 mm in size). The unaltered rock has a fresh appearance.

#### **Analogue sample PL-360 - Migmatized biotite gneiss (Fig. 1c)**

The rock is composed mainly of feldspar (39.5 %), quartz (27 %) and biotite (23 %) and subordinate sillimanite (4 %) and muscovite (2 %); apatite and titanite represent accessories constituting about 1 % of the rock. Feldspar (plagioclase) ranging between 0.4 to 2.5 mm in size is mostly about 1.2 mm in diameter on average. In addition some larger partially seriticized plagioclase grains between 3 and 4 mm in size were observed together with fewer non-seriticized grains between 2.5 to 3 mm. Quartz grains are seen to be between 0.3 and 1.1 mm in size with those of about 1 mm in diameter prevailing. Biotite forms irregularly spaced clusters or laminae 0.8 to 1.2 mm in size.

### *4.2. BOREHOLE SAMPLE FROM DEPTH OF 7913 M AND SURFACE ANALOGUE SAMPLES (FIG. 2)*

**Core sample No. 26609 – Muscovite-biotite gneiss (Fig. 2a)**

The rock has a lepidogranoblastic texture and sub-parallel structure. It is composed of feldspar (45.5 %), quartz (25 %), biotite (18 %) and muscovite (4 %); titanite (1.5 %), zircon (0.5 %), clinozoisite (1.5 %), epidote (0.5 %) and apatite (1 %) are the accessories. Feldspar growing as lamellar grains 0.1 to 1 mm in size corresponds to oligoclase, potassium feldspar occurs sporadically. Quartz appears as grains 0.1 to 0.5 mm in size interlocked with plagioclase. It has slightly wavy extinction. Biotite forms parallel-featured pleochroic lamellae 0.1 to 1.1 mm in size, of dark brown color and fresh appearance. Muscovite lamellae are 0.1 to 1.5 mm in size. Irregular titanite grains up to 0.4 mm in size locally replace biotite. Small needles of zircon up to 0.1 mm in size largely form the cores of titanite grains, as well as isolated grains. Both clinozoisite and epidote replace primary dark minerals. Clinozoisite forms small columnar crystals 0.1 to 0.4 mm in size, whilst epidote is enclosed by it and appears dark green in color. Hypidiomorphic apatite forms grains 0.05 to 1 mm in size.

**Analogue sample 2-02 - Biotite gneiss (Fig. 2b)**

Biotite gneiss with a lepidogranoblastic texture and sub-parallel structure is composed mainly of feldspar (63 %) and quartz (22 %), subordinate biotite (5 %), amphibole (2 %) and an opaque mineral (3 %). Zircon (0.7 %) and apatite (0.3 %) represent the accessories. Hypidiomorphic fresh feldspar grains 0.1 to 0.8 mm in size have albite-like lamellae patterns and correspond to oligoclase. Potassium feldspar occurs sporadically. Sub-oval quartz grains 0.05-0.4 mm in size have a slightly wavy extinction sometimes even straight. Dark green, intensely pleochroic (light brown-yellow to red-brown) amphibole grains have extinction angle 14-21°, corresponding to common amphibole. Dark brown, intensely pleochroic (light brown-yellow to red-brown) biotite lamellae 0.05 to 0.3 mm in size (rarely some are 1 mm) are slightly hematized, which influences the rock appearance as a whole. An opaque mineral 0.05-0.3 mm in size replaces dark minerals. Zircon has grown as small grains of columnar to irregular shape, 0.15 mm in size. Similarly shaped apatite is 0.2 mm in size.

**Analogue sample PL-366 - Migmatized biotite gneiss (Fig. 2c)**

Migmatized biotite gneiss consists mainly of feldspar (44 %), quartz (29 %) and biotite (14 %), subordinate garnet (3 %) and only thin section, amphibole (4 %) and accessories (2 % as a whole) being represented by muscovite, apatite and titanite. Feldspar appears as intensely sericitized grains 0.9 mm in size on average but also up to 1.3 mm, interlocked with amphibole, if present. Quartz forms grains 0.2-0.3 mm in size. Biotite is seen to form lamellae 0.7-0.8 mm long, arranged in parallel. The rock is composed of alternating bands – those of prevailing biotite with those of prevailing light minerals – feldspar and quartz. Individual layers (irregular strips or lenses) are up to 2 mm thick.

