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MINERALOGICAL AND GEOCHEMICAL STUDY OF THERMALLY ALTERED COUNTRY ROCKS OF GRANODIORITE INTRUSION IN THE BĘDKOWSKA VALLEY NEAR KRAKÓW (S POLAND)

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Abstract: Extensive zone of thermally altered sedimentary rocks occurring in the contact aureole of granodiorite intrusion has been described from the boreholes in the Będkowska Valley near Kraków. Depending on the composition of primary rocks and the distance from the intrusion the following metamorphic rocks were formed: fine-grained cordierite hornfelses, macroscopically spotted andalusite hornfelses, chlorite-bearing spotted rocks, metaconglomerates, metasandstones and metamudstones. These rocks consist of various neogenic minerals: cordierite, andalusite, biotite, muscovite, feldspars and corundum. The rocks and neogenic minerals have been investigated in details using optical and electron microscopy, X-ray diffraction, EDS and chemical methods (ICP, INAA, XRF).

Characteristic contact metamorphic mineral paragenesis suggests that the most altered rocks in question were formed within temperature range from 580 to 630°C and pressure about 1–2 kbar under conditions corresponding to the orthoclase-cordierite hornfels facies of thermal metamorphism.

Abstrakt: Rozległa strefa przeobrażonych termicznie skał osadowych tworzących aureolę kontaktową dookoła intruzji granodiorytu została opisana z wierceń (otwory DB-5 i WB-102A) usytuowanych w Dolinie Będkowskiej (na północny zachód od Krakowa). W zależności od odległości od intruzji oraz pierwotnego składu mineralnego i chemicznego skał osadowych, podczas metamorfizmu kontaktowego powstały następujące skały: drobnoziarniste hornfelsy kordierytowe, makroskopowo plamiste hornfelsy andaluzytowe, skały plamiste z chlorytem, metazlepieńce, metapiaskowce i metamułowce. W badanych skałach stwierdzono występowanie następujących neogenicznych minerałów: kordierytu, andaluzytu, biotytu, muskowitu, skaleni i korundu. Skały przeobrażone termicznie, oraz ich neogeniczne minerały zostały szczegółowo przebadane mikroskopowo (mikroskop polaryzacyjny i elektronowy), metodą rentgenowską oraz metodami chemicznymi (klasyczna analiza chemiczna, ICP, INAA, XRF oraz EDS i mikrosonda).

Obecność w badanych skałach paragenez mineralnych charakterystycznych dla facji ortoklazowo-kordierytowo-hornfelsowej metamorfizmu kontaktowego (według terminologii Winklera) może sugerować zakres temperatur (580–630°C) i ciśnień (1–2 kbar), w którym doszło do najintensywniejszej termicznej transformacji skał osadowych.

Key words: metamorphism, thermally altered, spotted hornfels, contact aureole, granodiorite, cordierite, andalusite.

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INRODUCTION

Lower Palaeozoic detritic complex (Bukowy & Ślósarz 1968) was found first in the Bębło borehole, situated on the southern margin of the Silesian-Cracovian monocline, NW of Kraków. Lower Palaeozoic series and granodiorite intrusion were found under Jurassic sequence in the Będkowska Valley, too (boreholes DB-4, DB-5 WB-55, WB-58, WB-102, WB-102A – (Harańczyk, 1982, 1984, 1994a, b). In Harańczyk's opinion (Harańczyk *et al.*, 1995, 1996), a tectonic unit called Jerzmanowice block occurs in the basement of this area. Its core is formed by plutonic granodiorite intrusion, causing large positive magnetic anomaly.

This intrusion (Fig. 1), showing the character of stitching intrusion, is localized east of sutural deep fault separating the Lubliniec-Zawiercie-Wieluń terrane from the Mało-

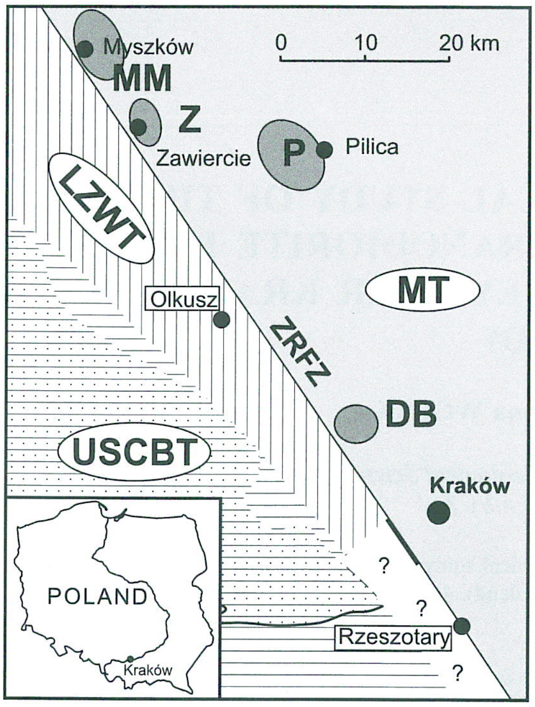


Fig. 1. Localization of granodiorite intrusion from Będkowska Valley (after Harańczyk 1988, 1994 a); LZWT – Lubliniec-Zawiercie-Wieluń Terrane; USCBT – Upper Silesian Coal Basin Terrane; MT – Małopolska Terrane; ZRFZ – Zawiercie-Rzeszotary Fault Zone; DB – granodiorite from Będkowska Valley; MM – granodiorite from Myszków-Mrzygłód; Z – monzogranite from Zawiercie; P – granodiorite from Pilica

polska Block (Harańczyk *et al.*, 1995; Unrug *et al.*, 1999). In some authors opinion e.g. (Bogacz, 1980; Pożaryski *et al.*, 1992; Buła, 1994, 1995; Buła & Kotas, 1994; Buła *et al.*, 1996; 1997, Dadlez *et al.*, 1994; Jachowicz & Moryc, 1995; Żaba, 1995) the Kraków-Lubliniec fault zone, which most probably represents a fragment of the transcontinental tectonic Hamburg-Kraków line, is a direct boundary between the Upper Silesia and Małopolska Blocks. This granodiorite is one of four intrusions (similarly as those of Myszków-Mrzygłód, Pilica and Zawiercie) situated within marginal zone of the Małopolska Block. Numerous common features suggest that they all represent apical parts of a larger batholith located in deeper (abyssal) zone (Żaba, 1999).

The age of this intrusion was discussed by numerous authors. Harańczyk considered granitoid plutonism to be post-Silurian but pre-Devonian (Harańczyk, 1985; Harańczyk *et al.*, 1980). Similarly, in Piekarski's (1985) opinion Devonian ore-bearing magmatism is related with Caledonian cycle. Several authors relate the emplacement of granitoids with Variscan magmatism of Upper Carboniferous age (Bukowy & Cebulak, 1964; Bukowy, 1984, 1994; Karwowski, 1988; Kośnik & Muszyński, 1990; Żaba, 1994, 1995, 1996).

Two boreholes DB-5 and WB-102A, localized in the Będkowska Valley area, have penetrated a complex of Cambrian black folded and faulted rocks and gained granodiorite intrusion (Fig. 2A & B).

The oldest part of the above tectonic block consists of Lower Cambrian Będkowska Valley conglomerate formation and of Middle Cambrian pyrite-bearing black metamudstone formation. They are dated on the base of acritarches and macrospores (Harańczyk, 1994a, b) and considered to represent flysch deposits related with rifting (Unrug *et al.*, 1976). It is composed of six beds of variegated polymictic metaconglomerates, several meters thick, interlayered with black, coarse- and fine-grained metasandstones, metamudstones and black fine-grained metamudstones several hundred meters thick, interlayered with black metapelites and medium- and fine-grained black metasandstones. These clastic rocks are characterized by well preserved sedimentary structures: bedding and lamination (Harańczyk, 1984). Besides, metatuffitic intercalations, showing lower hardness and grey-greenish coloration and differing from clastic Cambrian rocks, occur within this formation. The thickness of Cambrian formation amounts to about 700 m.

At first, the occurrence of biotite-quartz-albite hornfels from the borehole WB-102A was mentioned by Kośnik & Muszyński (1990). In individual samples of rocks from the DB-5 borehole Koszowska & Wolska (1994a, b) have found cordierite and andalusite (at the depth 888.0 m and 570.2 m) – characteristic contact metamorphic minerals. Local occurrence of these minerals in rocks from this borehole was reported by Czerny *et al.* (1997) – at the depth 443.3 m and 1024.7 m..

The aim of this paper is to define the range of contact alterations in the rocks surrounding the granodiorite body in the Będkowska Valley. Consequently, samples of dark rocks were selected from the zones altereted by thermal metamorphism, but showing no alterations caused by later hydrothermal activity. Such secondary, hydrothermal processes are observed around numerous veins cutting the Cambrian rock complex (Harańczyk *et al.*, 1995; Muszyński 1991; Czerny *et al.*,1997) and are manifested by discoloration of the rocks.

Samples of rocks were collected from the boreholes DB-5 and WB-102A.

The sections of the boreholes DB-5 and WB-102A are elaborated on the ground of earlier, Harańczyk's (1984), Harańczyk *et al.*, (1995) papers and the present authors detailed examination.

Section of the borehole DB-5 (Fig. 2A)

Cambrian rocks were drilled in the borehole DB-5 at the depth interval from 103.0 to 1142.7 m. They are Middle Cambrian (Harańczyk, 1984) clastic deposits represented by black coarse- and fine-grained metasandstones, metamudstones and metapelites cut by numerous porphyric dykes (at the depth intervals 232.1–283.1 m, 732.0–737.7 m and at 899.0 m), and metatuffitic intercalations (at the depth 486.8 m and 903.7 m to 904.2 m). At the depth interval 904.2–1142.7 m there occur coarse-grained Lower Cambrian metaconglomerates (Harańczyk, 1984), interlayered at the depth 1015.4–1035.0 m by metapelite intercalation and porphyric dyke (1094.0–1133.5 m). The top of granodiorite intrusion was penetrated at the depth 1142.7 m and till 1414.6 m it was not cut through. This intrusion is cut by numerous porphyry dykes (at the depths: 1229.4–1242.0 m, 1249.0–1256.0 m, 1257.8–1279.0 m, 1283.0–1298.0 m, 1299.0–1305.0 m, 1408.0–1414.6 m).

Section of the borehole WB-102A (Fig.2B)

In this borehole the rocks of the Cambrian complex were penetrated at the depth interval 171.0–1076.0 m under Jurassic limestones, variolitic porphyry sheet and Carboniferous Jerzmanowice conglomerate (Harańczyk, 1984). This complex consists of various clastic rocks as: metaconglomerates, coarse- and fine-grained metasandstones and metapelites, assigned by Harańczyk (1984) to Lower Cambrian and Middle Cambrian sequence. They are black, very hard, massive, sounding when hammering. These rocks are cut by numerous porphyry dykes (at the depths: 402.0–404.0 m, 406.0–412.0 m, 602.0–632.0 m, 814.0–823.0 m). The top of granodiorite body was penetrated at 1092.0 m and the intrusion was not pierced till 1455.0 m. Between detritic Cambrian rocks and granodiorite there occurs a zone of brecciated rocks ca. 20 m thick.

ANALYTICAL MATERIALS AND METHODS

Samples of metamorphosed detritic rocks have been collected from drill cores preserved in the store of borehole (DB-5, WB-102A) materials of the Warsaw State Geological Institute in Kielniki near Częstochowa.

The depths of sampling sites of Cambrian rocks, preliminarily selected and studied in detail, are marked in both sections (Fig.2 A, B). The whole Cambrian rocks are cut by numerous quartz and ore-bearing feldspar veinlets. In the zones adjacent to the latters we observe discoloration of rocks and retrogressive, hydrothermal, alteration phenomena. Therefore, the samples studied in detail were collected from hydrothermally unaltered zones, showing fine-grained structure and containing no detrital material. Only in such rocks the thermal alteration processes have lead to the formation of characteristic contact-metamorphic, neogenic minerals like cordierite and andalusite.

A microscopic study of these rocks was performed with a AMPLIVAL petrographic optical microscope.

X-ray diffraction patterns of the studied rocks were recorded by means of TUR M-62 diffractometer with a HZG-4 horizontal goniometer, using filtered CuKα radiation. The instrument settings were U=30 kV, I=30 mA, scanning speed was 1°/min., chart speed 10 mm/min.

Six samples of rocks of the studied complex were analysed using wet chemical method according to the procedure described by Narębski (1962). Other five samples were analysed in the Activation Laboratories Ltd. in Canada by means of the following methods: ICP (major elements), INAA (trace elements including REE) and XRF (Nb).

The chemical composition of minerals was analysed with an ARL SEMQ electron microprobe operated at the acceleration potential 20kV and sample current 120-150 µA. The following spectral lines and standards were used: NaKα($NaAlSi_3O_8$), MgKα(MgO), FeKα(FeS_2), AlKα-($KAlSi_3O_8$), SiKα($KAlSi_3O_8$), KKα($KAlSi_3O_8$), CaKα-($CaCO_3$), MnKα(Mn), TiKα(Ti). Correction ZAF for absorption, fluorescence and atomic number were calculated.