### *4.3. BOREHOLE SAMPLE FROM DEPTH OF 8411 M AND SURFACE ANALOGUE SAMPLES (FIG. 3)*

**Core sample No. 28938 - Biotite gneiss (Fig. 3a)**

Biotite gneiss with lepidogranoblastic texture and parallel structure consists of feldspar (50 %) and quartz (42.5 %) and subordinate biotite (4 %). Feldspar (plagioclase) corresponding to oligoclase forms grains 0.1 to 1 mm in size, with albite-like lamellae patterns. Potassium feldspar is sporadic. Quartz appears in grains 0.1-1 mm rarely 5 mm in size with slightly wavy extinction, elongated parallel to the foliation. Larger grains display straight extinction. Dark brown intensely pleochroic biotite lamellae 0.05-1.35 mm in size are arranged in parallel. The rock as a whole has a fresh appearance.

**Analogue sample 4-02 - Biotite gneiss (Fig. 3b)**

Biotite gneiss with lepidogranoblastic or poikiloblastic texture and non-laminated crystalline structure consists of feldspar (47 %), quartz (35 %) and biotite (13 %), the rest being accessories. Albite-like laminated sporadically chloritized feldspar crystals 0.6-2 mm in size correspond to oligoclase, potassium feldspar is less prevalent. Slight to medium extinguishing quartz grains 0.3-4 mm in size are tooth-shaped or have irregular edges. Sporadically chloritized dark brown intensely pleochroic biotite is seen to form either clusters 0.15-0.35 mm in size or is scattered in a feldspar mass, the latter about 0.01-0.07 mm in size. Accessory sekaninaite occurs in biotite clusters. The rock is slightly chloritized but of fresh appearance as a whole.

**Analogue sample PL-367 - Migmatized gneiss (Fig. 3c)**

The rock is mainly composed of feldspar (42.5 %), quartz (22.5 %), biotite (20 %) and subordinate muscovite (6%). Feldspar grains range between 0.4 and 1.3 mm in size. Quartz grains reach 0.6 mm in size on average, sporadically to 1.3 mm as

**Table 3** Physical properties

| Borehole core sample number | Particle density ($g/cm^3$) | Bulk density ($g/cm^3$) | Total porosity (%) |
|---|---|---|---|
| 22515 | 2.74 | 2.68 | 2.12 |
| 26609 | 2.76 | 2.71 | 1.81 |
| 28938 | 2.76 | 2.63 | 4.71 |

| Samples of surface analogues (GI Apatity) | Particle density ($g/cm^3$) | Bulk density ($g/cm^3$) | Total porosity (%) |
|---|---|---|---|
| 1-02 | 2.75 | 2.63 | 3.46 |
| 2-02 | 2.76 | 2.62 | 5.07 |
| 4-02 | 2.71 | 2.64 | 2.58 |

| Samples of surface analogues (IGEM Moscow) | Particle density ($g/cm^3$) | Bulk density ($g/cm^3$) | Total porosity (%) |
|---|---|---|---|
| PL-360 | 2.75 | 2.71 | 1.45 |
| PL-366 | 2.82 | 2.76 | 2.13 |
| PL-367 | 2.84 | 2.80 | 1.41 |

a maximum. Biotite laminae over 1 mm long were seen in thin section 838, whilst in thin section 839 they range between 0.2 and 0.5 mm. Sporadic fine biotite lamellae about 0.05 mm in size were also perceptible. Small muscovite lamellae are up to 0.2 mm long. A cracked garnet grain 1.5 x 1.3 cm in size with a considerable pressure shadow was observed.

## 5. PHYSICAL PROPERTIES

The basic physical properties – particle density, bulk density and porosity were determined (Table 3). The particle density (mass per unit volume) was determined by applying the pyknometer method on regular specimens. The bulk density was determined on irregular specimens coated with paraffin wax, using the water displacement method. The total porosity, defined as the volume of all pores to the total volume of the rock specimen, was calculated from the bulk density of the dry specimen $\rho_d$ and particle density $\rho_s$ from the formula:

$$n = (1 - \rho_d / \rho_s) \cdot 100 \quad (\%).$$

Physical properties are very similar for borehole core samples and surface analogues. Determined differences between particle density and bulk density of all tested rocks are small (on average 0.07 $g/cm^3$) as all core samples as their analogues because the rock material is very compact, therefore also porosity is low (on average 2.75 %).