Moreover, JEOL 5410 electron microscope equipped with an energy dispersive spectrometer Voyager 3100 (NORAN) was used. Thin section of samples coated were evaluated according to the "standardless" procedure of calculation in voyager software (i.e using standards from the software library supplied by the manufacturer).

Infrared absorption spectra were obtained with Zeiss UR-20 prismatic spectrometer, using KBr discs.

PETROGRAPHIC CHARACTERISTICS OF ROCKS

METACONGLOMERATES

Samples of metaconglomerates within Cambrian sequence rocks were collected from the borehole DB-5 from the depths: 906.6 m, 908.0 m, 920.0 m, and 936.8 m. They are very hard, massive and recrystallized rocks. Macroscopically we observe large, poorly rounded rock fragments, 0.5 to 4 cm in size, representing various rock types (granites, porphyries, sandstones, mudstones, siliceous rocks, dolerites, crystalline schists) and grains of detrital quartz, alkali feldspars and rare plagioclases. Black neogenic matrix is of porous-contact type.

Fragments of the following rock types occur in this conglomerate:

1) porphyries, containing zonal plagioclase phenocrysts embedded in fine-grained quartz-feldspar matrix

2) trachytes, showing fluidal structure with large alkali feldspar phenocrysts, surrounded by lathlike feldspar grains forming the matrix,

3) dolerites and diabases, showing ophitic texture,

4) granites, displaying coarse-crystalline structure, typical of plutonic rocks. They consist predominantly of quartz, often granulated and rarely showing myrmekitic intergrowths, and alkali feldspar grains. Less abundant are plagioclases and chloritized brown biotites,

5) metasandstones, in which fragments of detrital minerals (quartz, alkali feldspars, less abundant plagioclases) show symptoms of corrosion and are 0.3–0.6 mm in size. Cementing substance of contact type consists of fine brown biotite flakes (below 0.04 mm in size) showing distinct pleochroism,

6) siliceous rocks, consisting of very small quartz crystals formed by recrystallization of chalcedony,

7) metamudstones, composed of fine grains of detrital minerals: quartz, alkali feldspars and rare plagioclases. They are cemented by brown biotite flakes, 0.04–0.08 mm in size.

Moreover, fragments of detrital minerals, up to 0.3 mm in size, also occur in the study rocks. They are represented by quartz showing normal and wavy extinction as well as granulated one, alkali feldspar and rare plagioclases. These grains show small embayments.

The matrix of metaconglomerates is of porous-contact

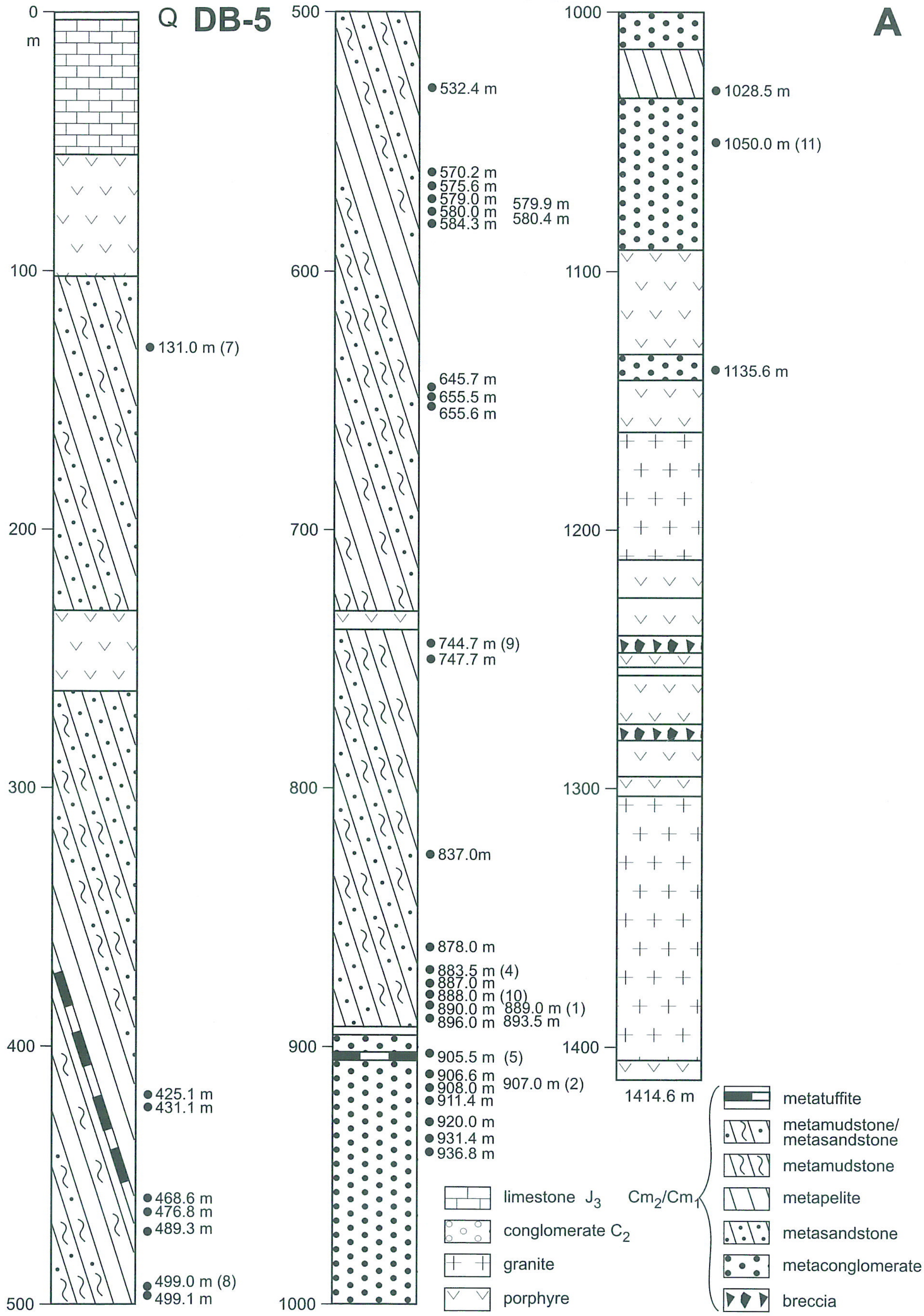
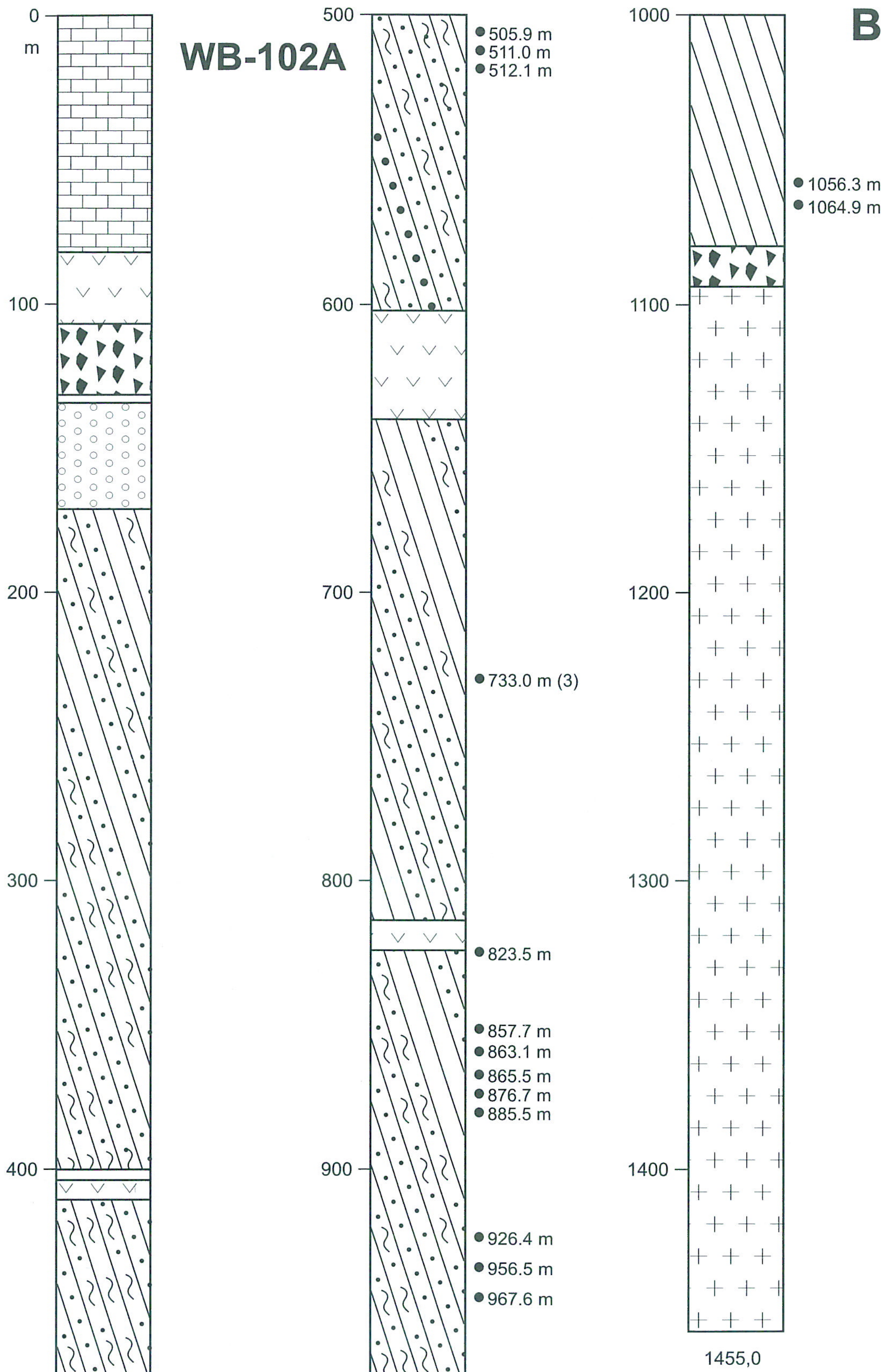


Fig. 2. Sections of the boreholes DB-5 (A) and WB-102A (B) after Harańczyk (1984)


WB-102A
B
0
m
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1455,0
505.9 m
511.0 m
512.1 m
733.0 m (3)
823.5 m
857.7 m
863.1 m
865.5 m
876.7 m
885.5 m
926.4 m
956.5 m
967.6 m
1056.3 m
1064.9 m

type. It consists of brown biotite flakes (0.08–0.21 mm) showing light green to olive-brown pleochroic colours. Fragments of rocks and minerals are contacting with each other. There also occur nests of aggregates of mutually intergrown brown biotite flakes.

Metaconglomerate rocks are often cataclized and cicatrized by quartz veins containing ore minerals (mainly pyrite). Besides, there occur mylonitized zones in which detrital material was crushed and alteration process resulted in retrogressive chloritization of biotite.

METASANDSTONES

Samples of sandstone intercalations occurring within Cambrian sedimentary sequence were collected in the borehole DB-5 from the depths 575.6 m, 579.0 m, 580.0 m, 896.0 m, 931.4 m, 1050.0 m, 1135.6 m. They represent sandstones consisting of detrital grains varying from 0.2 to 2 mm in size. Macroscopically they are black rocks with lighter coloured detrital minerals and rock fragments. They are strongly recrystallized, massive and hard.

Microscopic observation have shown that detrital fragments of minerals are represented by poorly rounded sharp-edged grains of detrital quartz, 0.85–1.8 mm in size. The most abundant quartz pebbles show, in general, normal extinction but there also occur those exhibiting wavy one, as well as granulated grains. Alkali feldspar grains, 0.5–1.8 mm in size, rarely display perthitic structure and twinning. They are often sericitized. Poorly rounded plagioclase grains, 0.2–0.6 mm in size, show characteristic polysynthetic twinning. Detrital mineral grains show symptoms of corrosion processes. The discussed sandstones locally contain fragments of various rock types (porphyries, dolerites, mudstones and siliceous rocks), 0.2–1 mm in size.

The primary matrix was of contact type and it was not abundant. Now it is corrosional in type and consists of fine-flaky brown biotite showing distinct pleochroism from light green to olive-brown tint. Its flakes are 0.01–0.04 mm in size. They are chaotically distributed, often mutually intergrown and even forming aggregate nests. Moreover, anhedral ore minerals (mainly pyrite), 0.03–0.6 mm in size, are disseminated in study rocks.

METAMUDSTONES

Samples of these rocks were collected from Cambrian rock complex in the borehole DB-5 from the following depths: 425.1 m, 499.0 m, 532.4 m, 575.6 m, 579.0 m, 584.3 m, 645.7 m, 655.6 m, 744.7 m, 837.0 m, 878.0 m, 911.4 m, 1028.5 m Sandstone samples studied from the borehole WB-102A were collected from the depths: 857.7 m, 876.7 m, 885.5 m, too. Macroscopically these are black, hard and massive rocks.