## 6. MECHANICAL AND DEFORMATIONAL PROPERTIES

Unconfined compressive strength, axial strain ($\varepsilon_A$) and lateral strain ($\varepsilon_L$) were measured at uniaxial compression test. Cylindrical specimens, 25 mm in diameter and 50 mm in height, were prepared by diamond drilling from borehole core with defined orientation parallel to the borehole axis for laboratory strength and deformational tests. The same size of specimens was used for surface analogues of rocks.

One cycle of loading and unloading was applied in the loading process during the compression test to calculate deformational properties. To obtain unconfined compressive strength, after this cycle, the samples were loaded until failure. Because the final strength value was not known, the cycle was assessed empirically and additionally it was calculated that it roughly corresponds to about 67 % on average (core samples) and 72 % on average (analogues) of the final strength value (Gorbatsevich et al., 2004).

From the measured strains, the values of the deformation modulus $E_{def}$, Young's modulus E and Poisson's ratio ν, were determined by formulae well-known in rock mechanics (Lama and Vutukuri, 1978).

In Table 4 results of unconfined compressive strength tests and deformational properties of rocks from Kola Superdeep borehole and their surface analogues are shown.

The average values of the unconfined compressive strength measured on the core samples (126.6 MPa) are lower then on the parallel surface analogue samples (168.1 MPa). This phenomenon is observed on values of the both moduli (33.8 GPa and

**Table 4** Mechanical and deformational properties.

| Borehole core sample number | Unconfined compressive strength (MPa) | Modulus of deformation (GPa) | Young´s modulus (GPa) | Poisson´s ratio |
|---|---|---|---|---|
| 22515 | 111.8 | 32.0 | 40.2 | 0.28 |
| 26609 | 99.4 | 26.0 | 36.0 | 0.34 |
| 28938 | 168.5 | 43.3 | 48.0 | 0.21 |

| Samples of surface analogues(GI Apatity) | Unconfined compressive strength (MPa) | Modulus of deformation (GPa) | Young´s modulus (GPa) | Poisson´s ratio |
|---|---|---|---|---|
| 1-02 | 158.2 | 56.3 | 65.0 | 0.24 |
| 2-02 | 146.0 | 61.5 | 68.4 | 0.33 |
| 4-02 | 213.5 | 89.0 | 114.5 | 0.33 |

| Samples of surface analogues (IGEM Moscow) | Unconfined compressive strength (MPa) | Modulus of deformation (GPa) | Young´s modulus (GPa) | Poisson´s ratio |
|---|---|---|---|---|
| PL-360 | 183.9 | 77.1 | 80.7 | 0.27 |
| PL-366 | 213.3 | 89.0 | 95.7 | 0.29 |
| PL-367 | 93.9 | 77.8 | 89.1 | 0.25 |

All unconfined compressive strengths were determined after one cycle of loading and unloading

41.4 GPa for core samples, 75.1 GPa and 85.6 GPa for surface analogues). 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.

## 7. RESULTS

From detailed mineralogical composition and analysis of microstructures of the borehole core samples and both their surface analogues, we present the following results:

Borehole core sample from a depth of 6849 m No. 22515 is similar to the rock representing analogue PL-360. It is suitable for comparative study. Analogue 1-02 consists of a rock of similar fabric but very different in mineral composition in the exact quantitative proportions of the constituent minerals.

Sample No. 26609 is similar to the rock included in analogue PL-366 by its mineral composition, including quantitative proportions. The rock representing analogue 2-02 differs strongly in either mineral composition or rock fabric.

Sample No. 28938 differs totally from analogue PL-367 either in mineral composition or rock fabric. Analogue 4-02 corresponds to core sample No. 28938, being of the same mineral composition.

The physical properties (particle and bulk density, total porosity) of the all tested samples, the core samples and both groups of surface analogues, are very similar regardless of whether a given analogue corresponds to a core sample.

The problem of determining mechanical properties of tested the rocks was the insufficient quantity of rock material of the specimens for standard rock mechanics laboratory tests. Only one specimen of three core samples and surface analogues 1-02, 2-02, 4-02 from the available rock material could be used for tests. In the case of the surface analogues PL-360, PL-366 and PL-367, more rock material was at our disposal, but not enough to obtain a statistically reliable set of laboratory test results. In spite of this problem, several results were achieved.

The simple compressive strength of the core samples is significantly less than that of the surface analogues. This can be partly due to decompaction during lifting the core from the depth of the borehole (Trčková and Živor, 2000; Trčková et al., 2002a).

Also, both moduli of core samples are much smaller than their surface analogues. This phenomenon is caused by higher axial strain of core samples, which are roughly twice as high, and this can be attributed to decompaction of core samples from the borehole during lifting.

A similar result was achieved during comparison of the amphibolite core samples from various depths of the borehole. The simple compressive strength and both moduli of the core samples significantly decreased with depth in the borehole (Trčková et al., 2002b).

The results of multidisciplinary studies of physical and mechanical properties of core samples from the Kola Superdeep borehole and their analogues from the surface have major importance for characterizing processes developed in deep zones of the continental crust.

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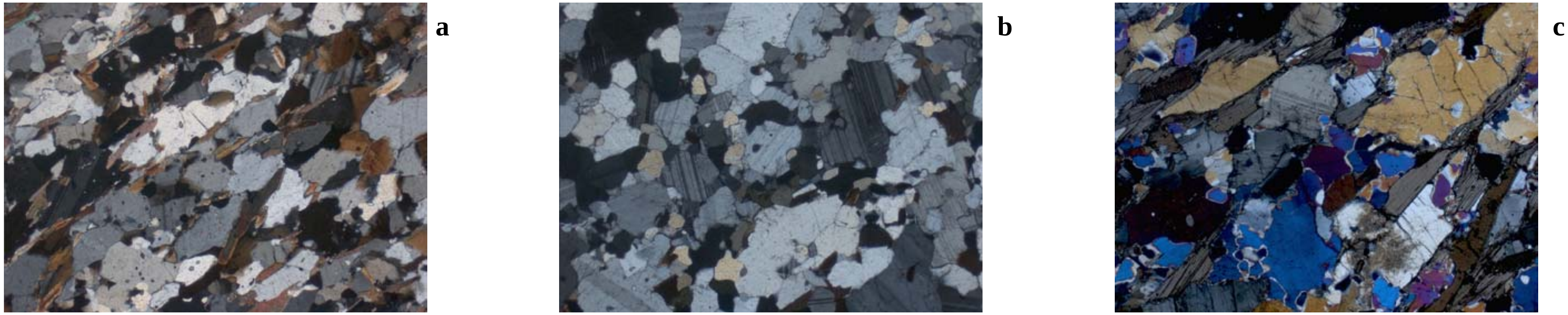

**Fig. 1** Microphotographs of the core sample from depths of 6849 m (a) and corresponding analogues 1-02 (b) and PL-360 (c).

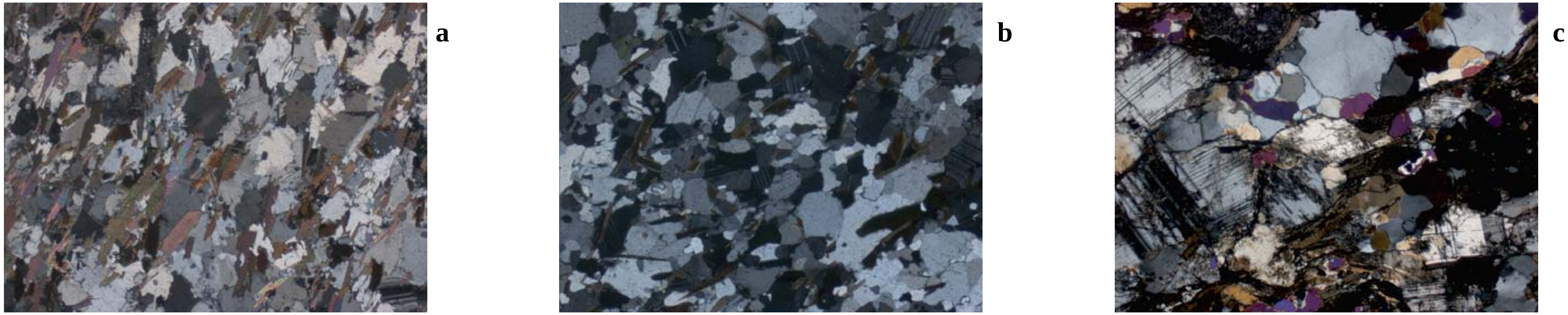

**Fig. 2** Microphotographs of the core sample from depths of 7913 m (a) and corresponding analogues 2-02 (b) and PL-366 (c).

**Fig. 3** Microphotographs of the core sample from depths of 8411 m (a) and corresponding analogues 4-02 (b) and PL-367 (c).