Microscopic studies have shown that these rocks have preserved their primary sedimentary bedding, expressed by distribution of interlayering detrital and pelitic material. Fragments of detrital materials are sharp-edged, poorly rounded and show symptoms of corrosion. Quartz grains display normal and wavy extinction, whereby some of them are granulated. Their grain size in samples from borehole WB-102A varies from 0.01 to 0.18 mm, while in those from borehole DB-5 from 0.07 to 0.35 mm. Grains of detrital plagioclases are sharp-edged, show polysynthetic twinning, and are 0.06–0.15 mm in size. They are often sericitized. Alkali feldspar grains, occurring mainly in metamudstones from the borehole WB-102A, are slightly larger (0.07–0.21 mm in size). They rarely exhibit perthitic structure and double twinning. Moreover, sharp-edged fragments of siliceous rocks 0.07–0.15 mm were found in the rocks studied.

Primary argilliceous fraction of mudstones is completely transformed and consists of fine-flaky biotite aggregates showing distinct pleochroism (light green to olive-brown). Biotite flakes are chaotically distributed and are not oriented concordantly to bedding. Biotite flakes are 0.02–0.03 mm in size. Locally, there occur larger nests up to 0.2 mm in size, consisting of intergrown biotite flakes.

Metasandstones and metamudstones are cut by pyrite-bearing quartz-chlorite, quartz-feldspar and quartz-sericite-chlorite veinlets. Besides, chaotically distributed anhedral pyrite grains 0.01–0.08 mm in size occur in these rocks. Transformation of brown biotite into light green chlorite showing weak pleochroism and subnormal indigo-brown interference colours is observed at the margin of veinlets.

FINE-GRAINED CORDIERITE HORNFELSES

Cordierite hornfelses were found in several zones in the section of the borehole WB-102A. Samples of these rocks were collected from the depths: 823.5 m, 865.3 m, 876.7 m, 885.5 m, 1056.3 m, 1064.9 m. They occur as intercalations in metamudstones, several to several tens centimetres thick, and in metasandstones (Fig. 3). In the borehole DB-5 cordierite hornfelses were found to occur at the following depths: 468.6 m, 476.8 m, 489.3 m, 499.1 m, 579.9 m, 580.0 m, 580.4 m, 655.5 m, 837.0 m, 878.0 m, 885.0 m, 887.0 m, 888.0 m, 889.0 m, 890.0 m, 1028.5 m.

Cordierite hornfelses are black, hard and massive showing cryptocrystalline structure. These rocks do not differ from metasandstones and metamudstones. Macroscopically it is impossible to distinguish individual minerals and to observe spotted texture. Only in the samples from the borehole

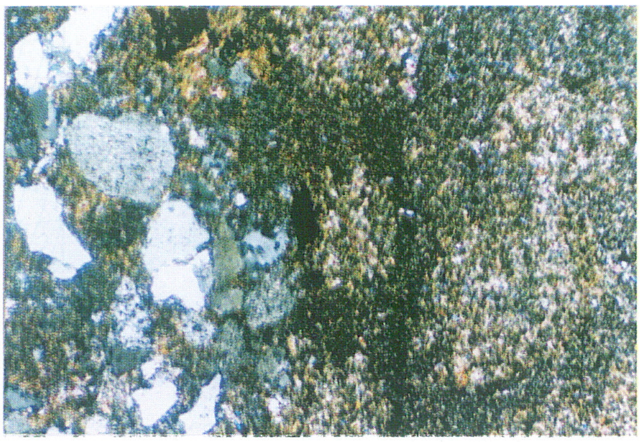


Fig. 3. Sharp boundary between metasandstones and fine-grained cordierite hornfels. Borehole DB-5, depth 905.3 m; Crossed polars

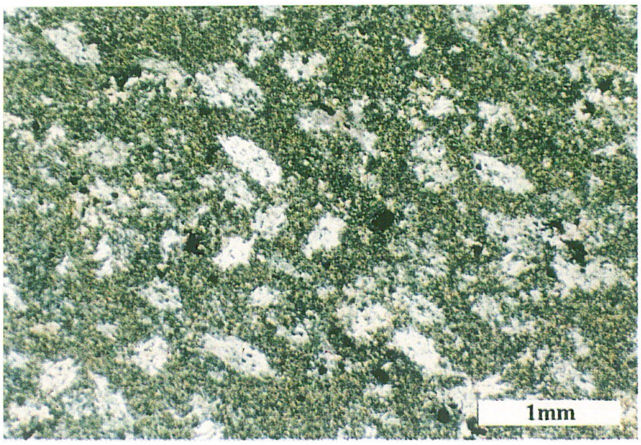


Fig. 4. Cordierite spots in fine-grained cordierite hornfels. Borehole DB-5, depth 888.0 m; Crossed polars

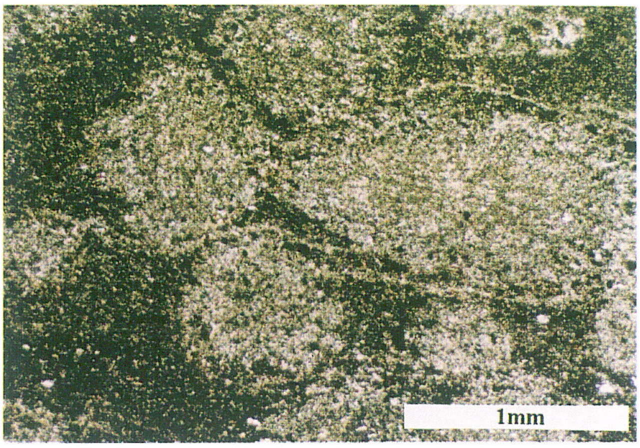


Fig. 5. Oval and ellipsoidal cordierite spots in fine-grained cordierite hornfels. Borehole DB-5, depth 905.9 m; Plane-polarized light

DB-5 collected at depths 878.0 m, 885.0 m, 888.0 m, 889.0 m, 905.3 m, 905.9 m, and from the borehole WB-102A at depths 926.4 m, 956.5 m, 967.5 m, 1056.3 m, in which the size of cordierite blasts is in the range 0.6-0.9 mm, the rocks displays macroscopically spotted texture.

Under the microscope the rocks under consideration show spotted texture (Fig. 4). Light-coloured spots of different shape (circular, oval, rectangular, square) consist of cordierite (Fig. 5), showing low relief and low birefringence. Locally, cordierite forms intergrowths with alkali feldspars. They are covered by numerous submicroscopic inclusions of opaque minerals and brown biotite flakes (less than 0.1 mm in size). Consequently, the rocks show sieve texture, characteristic of hornfelses. The size of these spots depends on the depth of sampling. The spots from samples collected in the borehole DB-5 from the depths 460–590 m are 0.29–0.35 mm in size whilst those in samples situated closer to the intrusion 870–89 m are larger (0.35–0.50 mm in size). In the samples from borehole WB-102A these spots are generally considerably smaller (0.15–0.28 mm) though in zones closer to intrusion their sizes increase up to 0.90 mm. The matrix between spots consists of chaotically distributed thin brown biotite flakes (0.01–0.04 mm in size), showing distinct pleochroism from light green to olive-brown and very fine blasts of plagioclases.

Identification of cordierite on the ground of optical data only is often unreliable. However, by means of X-ray pattern, on the base of characteristic reflection corresponding to interplanar spacing 8.5 Å (Fig. 6) it was possible to identify this mineral.

In these parts of the rock where biotite, sericite or quartz-chlorite veinlets occur, we observe in marginal zone the transformation of cordierite blasts into an aggregate of mutually interpenetrating minerals: light mica and light green chlorite. The nests composed of light mica (0.15 mm in size) occur close to biotite veinlets in the samples from the depth 905.3 and 905.9 m. Their cores contain anhedral corundum blasts, 0.07 mm in size, showing distinct spotty pleochroism from light green to blue. Moreover there occur chaotically distributed ore minerals (mainly pyrite) 0.01–0.15 mm in size.

CHLORITE SPOTTED ROCKS

The rocks of this type occur only in the borehole DB-5 at the depth 131.0 m, 214.7 m and 431.1 m. Macroscopically they do not differ from other rocks of this sequence. However, microscopic examination revealed them to show well preserved spotty texture (Fig. 7). The spots are oval in shape and 0.1–0.14 mm in dimension. They consist of fine flaky aggregate (individual flakes are less than 0.01 mm) of light green chlorite showing weak pleochroism and very low birefringence. The matrix is composed of fine flaky aggregate of neogenic light mica, olive-brown biotite and albite, whereby individual crystals are less than 0.01 mm in size. Anhedral blasts of opaque minerals of different size (0.01–0.28 mm) are chaotically distributed in the rock, as well as scarce poorly rounded detrital quartz grains 0.04 mm in size.

MACROSCOPICALLY SPOTTED ANDALUSITE HORNFELSES

In both the boreholes examined (DB-5 and WB-102A), within the Cambrian complex, spotted rocks, distinguishing by lower hardness, grey-greenish colour and macroscopically visible spotted texture were found. These rocks occur as inlayers, several to a dozen centimetres thick. Their samples were collected from both boreholes at the following depths: 505.9 m, 511.0 m, 512.1 m, 733.0 m, 863.1 m (borehole WB-102A) and 570.2 m, 883.5 m, 893.5 m, 905.5 m, 907.0 m (borehole DB-5). Oval spots are black, darker from embedding rock, 1–3 mm in size, and display distinct concentric structure with lighter coloured centres.

As follows from microscopic examination, these spots consist of fine flaky brown biotite (Fig. 8) showing distinct pleochroism from light orange to reddish-brown and forming aggregates of mutually intergrown flakes, 0.01–0.03 mm in size. At the margins of the spots the biotite flakes are larger – up to 0.04 mm. Consequently, these margins are tattered and irregular in shape.

The matrix of these hornfels rocks consists of an aggregate of intergrowing very fine light mica flakes (less than

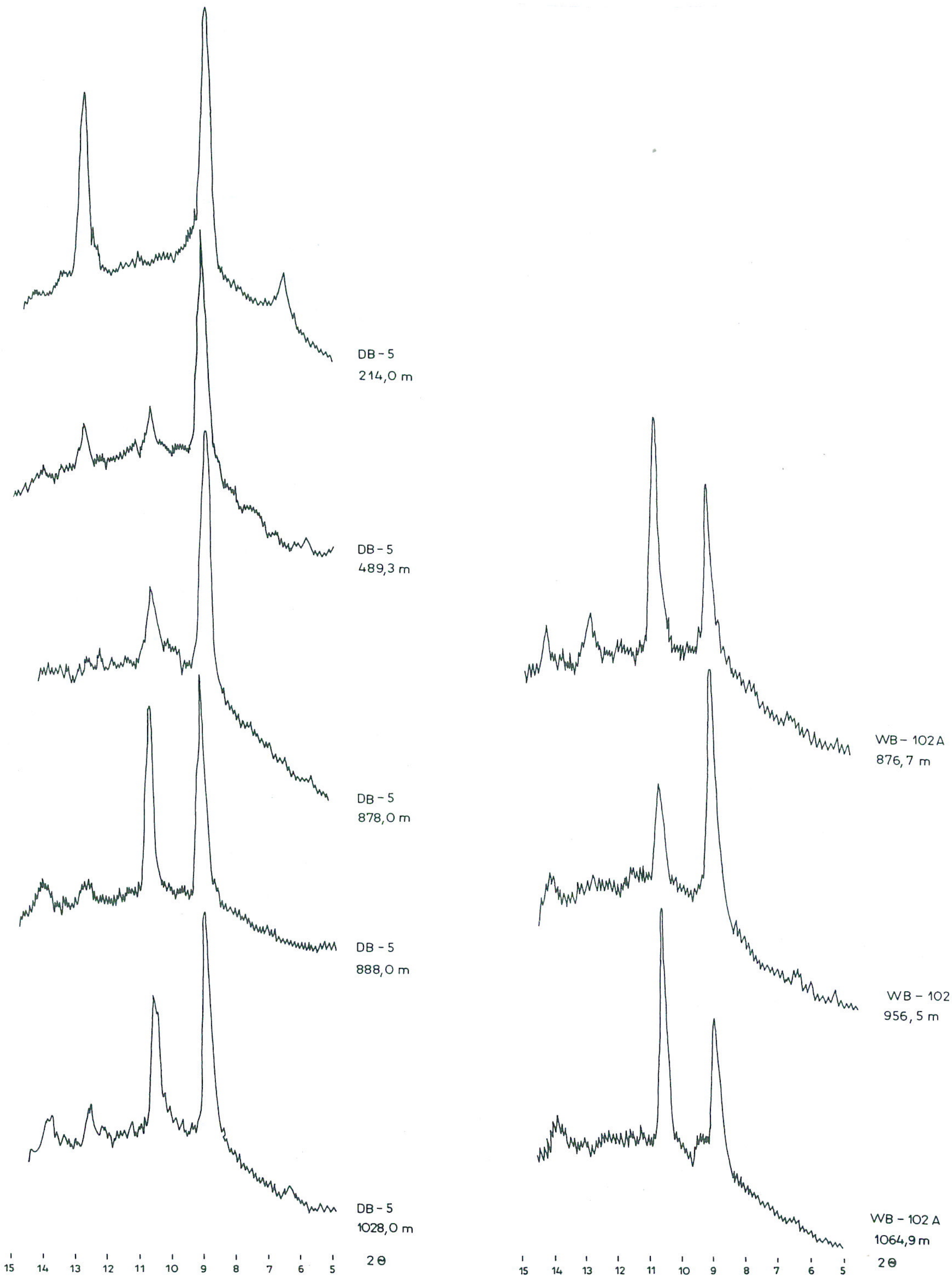


Fig. 6. Variability of cordierite, biotite and chlorite amounts on the base of the following X-ray reflections 7 Å, 14 Å for chlorite, 8,5 Å for cordierite, and 10 Å for biotite

0.01 mm in size). Most probably, this mica is the alteration product of andalusite. Relicts of andalusite crystals, up to 0.8 mm in size occur in the rock studied. Andalusite is colourless, showing no pleochroism and in the cross-sections parallel to prismatic faces a cleavage is observed (Fig. 9). The crystalloblasts of this mineral are often filled with numerous submicroscopic inclusions of opaque minerals.

In the borehole WB-102A fine corundum crystalloblasts, about 0.15 mm in size, were found to be embedded in sericitic matrix of these rocks. They occur in nests composed of light mica flakes, about 0.25 mm in size. On the other hand, corundum crystalloblasts in samples, collected from borehole DB-5, are larger – up to 0.5 mm in size and embedded in significantly larger nests, about 0.7 mm in

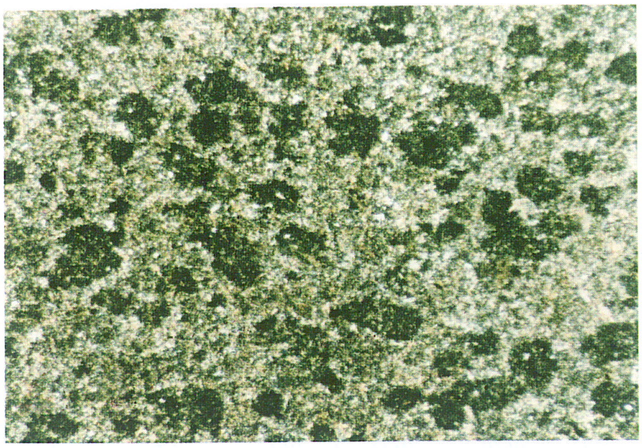


Fig. 7. Chlorite spots in chlorite-bearing spotted rocks. Borehole DB-5, depth 131.0 m; Crossed polars

Fig. 9. Subhedral andalusite in macroscopically spotted andalusite hornfels. Borehole DB-5, depth 570.2 m; Crossed polars

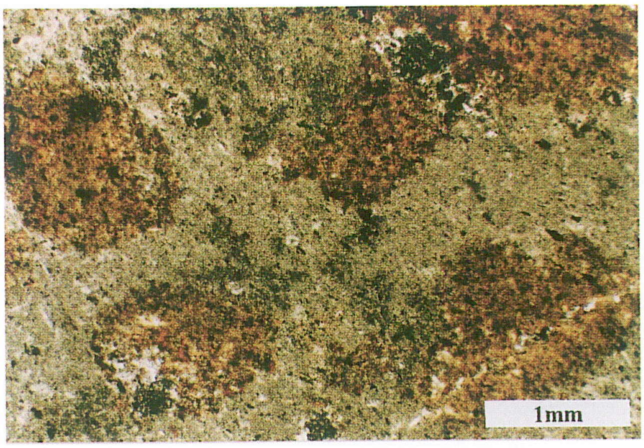


Fig. 8. Dark spots containing fine-flaky aggregates of brown biotite in macroscopically spotted andalusite hornfels. Borehole DB-5, depth 570.2 m; Plane-polarized light

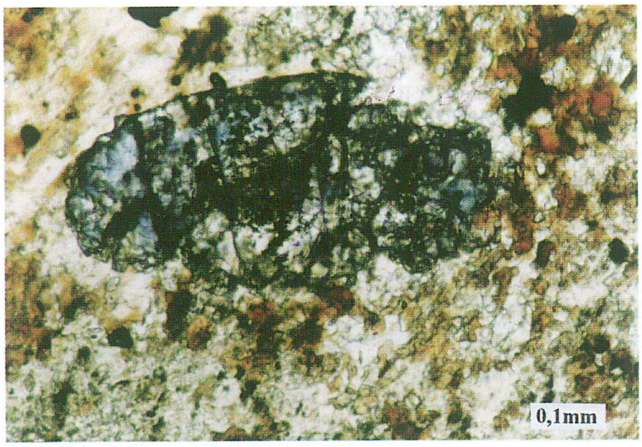


Fig. 10. Blue spotty corundum crystalloblasts displaying characteristic barrel-shaped habit in macroscopically spotted andalusite hornfels. Borehole DB-5, depth 570.2 m; Plane-polarized light

size. Corundum shows spotty pleochroism from light green to blue (Fig. 10).

Andalusite hornfelses can contain sulphide minerals (mainly pyrite) occurring as chaotically distributed grains, 0.2 mm in size. The rocks are cut by numerous pyrite-bearing quartz-biotite and quartz-chlorite veinlets, as well as ore-bearing carbonate ones.

NEOGENIC MINERALS

CORDIERITE

Cordierite is the most important mineral related with thermal metamorphism of the Cambrian rocks complex. Its occurrence in one of the samples from the borehole BD-5 was reported earlier (Koszowska & Wolska, 1994b; Czerny *et al.*, 1997). As follows from the present detailed studies cordierite occurs in this borehole in three zones at the depth intervals: 460–590 m, 830–910 m and about 1028 m. In the second borehole situated in the Będkowska Valley (WB-102A) cordierite-bearing rocks were found to occur at the depth interval 810–1070 m.

Usually this mineral appears in fine-crystalline rocks. However, when cordierite blasts are 0.6–0.9 mm in size we can observe even macroscopically, spotted structure of rocks. As follows from microscope examination, these spots of different shape are mainly 0.3–0.6 mm in size and consist predominantly of cordierite locally intergrown with feldspars (mainly K-feldspars).

Cordierite grains are grey and not pleochroic and contain fine, black poikilitic inclusions. Some larger inclusions represent opaque minerals (pyrite, iron oxides). Besides, there occur small olivaceous-brown biotite flakes within these blasts. Some crystalloblasts of cordierite in the section perpendicular to 001 exhibit sectoral twinning, trilling and sixling (Fig. 11).

As follows from microprobe data, the cordierites studied are rich in iron replacing magnesium in their crystal lattice. The atomic Mg/Fe ratio varies from 2.0 to 2.2 in them. Consequently about 1/3 of Mg positions are replaced by Fe. The iron content in cordierite reflects that in the rocks. In the sample from the depth 888 m in the borehole DB-5 the weight ratio MgO/FeO amounts to 1.1 whilst in its cordier-

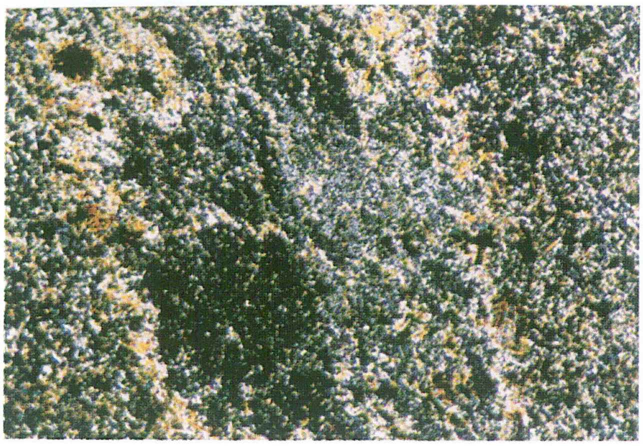


Fig. 11. Sector twinning in cordierite with rim consisting of light micas in fine-grained cordierite hornfels. Borehole DB-5, depth 905.3 m; Crossed polars

ites – varies in the range 1.1–1.3. TiO_2 and MnO contents in cordierite grains are small, and do not exceed 0.13 and 0.40 wt.% respectively (Table 1 & 2).

ANDALUSITE

Andalusite is much less common when compared with cordierite. Its occurrence was evidenced only in macroscopically spotted andalusite hornfelses, distinctly enriched in alumina (Al_2O_3 content higher then 25 wt. %). Andalusite is only locally preserved, being usually to higher or lesser degree transformed into muscovite. Subhedral or, less common euhedral andalusite crystalloblasts are 0.3–0.8 mm in dimension (Fig. 9). In some crystalloblasts we observe, in section parallel to 001, the cleavage planes cutting at 90°. In individual andalusite crystalloblasts accumulations of dark carbonaceous (graphitic) inclusions occur typical of its variety called chiastolite.

In thin section andalusite is colourless, nonpleochroic and only in thicker section we observe spotty pleochroism ranging from colourless to pale pinkish. Andalusite crystals are optically positive, biaxial, showing high optic axis angle.

The nature of this mineral was confirmed by X-ray analysis (Koszowska & Wolska, 1994a). Moreover, microprobe data have confirmed the occurrence of andalusite in the rock studied showing the following formula: $(Al_{1.97}Fe_{0.03})_{2.0}$ $[O/SiO_4]$.

BIOTITE

In spotted andalusite hornfelses, containing macroscopically visible spots, biotite occurs in them (Fig. 7) as mutually intergrown flakes 0.01–0.03 mm in size. Slightly larger biotite flakes, up to 0.04 mm in size, occur only at spot margins. This mineral shows distinct pleochroism from light orange to reddish-brown. Instead, in fine-grained cordierite hornfelses, fine differently oriented biotite flakes (0.01–0.03 mm in size) occur in the matrix with feldspars, which is surrounding light spots consisting of cordierite.

Table 1

Electron microprobe analyses of studied cordierites

Com-ponents	Cordierite DB-5 888.0 m		Cordierite DB-5 888.0 m		Cordierite DB-5 888.0 m		Cordierite WB-102A 1056.3 m		Cordierite WB-102A 1056.3 m	
	in weight %									
SiO_2	49.4		50.4		48.0		51.3		47.3	
Al_2O_3	28.85		29.20		30.80		28.50		33.18	
TiO_2	0.12		0.15		0.14		<0.0X		<0.0X	
$FeO_{tot.}$	8.06		8.50		9.02		6.65		9.38	
MnO	0.36		0.36		0.36		<0.0X		0.0X	
MgO	10.26		10.12		10.27		9.90		9.87	
CaO	0.16		0.06		0.06		<0.0X		<0.0X	
K_2O	0.17		0.40		0.21		<0.0X		<0.0X	
Total	97.38		99.19		98.86		96.57		99.73	
Number of ions on the basis of 18 O										
Si	5.15		5.17	6.00	4.97	6.00	5.33		4.75	6.00
Al	0.85		0.83		1.03		0.67		1.25	
Al	2.70	2.71	2.70	2.77	2.72	2.73	2.82	2.82	2.67	2.67
Ti	0.01		0.07		0.01		-		-	
Fe	0.70		0.73		0.78		0.58		0.78	
Mg	1.59		1.55		1.58		1.53		1.48	
Ca	0.02	2.37	0.01	2.36	0.01	2.43	-	2.12	-	2.27
Mn	0.03		0.03		0.03		-		-	
K	0.02		0.05		0.03		0.01		0.01	

Table 2

EDS analyses of studied cordierite

Components	Cordierite WB-102A 956.5 m		Cordierite WB-102A 967.6 m	
	in weight %			
SiO_2	49.42		51.70	
Al_2O_3	34.09		32.46	
$FeO_{Tot.}$	7.07		7.21	
MnO	0.67		0.63	
MgO	8.75		8.00	
Total	100.00		100.00	
Number of ions on the basis of 18 O				
Si	4.98	6.00	5.19	6.00
Al	1.02		0.81	
Al	3.03	3.03	3.03	3.03
Fe	0.60		0.60	
Mg	1.31	1.97	1.20	1.86
Mn	0.06		0.06	

Table 3

Electron microprobe analyses of studied micas

Components	Biotite olive-brown DB-5 888.0 m		Biotite reddish-brown DB-5 907.0 m		Muscovite DB-5 893.5 m	
	in weight %					
SiO_2	38.40		34.85		48.49	
Al_2O_3	18.28		19.18		32.62	
TiO_2	2.75		2.96		<0.0X	
$FeO_{Tot.}$	19.33		19.84		3.77	
MnO	0.24		0.10		<0.0X	
MgO	7.58		9.19		2.47	
CaO	0.52		<0.0X		<0.0X	
Na_2O	0.48		<0.0X		<0.0X	
K_2O	9.53		9.27		9.50	
Cr_2O_3	<0.0X		<0.0X		0.09	
Total	97.11		95.46		96.94	
	Numbers of ion on the basis of 24 O					
Si	5.85	8.00	5.27	8.00	6.49	8.00
Al	2.15		2.73		1.51	
Al	1.12	5.65	0.59	5.34	3.63	4.55
Cr	-		-			
Ti	0.31		0.33		0.01	
Fe	2.46		2.43		0.42	
Mn	0.03		0.01		-	
Mg	1.72		1.99		0.49	
Ca	0.09	2.08	0.01	1.73	-	1.62
Na	0.14		-		-	
K	1.85		1.72		1.62	

Larger biotite flakes occur but in the contacts with quartz and feldspars veinlets. Blasthesis related with potassium metasomatism resulted in the formation of these flakes, about 0.06 mm in size. In this rock type biotite is dark and shows distinct pleochroism from light green to olive-brown.

The FeO_{tot}/MgO weight percent ratio in two types biotites varies from 2.5 (fine-grained cordierite hornfels-sample from the depth 888.0 m in the borehole DB-5) to 2.2 (sample of macroscopically spotted andalusite hornfels from the depth 907.0 m in this borehole) and indicates distinct prevalence of Fe over Mg. The amount of MgO in biotite from macroscopically spotted andalusite hornfels is higher then in that from fine-grained cordierite hornfels. This FeO_{tot}/MgO weight percent ratio reflects mutual ratio of these elements in the rock, which amounts to 2.6 and 2.3 respectively and indicates the growth of biotite flakes in the course of thermal metamorphism under isochemical conditions. This conclusion is confirmed by TiO_2/FeO_{tot} ratio in biotites which in various samples is very similar and varies from 0.14 to 0.15. It corresponds to the ratio of these elements in rocks, which amounts to the range 0.13–0.18. Considerable content of Ti in biotite (ca. 3 wt.% TiO_2) is, together with high Fe^{+3} content, the cause of characteristic reddish-brown coloration of this mineral (Table 3), occurs in macroscopically spotted andalusite hornfelses.

MUSCOVITE

Fine flakes of white mica are intergrown with fine-flaky chlorite, and occur as pseudomorphs after cordierite. They were formed in the neighbourhood of biotite, sericite and quartz-chlorite veinlets, cutting fine-grained cordierite hornfelses. Fine flakes of light mica (less than 0.01 mm in size), intergrown with biotite, occur in the matrix of chlorite-bearing spotted rocks. In some samples of cordierite hornfelses showing spotted texture it forms nested aggregates, in which light micas flakes are 0.03–0.04 mm in size, coexisting with corundum and, sometimes, with diaspore (?). On the other hand, light mica is a major component of rock in spotted andalusite hornfelses. The flakes of colourless muscovite are 0.01–0.02 mm in size. Based on EDS and microprobe analyses, this mineral is an aluminous mica (close to the muscovite composition) characterized by low contents of Fe, Mg and Ti, total content of which does not exceed 3 wt. %. (Table 3).

CORUNDUM

The occurrence of corundum is limited to the rocks containing macroscopically visible spots (andalusite hornfelses) and, sometimes, to cordierite hornfelses. However, rocks have to be cut by numerous feldspar veinlets. This mineral was described first by Koszowska & Wolska (1994 a) to occur in a sample from the depth 570.2 m in the borehole DB-5. Though it is not so widespread as other minerals, corundum was found in rocks from other depths of the borehole DB-5 (893.5 m, 907.0 m) and in the neighbouring one WB-102A at the depths 505.9 m, 511.0 m, 512.4 m, 863.1 m.

Corundum crystalloblasts are usually linearly distributed along feldspar veinlets. Its individual crystalloblasts or their aggregates are most often embedded in muscovite nests. Corundum blasts are 0.15–0.50 mm in dimension. In general, they are anhedral but locally short prismatic forms are observed showing hexagonal shape in sections perpendicular to Z axis. Crystals exhibiting characteristic barrel-shaped habit are rather rare (Fig. 10). This mineral often coexists with ilmenite and rutile, forming with the latter oriented intergrowths. It shows very high positive relief and spotty coloration. Corundum crystalloblasts exhibit distinct pleochroism ε-colourless, light green, light yellow, ω-blue-green, blue or blue-violet. It is uniaxial and optically negative. In the scanning microscope image characteristic curved edges typical of barrel-shaped forms are observed.

As follows from microprobe and EDS analysis, Ti and Fe admixtures, responsible for coloration of this mineral occurs in corundum crystalloblasts in variable amounts: 0.3–2.0 wt. % of titanium oxide and 0.5–1.9 wt. % of iron oxide.

Table 4

Electron microprobe analyses of studied feldspars

Components	Feldspar DB-5 888.0 m	Feldspar DB-5 888.0 m	Feldspar DB-5 888.0 m	Feldspar WB-102A 1056.3 m	Feldspar DB-5 888.0 m
	in weight %				
SiO_2	64.7	63.6	64.7	64.2	63.0
Al_2O_3	18.44	18.56	19.84	17.90	21.40
TiO_2	0.08	0.08	0.08	<0.0X	0.08
$FeO_{Tot.}$	0.32	0.31	0.47	0.05	2.58
MnO	<0.0X	0.09	0.08	<0.0X	0.08
MgO	0.18	0.15	0.21	<0.0X	4.08
CaO	0.25	0.36	2.19	<0.0X	7.96
Na_2O	0.24	1.60	6.76	<0.0X	7.96
K_2O	16.40	14.32	5.31	15.61	1.38
Total	100.64	99.07	99.82	98.28	100.71
Numbers of ion on the basis of 32 O					
Si	11.92	11.84	11.65	12.04	11.23
Al	4.00	4.07	4.21	3.95	4.49
Ti	0.01	0.01	0.01	-	0.01
Fe	0.04	0.04	0.06	0.01	0.36
Mn	-	0.02	0.01	-	0.01
Mg	0.05	0.04	0.06	0.15	0.05
Ca	0.05	0.07	0.42		0.78
Na	0.09	0.58	2.36	-	2.79
K	3.84	3.41	1.22	3.73	0.31
An	1	2	11	-	22
Ab	2	16	59	-	69
Or	97	82	30	100	9

Table 5

EDS microprobe analyses of studied feldspars

Components	Feldspar DB-5 907.0 m	Feldspar WB-102A 956.5 m	Feldspar DB-5 907.0 m	Feldspar DB-5 907.0 m	Feldspar WB-102A 967.6 m	Feldspar DB-5 907.0 m
	in weight %					
SiO_2	63.90	64.86	64.60	62.70	62.70	60.64
TiO_2	<0.0X	0.24	0.28	<0.0X	<0.0X	<0.0X
Al_2O_3	19.76	19.40	19.47	23.93	24.07	25.33
$Fe_2O_{3Tot.}$	<0.0X	0.30	0.14	0.29	<0.0X	<0.0X
CaO	<0.0X	<0.0X	0.21	3.13	4.30	5.60
Na_2O	1.14	1.33	0.93	9.57	8.93	8.33
K_2O	14.02	13.88	14.39	0.38	<0.0X	0.10
BaO	1.17	<0.0X	<0.0X	<0.0X	<0.0X	<0.0X
Total	100.00	100.00	100.00	100.00	100.00	100.00
Numbers of ion on the bais of 32 O						
Si	11.80	11.87	11.85	11.09	11.07	10.76
Al	4.30	4.18	4.21	4.99	5.01	5.30
Ti	-	0.03	0.04	-	-	-
Fe	-	0.04	0.02	0.04	-	-
Ca	-	-	0.04	0.59	0.81	1.07
Na	0.41	0.47	0.33	3.28	3.06	2.88
K	3.31	3.24	3.37	0.09	-	0.02
Ba	0.09	-	-	-	-	-
An	-	-	1	15	21	27
Ab	11	13	9	83	79	72
Or	87	87	90	4	-	1
Cn	2	-	-	-	-	-

NEOGENIC FELDSPARS

Apart from micas, feldspars are the commonest minerals occurring in fine-grained cordierite hornfelses. Because of very small sizes of grains (below 0.01 mm) their identification using optical microscope is difficult since in the matrix they are intergrown with micas. Therefore, the presence of feldspar was confirmed by X-ray and microprobe analyses (Table 4 & 5). Moreover, plagioclases were identified on the base of characteristic bands in infrared spectra: 1010 cm^{-1}, 1105 cm^{-1}, 1160 cm^{-1}

Two feldspar varieties occur in the rocks studied:

1. plagioclases are represented by crystalloblasts of variable composition (Table 4, 5) from oligoclase-andesine (Ab_{69-59}). Oligoclases (Ab_{83-72}) are the commonest. Plagioclase crystalloblasts are below 0.01 mm in size. X-ray studies have shown them to represent mainly structural modification of low-temperature albite.

2. alkali feldspar (Or_{100-82} – Table 4 & 5) occurs within spots as intergrowths with cordierite or as blasts associated with micas in the matrix.

Moreover, potassium feldspar is the component of numerous feldspar veinlets cutting the rocks studied. Analytical data indicate that it contains Ba admixture too (Table 5).

ACCESSORY MINERALS

The following accessory minerals were found in the rocks studied:

Zircon – is not very abundant. It occurs both as rounded (often metamictized) grains and as euhedral prismatic crystals showing elongation 2:1 and dimension less than 0.01 mm. The latter display very high relief, high birefringence and straight extinction. The total content of Zr in the rocks studied amounts to 190–230 ppm (Table 6).

Apatite – is rarely found as short prismatic crystals with hexagonal shape when cut perpendicularly to Z axis. Its presence was confirmed by microprobe analysis and chemical data evidencing that the rocks in question contain 0.09–0.39 wt. % P_2O_5 (Table 6 & 7).

Magnetite – is fairly common opaque mineral. It occurs as fine, anhedral grains dispersed in the matrix. The content of magnetite fraction increases in zones containing cordierite (Sapota & Koszowska, 1999).

Ilmenite – occurs in paragenetic association with corundum as opaque grains. In ore microscope it is light grey and

Table 6

Chemical composition of metamorphosed rocks from the Będkowska Valley

Components	DB-5 889.0 m (1)	DB-5 907.0 m (2)	WB-102A 733.0 m (3)	DB-5 883.5 (4)	DB-5 905.5 m (5)
	in weight %				
SiO_2	56.99	48.38	46.94	48.25	49.33
TiO_2	0.88	1.15	1.33	1.22	1.28
Al_2O_3	19.91	24.89	24.85	27.38	24.83
Fe_2O_3	8.01	6.92	7.91	4.59	6.52
MnO	0.11	0.05	0.06	0.03	0.04
MgO	2.67	2.75	3.37	2.06	2.73
CaO	1.58	1.09	2.51	2.41	0.71
Na_2O	2.28	2.10	2.97	2.92	2.18
K_2O	5.41	7.45	6.34	6.17	6.65
P_2O_5	0.29	0.15	0.17	0.18	0.26
LOI	1.69	3.50	2.61	3.54	4.70
Total	99.82	98.44	99.06	98.74	99.23

Components	DB-5 889.0 m (1)	DB-5 907.0 m (2)	WB-102A 733.0 m (3)	DB-5 883.5 (4)	DB-5 905.5 m (5)
	Trace elements (ppm)				
Ag	1.0	1.9	1.7	1.3	4.8
As	<2	69	4	7	18
Au *(ppb)*	7	<5	8	<5	<5
Ba	849	1880	1399	1420	4853
Be	3	4	3	2	3
Bi	<5	<5	<5	<5	<5
Br	<1	<1	<1	<1	<1
Cd	0.5	3.5	<0.5	<0.5	<0.5
Co	22	18	26	5	14
Cr	58	102	88	91	85
Cs	20.3	23.8	23.1	19.5	15.3
Cu	15	51	811	36	52
Ga	22	38	37	39	40
Hg	<1	<1	<1	<1	<1
Hf	5.7	6.2	6.5	6.1	4.7
Ir *(ppb)*	<5	<5	<5	<5	<5
Mo	<5	<5	6	<5	<5
Nb	11	18	20	17	15
Ni	38	50	47	29	32
Pb	10	271	20	16	370
Rb	216	300	337	268	299
S	295	595	13750	1215	1075
Sb	0.5	2.6	0.8	0.5	1.7
Sc	20.4	28.5	26.9	29.4	29.4
Se	<3	<3	<3	<3	<3
Sn	<5	6	6	9	12
Sr	184	132	181	212	341
Ta	<1	2	<1	2	<1
Th	8.1	12.0	10.7	10.7	9.9
U	2.0	2.6	3.4	1.7	3.4
V	134	195	161	204	189
W	<3	11	38	15	41
Y	33	36	35	31	41
Zn	87	812	88	68	33
Zr	192	218	227	219	218
	Rare earth elements (ppm)				
La	31.1	32.3	21.9	31.7	34.9
Ce	75	79	54	78	86
Nd	34	34	26	29	41
Sm	6.7	6.8	6.1	6.4	7.9
Eu	1.5	1.4	1.2	1.4	1.7
Tb	1.0	<0.5	1.2	1.2	1.3
Yb	3.5	4.1	4.2	4.0	4.3
Lu	0.57	0.66	0.63	0.61	0.62

shows distinct anisotropy. The identification of this mineral was confirmed by microprobe examination. It shows the following formula: $(Fe_{1.99}Ti_{1.93}\ Mn_{0.10.})_{4.02}\ O_6$.

Rutile – occurs in association with corundum as euhedral short prismatic crystals with bipiramidal terminations or as "knee-shaped" twins. Rutile is brown-orange showing high relief and high birefringence, whereby interference colours are masked by intense coloration of this mineral. Its presence was confirmed by X-ray data (Koszowska &Wolska, 1994a).

Moreover, disseminated pyrite and pyrrhotine are common in the rocks studied.

GEOCHEMICAL INVESTIGATIONS

Various rock types, distinguished in the complex of the studied rocks, were geochemically analysed. These rocks are represented by the following samples:

I. fine-grained cordierite hornfelses [borehole DB-5, depths: 889.0 m (**1**) and 888.0 m (**10**)]

II. macroscopically spotted andalusite hornfelses [borehole WB-102A, depth 733.0 m (**3**); borehole DB-5, depths: 883.5 m (**4**), 905.5 m (**5**) and 907.0 m (**2**)]

III. spotted chlorite rocks [borehole DB-5, depth 131.0 m (**7**)]

IV. metamudstones [borehole DB-4, depth 66.5 m (**6**), borehole DB-5, depths: 499.0 m (**8**) and 744.7 m (**9**)]

V. coarse-grained metasandstone [borehole DB-5, depth 1050.0 m (**11**)]

Four samples of the macroscopically spotted andalusite hornfelses (samples 2, 3, 4, 5) and for comparison one sample of fine-grained cordierite hornfels (sample 1) were analysed for major and trace elements (Table 6). Other samples (6, 7, 8, 9, 10, 11) were analysed only for major elements (Table 7).

Table 7

Chemical composition of metamorphosed rocks from the Będkowska Valley

Components	DB-4 66.5 m (6)	DB-5 131. 0 m (7)	DB-5 499.0 m (8)	DB-5 744.7 m (9)	DB-5 888.0 n (10)	DB-5 1050.0 m (11)
	in weight %					
SiO_2	57.80	55.50	5.60	56.50	58.10	67.60
TiO_2	0.19	1.08	0.74	0.77	0.88	0.71
Al_2O_3	18.65	20.62	19.49	18.10	19.42	14.32
Fe_2O_3	5.60	6.90	7.51	4.09	4.81	2.09
FeO	1.81	1.79	1.85	3.65	2.60	2.83
MnO	0.05	0.10	0.06	0.10	0.05	0.03
MgO	2.80	3.50	3.11	3.10	2.71	1.99
CaO	2.02	0.65	1.20	4.11	2.09	2.40
Na_2O	1.51	0.52	2.25	3.91	3.26	4.69
K_2O	3.53	4.29	4.67	3.18	4.94	2.80
P_2O_5	0.14	0.10	0.13	0.39	0.18	0.09
LOI	5.07	4.43	2.82	1.49	0.86	0.91
Total	99.82	99.48	99.43	99.39	99.90	100.46

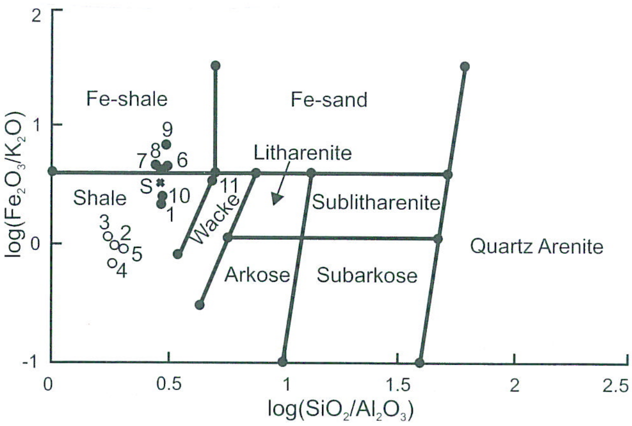


Fig. 12. Log Fe_2O_3/K_2O - log SiO_2/Al_2O_3 diagram after Pettijohn *et al.*, (1972), (modified after Herron 1988, vide Rollinson 1993). S – Skiddaw (spotted slates); sample numbers: fine-grained cordierite hornfelses: borehole DB-5, depth 889.0 m (**1**), borehole DB-5, depth 888.0 m (**10**); macroscopically spotted andalusite hornfelses: borehole WB-102A, depth 733.0 m (**3**), borehole DB-5, depth 883.5 m (**4**), borehole DB-5, depth 905.5 m (**5**), borehole DB-5, depth 907.0 m (**2**); chlorite spotted rocks: borehole DB-5, depth 131.0 m (**7**); metamudstones: borehole DB-4, depth 66.5 m (**6**), borehole DB-5, depth 499.0 m (**8**), borehole DB-5, depth 744.7 m (**9**); coarse-grained metasandstone: borehole DB-5, depth 1050.0 m (**11**)

The diversity of major elements ratios (SiO_2, Al_2O_3, Fe_2O_3, K_2O, Na_2O) in the samples studied is, first of all, related to variable content of detrital material in them. In Pettijohn's classification diagrams modified by Herron (fide Rollinson, 1993) (Fig. 12) all these rocks are plotted in the fields of shales (samples 1, 10), ferrouginous shales (samples 6, 7, 8, 9) and at the boundary of shales and wackes fields (sample 11). When compared with chemical composition of typical spotted slates from Skiddaw (S) – Mason (1990), the rocks studied represented by samples 1, 6, 7, 8, 9 and 10 are enriched both in alkalis (Na_2O and K_2O) and in CaO. The content of other elements is similar. Macroscopically spotted andalusite hornfelses (samples 2, 3, 4, 5) differ distinctly in chemical composition from both the other studied rock types and the spotted slates from Skiddaw (S). They display low SiO_2/Al_2O_3 ratio resulting from high Al_2O_3 content and simultanously lower SiO_2 content, comparing to other rocks studied. On the base of petrographical observations and discussed above geochemical data, it is supposed, that macroscopically spotted andalusite hornfelses originated from primarily tuffitic rocks. Low SiO_2, and higher Al_2O_3 content can be related with transformation of primary volcanic material into clay minerals, whereby the deficit in Si^{4+} was equalised by (Al^{3+}+K^+) (Batchelor & Weir, 1988).

This geochemically distinct character of macroscopically spotted andalusite hornfelses is also visible at the K_2O/Al_2O_3-SiO_2/Al_2O_3 diagram (Fig. 13), where samples of these rocks (trend A), originated probably from tuffitic rocks, are plotting within Dob's Linn metabentonite field (Batchelor & Weir, 1988). Originally detrital rocks (cordierite hornfelses and metamudstones – trend B) are plotting between the fields of Dob's Linn shales and metabentonites. Distinct enrichment in SiO_2 is marked in coarse-grained metasandstone (sample 11), which is plotting outside these both trends.

Geochemical data were used to obtain the character of

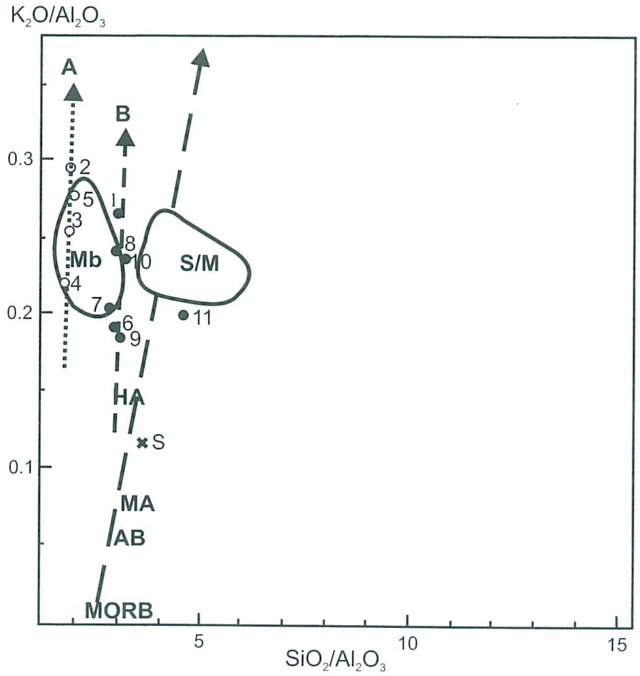


Fig. 13. K_2O/Al_2O_3 - SiO_2/Al_2O_3 diagram after Batchelor & Weir 1988); Mb – field of Ordovician metabentonites (Scotland); S/M – field of Ordovician mudstones and pelites (Scotland); S – Skiddaw (spotted slates); HA – High-K andesite; MA – Medium-K andesite; AB – Alkali basalt; MORB – Mid Ocean Ridge Basalt; sample numbers (**1-11**) as in Fig. 12

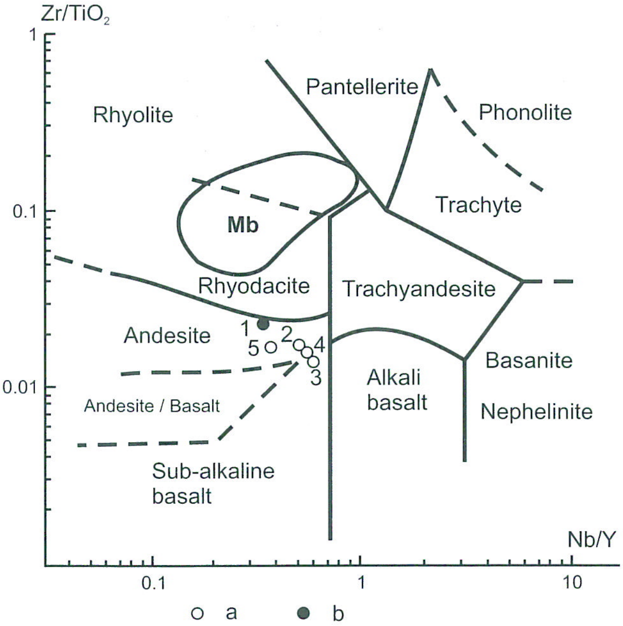


Fig. 14. Zr/TiO_2 - Nb/Y classification diagram after Winchester & Floyd (1977). Mb – Ordovician metabentonite field; **a** – macroscopically spotted andalusite hornfelses (primarily tuffites): borehole WB-102A, depth 733.0 m (**3**), borehole DB-5, depth 883.5 m (**4**), borehole DB-5, depth 905,5 m (**5**), borehole DB-5, depth 907.0 m (**2**); **b** – fine-grained cordierite hornfels (primarily pelites): borehole DB-5, depth 889.0 m (**1**)

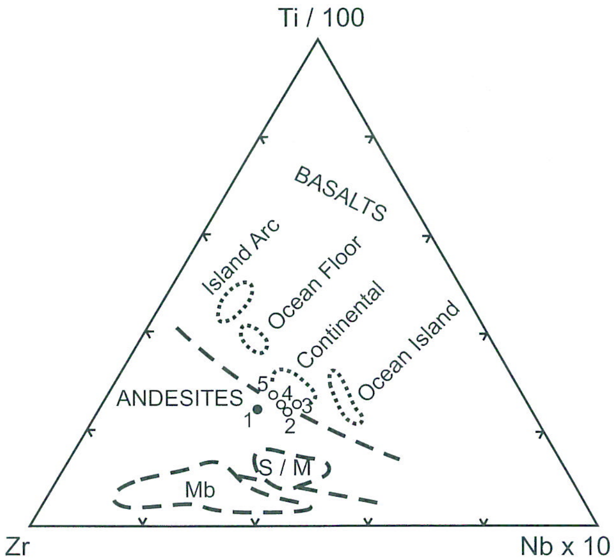


Fig. 15. Zr - Ti/100 - Nb∗10 diagram after Pearce & Cann (1973) vide Batchelor & Weir (1988); Mb – Ordovician metabentonite field (Scotland); S/M – field of Ordovician mudstones and pelites (Scotland); sample numbers (**1-5**) as in Fig. 14

magma as the source material for pyroclastic rocks. On the both, Zr/TiO_2-Nb/Y diagram (Winchester & Floyd 1977 – Fig. 14) and Zr- Nb-Ti triangular (Fig. 15), macroscopically spotted andalusite hornfelses plot within andesite and basalt fields. It may suggests that mafic magma could be the source material of tuffogenic rocks. Moreover, according to

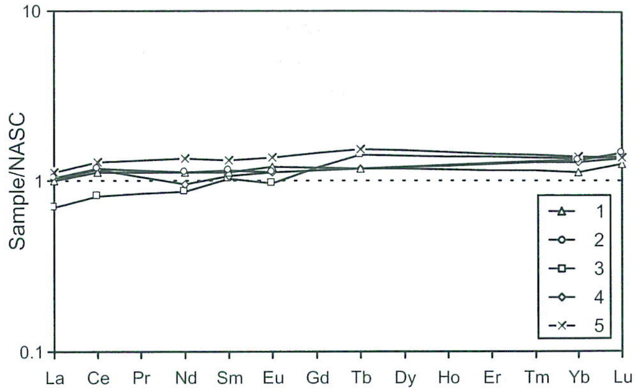


Fig. 16. NASC-normalized REE diagram for: fine-grained cordierite hornfels borehole DB-5, depth 889 m. (**1**); macroscopically spotted andalusite hornfelses: borehole WB-102A, depth 733 m. (**3**), borehole DB-5, depth 883.5 m. (**4**), borehole DB-5, depth 905.5 m. (**5**), borehole DB-5, depth 907 m. (**2**); NASC – North American Shale Composite

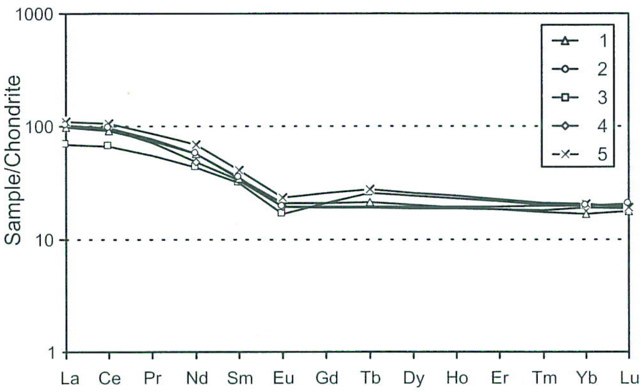


Fig. 17. Chondrite-normalised REE diagram for: fine-grained cordierite hornfels borehole DB-5, depth 889 m. (**1**); macroscopically spotted andalusite hornfelses (borehole WB-102A, depth 733 m. (**3**), borehole DB-5, depth 883.5 m. (**4**), borehole DB-5, depth 905.5 m. (**5**), borehole DB-5, depth 907 m. (**2**)

(Batchelor & Weir, 1988), low Ti/V (35–49) and high 10x[Ni/Th] (27–46) ratios in the studied rocks seem to indicate mafic character of parent magmatic material. The application of geochemical TAS classification diagram, based on silica and alkalis contents, gives no reliable results. The projection points of spotted andalusite hornfelses (samples 2, 3, 4, 5), showing very high alkali content, are plotting within phonotephrite field. It may be explained by metasomatic influx of alkalis. These processes are evidenced by numerous veinlets containing potassium feldspars, cutting the rocks studied.

The NASC-normalized REE diagrams (Fig. 16) indicates that spotted andalusite and cordierite hornfelses are characterized by relatively smooth curves and negligle enrichment in REE comparing with NASC. The minimal deviation from NASC line shows the sample of cordierite hornfelses (1). Instead, the sample (3) – [WB-102A, 733.0 m] shows little deficiencies in LREE. No visible europium or cerium anomalies are observed. Consequently, the contents of REE in the rocks and in standard North-American shales NASC are nearly identical (Gromet *et al.*, 1984).

Relative to chondritic meteorites, the studied rocks, have about 100 times higher LREE and about 20 times higher HREE content and small, negative Eu anomaly. The shape of the curves is more similar to sedimentary then magmatic rocks.

The shape of the patterns and the distribution of anomalies, in chondrite – normalized REE diagrams (Fig. 17), are more similar to those reported for pyritiferous shales, deposited in anoxic regime (Avalon Zone) then the shales from the Laurentian craton (Fyffe & Pickerill, 1993). In Harańczyk's (1994b) opinion the parent terrane of the Cambrian rocks studied comes just from this area. These preliminary geochemical do not deny this hypothesis. The index of anoxic condition is a V/V+Ni ratio (Hatch & Leventhal 1992). The high of V/V+Ni ratios (between 0.8 and 0.9) in the studied rocks reflect anoxic conditions of their sedimentation environment, suggested by Harańczyk (1984, 1994a, b).

On the other hand, the observed similarity of trace element concentrations in cordierite hornfelses (sample 1) and spotted andalusite hornfelses (samples 2, 3, 4, 5) suggest that the latter rocks could originate from mixed tuffogenic-detrital material and the contribution of detrital material could be considerable.

The content of such elements as Cu, Pb and Zn is another geochemical problem. Samples of rocks, which are cut by veinlets containing sulphide minerals, are enriched in these elements (Table 6). The sample (3) – [WB-102A, 733.0 m] contains 811 ppm Cu, whilst the average content of this element in other rocks studied is from 15 to 52 ppm. This is related to the occurrence of chalcopyrite, resulted in high concentration of S (13 750 ppm). Similarly, a distinct enrichment in Pb in the samples (2) – 271 ppm and (5) – 370 ppm, and in Zn in sample (2) – 812 ppm, is connected with later hydrothermal processes accompanied by precipitation of galena and sphalerite. The presence of galena within veinlets (the sample DB-5, 904.3 m) was confirmed by EDS analysis.

The spotted andalusite and cordierite hornfelses are characterised by high Rb, Ba and Sr contents, distinctly exceeding their clarks in clay rocks. Cordierite hornfels contains up to 216 ppm and spotted andalusite hornfelses contain from 270 to 380 ppm Rb whilst its clark for sediments is up to 150 ppm. In the studied rocks Rb contents are distinctly correlated with that of K (what can suggest their common migration during metasomatic processes).

Ba enters predominantly into the crystal lattices of potassium feldspars and micas. The K/Ba ratio in spotted andalusite hornfelses is up to 40–45 whilst cordierite hornfels is relatively deficient in Ba where this ratio is 64. Distinct enrichment in Ba (4853 ppm) of the sample (5) – [DB-5, 905.5 m] – is connected with the presence of baryte-bearing veinlets. The increased contents of Ba and its positive correlation with K are one more argument that potassium metasomatism has modified the composition of the rocks studied, enriching them in alkali metals, especially in potassium.

Strontium, as isomorphic with Ca^{+2} and K^{+}, is located both in crystal lattices of plagioclases and potassium feldspars. Therefore, its correlation with K is less pronounced.

DISCUSSION

Metamorphosed Cambrian rock complex, penetrated by boreholes under Mesozoic cover, consisted of primarily detrital sediments (conglomerates, sandstones, mudstones interlayed with claystones). Preliminary data on the presence of tuffogenic intercalations in this complex were reported by Harańczyk *et al.*, (1996). In Harańczyk's (1984, 1994a, b) opinion, the Cambrian rock complex was deposited under conditions of quiet sedimentation on abyssal planes in anoxic regime far from continental border. Some of presented geochemical data confirm this thesis.

Harańczyk (1994b) suggested that the Palaeozoic (Cambrian-Ordovician) cover in the area studied was subjected to regional metamorphism at temperature about 450°C. In the northern part of this area (the Mrzygłód-Myszków region) the conditions of regional metamorphism were defined as corresponding to biotite zone of the greenstones facies (Ryka, 1971, 1973, 1978; Łydka, 1973; Szymański & Nehring-Lefeld, 1995; Nehring-Lefeld & Szymański 1998). In several recent papers (Buła & Kotas, 1994; Żaba, 1995, 1999; Bełka & Siewniak-Madej, 1996) regional metamorphic phenomena have influenced only Vendian–Lower Cambrian (?) rocks complex, whereas younger Palaeozoic rocks occurring in the zone of thermal activity of igneous intrusions were subjected to contact metamorphic alterations.

Within the whole area of marginal zone of the Małopolska Block contact metamorphic phenomena are observed around granodiorite intrusions in the regions Myszków–Mrzygłód, Zawiercie, Będkowska Valley and Pilica. They are evidenced by the occurrence of hornfelses, spotty schists, skarns and marbles reported in numerous papers: Ryka (1971, 1973, 1978), Łydka (1971, 1973), Harańczyk *et al.* (1980), Harańczyk (1985), Ślósarz (1985, 1994), Karwowski (1988), Muszyński (1991), Heflik & Piekarski (1992), Czerny *et al.* (1997). Black massive rocks, showing sieve texture, consisting of quartz, albite, potassium feldspar, biotite, chlorite and sometimes epidote, were reported by Truszel (1994) to occur in the Myszków–Mrzygłód region. Biotite-quartz-albite hornfels was mentioned by Kośnik & Muszyński (1990) from thermally metamorphosed cover of granodiorite intrusion in the Będkowska Valley. Later, in the same area, individual occurrences of characteristic contact metamorphic rocks – andalusite and cordierite hornfelses, were described (Koszowska & Wolska, 1994a, b; Czerny *et al.*, 1997).

The emplacement of large magmatic body into the clastic rocks in Będkowska Valley resulted in isochemical thermal metamorphism. The type of metamorphic rocks formed depends on primary chemical and mineral composition of intruded country rock. Consequently, the effects of thermal metamorphism in various rocks of the Cambrian complex were distinctly different. Larger detrital components of metaconglomerates, metasandstones and metamudstones were not altered since feldspars and quartz are stable within the whole range of temperatures and pressures of thermal metamorphism. Therefore, sedimentary structures such as bedding and lamination were preserved in these rocks.

Alteration processes of sedimentary rocks related with

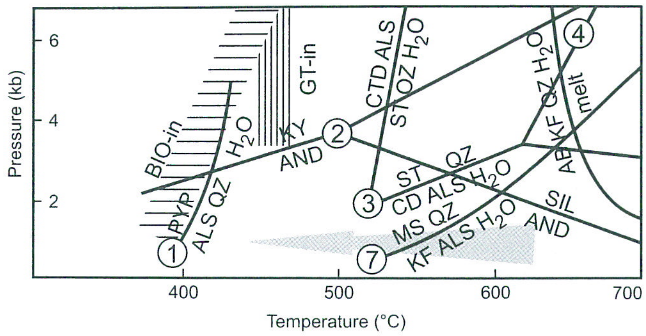


Fig. 18. Suggested PT path of metamorphic conditions of the hornfelses from Będkowska Valley (on the base of mineral paragenesis). Data sources for the curves are as follows: 1 – Kerrick (1968), 2 – Holdaway (1971), 3 – Richardson (1968), 4 – Yardley (1981), 7 – Chatterjee & Johannes (1989) – all data after Yardley (1989); ST = staurolite, CTD = chloritoid, CD = cordierite, SIL = sillimanite, Ms = muscovite, KF = K-feldspar, BIO = biotite, PYP = pyrope, ALS = Al-silicate, QZ = quartz, KY = kyanite, AND = andalusite, AB = albite, GT = garnet

thermal metamorphism resulted in recrystallization of chalcedony into quartz in pebbles of siliceous rocks and in the formation of small corrosional embayments at detrital minerals grains. Another evidence of these processes is the transformation of primary minerals of cementing matrix into neogenic, fine-flaky aggregates of olivaceous-brown biotite.

On the other hand, in pelitic intercalations, due to fine-grained character of primary material, cordierite was formed as typical mineral of thermal metamorphism, accompanied by neogenic olivaceous-brown biotite. Locally, cordierite hornfelses also contain blasts of corundum. Cordierite-biotite-corundum paragenesis in these rocks may suggest the temperature range 510–525°C and the pressures 0.5–2 kbar (Fig. 18) what is characteristic of lower limit of hornblende-hornfels facies (Winkler 1986).

On the contrary, the paragenesis of andalusite and biotite is observed in macroscopically spotted andalusite hornfelses, originated from primary tuffogenic material enriched in Al_2O_3. Andalusite can crystallize already at temperature about 500°C what corresponds to the boundary of albite-epidote-hornfels and hornblende-hornfels facies. This mineral is stable even under conditions of orthoclase-cordierite-hornfels facies i.e. at temperature 580–630°C and pressure 1–2 kbar (Fig. 18).

In the outermost zones of contact aureole chlorite-bearing spotted rocks were formed in temperature above 400°C, in which chlorite is stable yet and biotite is already stable (Winkler 1986).

The thickness of contact aureole which embraced metaconglomerates, metasandstones, metamudstones and fine-grained cordierite hornfelses reaches several hundred meters, whereby the thickness of cordierite hornfelses amounts to 250–300 m. Until recent publication the occurrence of only initial hornfelses have been reported in the contact zone of the granodiorite intrusion in the Będkowska Valley (Harańczyk *et al.*, 1995). The occurrence of andalusite and cordierite in the contact aureole of granodiorite intrusion suggests the depth of emplacement from 5–10 km (Carmichael *et al.*, 1974). Instead, small dimensions of neogenic minerals indicate a short period of thermally transformation of the host rocks.

Later transformation related with potassium metasomatism characteristic of porphyry copper deposits formation resulted in the origin of secondary ore-bearing quartz-feldspar veins in thermally metamorphosed rocks. In andalusite hornfelses there appear large euhedral corundum blasts along these veins. Contrary to early generation of fine-blastic corundum in fine-grained cordierite hornfelses, they were formed during metasomatic influx of potassium by decomposition of andalusite into light mica. Similar processes of metasomatic-hydrothermal transformations were described in other rock complexes of this type (Rose, 1957; Wojdak & Sinclair, 1984).

CONCLUSIONS

1. In the region of Będkowska Valley thermal action of granodiorite intrusion resulted in contact metamorphism of the Cambrian detritic complex within the distance up to 250–300 m. (inner part of the contact aureole). The intensity of metamorphic alterations was determined, first of all, by lithology of the country rocks and their distance from the intrusion.

2. The contact metamorphic rocks studied are represented by: fine-grained cordierite hornfelses formed at the expense of pelitic rocks, macroscopically spotted andalusite hornfelses produced from volcanoclastic rocks and chlorite spotted rocks generated from pelitic rocks more distant from the intrusion (outer part of the contact aureole).

In the coarser grained detritic rocks (metaconglomerates and coarse to medium grained metasandstones) the skeleton grains were resistant to metamorphic alteration, whereas fine-grained matrix was entirely transformed into biotite aggregates.

3. Metamorphic contact minerals such as: cordierite, andalusite and corundum were formed only at the expense of pelitic and volcanoclastic parent rocks.

4. The Mg/Fe_{Tot} and Ti/Fe_{Tot} ratio of the parent rock was preserved in the newly crystallized biotites. This indicates the growth of the biotite under isochemical conditions in the course of thermal metamorphism. An analogous phenomenon appears in cordierite, in which Mg/Fe^{+2} ratio reflects that of the rocks. Fe significantly replaced Mg in the lattice of cordierite due to high iron content in the rock studied.

5. The occurrence of contact metamorphic minerals in fine-grained cordierite hornfelses and macroscopically spotted andalusite hornfelses suggests that these rocks were formed under conditions corresponding to the orthoclase-cordierite hornfels facies of thermal metamorphism after Winkler (1986). Neogenic contact-metamorphic minerals were formed at 580–630°C and 1–2 kbar according to the reactions (Winkler, 1986):

muscovite + quartz = K-feldspar + andalusite + H_2O

6 muscovite + biotite + 15 quartz = 3 cordierite + 8 K-feldspars + $8H_2O$

6. It is supposed that fine-blastic corundum occurring in

fine-grained cordierite hornfelses is the product of transformations related with contact metamorphism under conditions: temperature 510–525°C and pressure: 0.5–2 kbar (hornblende hornfels facies), according to the reaction proposed by Winkler (1986):

chlorite + muscovite + quartz = cordierite + biotite + corundum + H_2O

Moreover, chlorite, occurring in chlorite spotted rocks, associated with muscovite and albite, is stable above 400°C (albite-epidote hornfels facies).

7. The formation of corundum occurring in macroscopically spotted andalusite hornfelses was due to superposition of potassium metasomatism on the above processes (Koszowska & Wolska, 1994a). The decomposition of andalusite into sericite aggregate, stimulated by influx of potassium, resulted in the release of Al_2O_3 from crystal lattice and recrystallization of large euhedral corundum crystalloblasts at temperature above 400°C and pressure about 0.5 kbar. This process was described by Rose (1957) and Wojdak & Sinclair (1984) to occur in altered rocks of porphyry copper-molybdenum-type deposits.

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Streszczenie

MINERALOGICZNE I GEOCHEMICZNE BADANIA PRZEOBRAŻONYCH TERMICZNIE SKAŁ OTACZAJĄCYCH INTRUZJĘ GRANODIORYTOWĄ W DOLINIE BĘDKOWSKIEJ KOŁO KRAKOWA (POŁUDNIOWA POLSKA).

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W otworach wiertniczych (DB-5 i WB-102A) usytuowanych w Dolinie Będkowskiej (na północny zachód od Krakowa) stwierdzono, pod utworami jurajskimi, występowanie klastycznych metasedymentów dolnego i środkowego kambru. Są one reprezentowane przez formację wielobarwnych zlepieńców z Doliny Będkowskiej i przez formację ciemnych pirytonośnych metamułowców. Formacje te były datowane akritarchami i mikrosporami odpowiednio na kambr dolny i środkowy Harańczyk, 1982, 1994 a, b). Na głębokości 1092,0 m (WB-102A) i 1142,7 m (DB-5) nawiercono intruzję granodiorytu, której w obu otworach nie przebito. Intruzja ta ma charakter intruzji zszywającej (stitching intrusion) (Harańczyk *et al.*, 1995) i jest związana z suturalnym rozłamem wgłębnym.

Kompleks klastycznych metaskał kambryjskich reprezentuje osady fliszowe związane z procesem tworzenia się ryftu (Unrug *et al.*, 1976). Występują w nim metazlepieńce grubo- i średnioziarniste, grubo- i średnioziarniste metapiaskowce, metamułowce i metaiłowce. Skały te są ciemne, prawie czarne i wykazują bardzo dużą twardość (dźwięczą przy uderzeniu młotkiem). Charakteryzują się dobrze zachowanymi strukturami sedymentacyjnymi: laminacją i frakcjonalnym uziarnieniem. W obrębie skał kompleksu kambryjskiego występują wkładki jasnozielonych metatufitów o niższej twardości, które ostro odgraniczają się od skał klastycznych.

Pod wpływem termicznego oddziaływania dużej intruzji magmowej, dającej pozytywną anomalię magnetyczną (Harańczyk *et al.*, 1995), skały kompleksu kambryjskiego uległy przeobrażeniu w metasedymenty.

Celem pracy było określenie zasięgu aureoli kontaktowej w skałach osłony granodiorytu, dlatego do badań starano się pobrać próbki skał, na które nie nałożyły się późniejsze procesy hydrotermalne rozwijające się w strefach okołożyłowych.

W zależności od odległości od intruzji, ilości składników detrytycznych i składu chemicznego spoiwa i matrix, oraz dodatkowo w niektórych strefach, od ilości i składu chemicznego materiału piroklastycznego, skały opisywanego kompleksu uległy przekształceniu w: drobnoziarniste hornfelsy kordierytowe, makroskopowo plamiste hornfelsy andaluzytowe, skały plamiste z chlorytem, metazlepieńce, metapiaskowce i metamułowce.

W skałach klastycznych (metazlepieńce, metapiaskowce i metamułowce) składniki detrytyczne, reprezentowane przez kwarc i skalenie, są trwałe w całym zakresie temperatur opisywanych przemian metamorficznych. W minerałach tych jedynie na brzegach ziarn zaznacza się proces korozji. Natomiast pierwotne spoiwo ilaste uległo rekrystalizacji w agregaty drobnoblaszkowego, oliwkowo-brązowego biotytu.

Pierwotne skały ilaste, zawierające niewielką domieszkę frakcji mułowcowej, uległy całkowicie przeobrażeniom termicznym, stając się drobnoziarnistym hornfelsem kordierytowym. Skały te wykazują mikroskopowo widoczną strukturę plamistą. Jasne, owalne, elipsoidalne lub o zarysach kwadratowych "plamy" składają się głównie z kordierytu, który czasami tworzy przerosty ze skaleniem potasowym (100–82% mol. Or). Ponadto w kordierycie występują liczne wrostki minerałów nieprzeźroczystych, co nadaje skale charakter tekstury sitowej. Minerał ten często wykazuje zbliźniaczenia podwójne, potrójne a nawet sześciokrotne i charakteryzuje się przewagą Mg nad Fe^{+2}. Stosunek tych pierwiastków w kordierycie odzwierciedla ich wzajemną relację w skale. Matrix pomiędzy "plamami" składa się ze wzajemnie poprzerastanych blaszek brązowego biotytu, charakteryzującego się pleochroizmem od jasnozielonego do oliwkowo-brązowego i pod względem chemicznym wyraźną przewagą Fe_{Tot} nad Mg oraz blastów plagioklazów (69–59% mol. Ab).

Pierwotne skały tufitowe, zawierające nawet do 25% wag. Al_2O_3, uległy całkowicie procesom przeobrażeń termicznych i utworzyły się z nich makroskopowo plamiste hornfelsy andaluzytowe. Andaluzyt występuje w nich w postaci hipidiomorficznych kryształów z charakterystyczną łupliwości, oraz jako odmiana chiastolitowa. Większość kryształów tego minerału uległa przeobrażeniu w drobnoblaszkowy jasny łyszczyk, który wypełnia przestrzenie między "plamami". Owalne "plamy", widoczne makroskopowo, są zbudowane z agregatu bezładnie poprzerastanych blaszek czerwono-brązowego biotytu. Skład chemiczny tego łyszczyku różni się od składu chemicznego biotytu z drobnoziarnistych hornfelsów kordierytowych. Charakteryzuje się on wyższą zawartością MgO i niższym stosunkiem FeO_{Tot}/MgO. Jego odmienna barwa i pleochroizm mogą być związane z większą ilością Ti i Fe^{3+} w strukturze.

W drobnoziarnistych hornfelsach kordierytowych i w makroskopowo plamistych hornfelsach andaluzytowych pojawiają się drobne krystaloblasty korundu o charakterystycznym beczułkowatym pokroju, w przekroju równoległym do osi Z i plamistym pleochroiźmie w barwach od jasnozielonej do ciemnoniebieskofioletowej. Zabarwienie to jest związane z obecnością domieszek tytanu i żelaza w jego strukturze.

Plamiste skały zawierające drobnoblaszkowy chloryt i biotyt występują w zewnętrznej strefie aureoli kontaktowej granodiorytu.

Badania geochemiczne, obejmujące oznaczenia zawartości pierwiastków głównych i śladowych (w tym REE) w metaskałach klastycznych i tufitowych, wykazały różnice w ich składzie chemicznym. Metaskały powstałe ze skał osadowych są wzbogacone w Na_2O i K_2O, jak również w CaO. Skały pochodzenia tufogenicznego charakteryzują się niskim stosunkiem SiO_2/Al_2O_3 wynikającym z podwyższonej zawartości Al_2O_3 i na diagramie Batchelor'a & Weir'a (1988) – fig.13 znalazły się w polu metabazytów, natomiast skały powstałe z pierwotnych skał osadowych w polu łupków. Na podstawie zawartości pierwiastków śladowych określono pochodzenie skał tufitowych z magmy bazaltowej lub pośredniej bazaltowo-andezytowej – fig.14. Niski stosunek Ti/Y i wysoki Ni/Th wskazuje na maficzny charakter źródłowej magmy. Odrębnym zagadnieniem jest podwyższona zawartość w niektórych próbkach Cu, Pb i Zn, związana z występowaniem w omawianym kompleksie skał żył z późniejszą mineralizacją kruszcową. Wysoka zawartość Ba i Sr w makroskopowo plamistych hornfelsach andaluzytowych świadczy również o późniejszym rozwoju w omawianych skałach, procesów metasomatozy potasowej.

Stwierdzono, że wysoko temperaturowe zmiany termiczne zaznaczyły się w skałach omawianego kompleksu paleozoicznego na przestrzeni ok. 250–300 m (wewnętrzna część aureoli kontaktowej). Szacunkowo określony zasięg zmian termicznych wydaje się być prawdopodobny, gdyż przyjmuje się na podstawie badań geofizycznych, że intruzja granodiorytu była intruzją średniej wielkości (Harańczyk *et al.*, 1995)

Obecność paragenezy skaleń potasowy-kordieryt-biotyt może sugerować, że zmiany termiczne, prowadzące do powstania hornfelsów kordierytowych zachodziły w temperaturze 580–630°C, przy ciśnieniu 1–2 kbar, co odpowiada facji ortoklazowo-kordierytowo-hornfelsowej metamorfizmu termicznego wg. klasyfikacji Winklera.

Natomiast andaluzyt może krystalizować już w temperaturze ok. 500°C i jest stabilny nawet w warunkach facji ortoklazowo-kordierytowo-hornfelsowej. Tak więc zakres trwałości obu minerałów obejmuje interwał temperatur 580–630°C charakterystyczny dla dolnego zakresu facji ortoklazowo-kordierytowo-hornfelsowej (Fig.18).

Osobnym zagadnieniem jest obecność krystaloblastów korundu w opisywanych hornfelsach. Sporadyczne wystąpienia korundu w drobnoziarnistych hornfelsach kordierytowych i utworzenie się paragenezy kordieryt-biotyt-korund może sugerować przeobrażenia w temp. 510–525°C i ciśnieniu 0,5–2 kbar, co wg. Winklera (1986) jest charakterystyczne dla dolnej granicy hornblendowo-hornfelsowej facji metamorfizmu termicznego. Natomiast pojawienie się dużych krystaloblastów korundu występujących wzdłuż żył kwarcowo-skaleniowych w makroskopowo plamistym hornfelsie andaluzytowym może sugerować, że powstawał on podczas metasomatycznego przeobrażenia, przy dopływie potasu, pierwotnego andaluzytu w jasny łyszczyk. Tego rodzaju proces wtórnego przeobrażania skał zmienionych termicznie był opisywany w skałach związanych z mineralizacją typu złóż porfirowych Cu-Mo (Rose, 1957, Wojdak & Sinclair, 1984).