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Rodingite from Nasławice and the other occurrences of these rocks in Lower Silesia (SW Poland)

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Rodingites from Nasławice of the Jordanów-Gogołów serpentinite massif in SW Poland are composed of augite/diopside, grossular and hornblende/tremolite. The accessory components are represented by vesuvianite, adularia, basaltic hornblende and picotite. Apatite, millerite?, sphalerite, galena, Fe-sulphides, Ni-sulphides and Ni-arsenates were also observed as trace phases in these rocks. Generally, rodingites from Nasławice are enriched in numerous polymetallic compounds of Cu, Ag, Fe, Ni, Co, Fe, Pb, Zn, As and Bi, and show a similar mineral association and texture as rodingites from the other occurrences in SW Poland, i.e. from the Szklary and Braszowice-Brzeźnica massifs. They most probably developed from a mafic protolith (fine-grained gabbro) intruding into serpentinized ultramafic rocks under metasomatism conditions. The secondary pneumo-hydrothermal post-granitic activities also affected the final formation of these metasomatic rocks.

Key words: rodingite, Nasławice, Sudetes, polymetallic compounds, mafic protolith.

INTRODUCTION

Rodingite is a rare, garnet (grossularite, hydrogrossularite, andradite)-diopside (diallage) rock formed by metasomatism. It can be enriched in other Ca-silicates, like epidote, prehnite and vesuvianite. The worldwide bibliography on this rock is quite rich; including papers as early as e.g., Bell et al. (1911) and Benson (1914). Some papers present the occurrences of rodingites in various parts of the world, as e.g. Bloxam (1954), Bilgrami and Howie (1960), Vuagnat and Pusztaszeri (1964), Seki (1965), Coleman (1966), O'Brien and Rodgers (1973), Evans et al. (1979), Barriga and Fyfe (1983), Sivell and Waterhouse (1986), Schandl et al. (1989), O'Hanley et al. (1992), Mogessie (1994), Kobayashi et al. (1997) and the latest ones, as e.g. Schandl and Mittwede (2001), Kobayashi and Kaneda (2010), Perraki et al. (2010) and references therein. In Poland, rodingites are associated mainly with ultramafic and mafic rocks of ophiolitic complexes within the Góry Sowie Block (Gunia, 1996; Kryza, 2011). The characteristics of the rodingites from the Jordanów-Gogołów Massif (Majerowicz, 1979, 1984; Heflik and Żabiński, 1980; Heflik, 1982; Heflik and Sobczak, 1988; Dubińska, 1989, 1995, 1997; Dubińska et al., 1991, 2004; Dubińska and Gunia, 1997; Gałuskin and Szełęg, 2003) and the Braszowice-Brzeźnica Massif (Gunia, 1986a, b, 1989, 1992) are well-known. However, rodingites from the Szklary Massif seem to be less known; they were described by Heflik and Natkaniec-Nowak (1987, 1989) and Dubińska et al. (1991).

The overriding purpose of the study is to describe the presence of new mineral phases in rodingites from Nasławice and to give a short summary of the general data about rodingites from Lower Silesia (SW Poland).

GEOLOGICAL SETTING

Nasławice Quarry is located within the Jordanów-Gogołów serpentinite massif (Fig. 1), which is the largest of the three ultramafic bodies of the Sudetic ophiolite (Dubińska et al., 2004). This massif occurs close to the northern border of the Góry Sowie Block (Fig. 2). In the north, serpentinites of the massif display thermal-metasomatic contacts with Variscan granitoids of the Strzegom-Sobótka Massif (Majerowicz and Pin, 1989). The Jordanów-Gogołów Massif is composed mainly of serpentinites and subordinate fresh or slightly altered peridotites. The serpentinites are considered to be the lower part of the Ślęża ophiolitic sequence (Narębski and Majerowicz, 1985) of Early Devonian age (Dubińska et al., 2004; Kryza, 2011). The primary mineralogy of ultramafic rocks suggests that serpentinites were developed from harzburgites and lherzolites (Dubińska and Gunia, 1997). Several occurrences of rodingites and other leucocratic rocks were found within the serpentinized rocks of the Jordanów-Gogołów Massif (Gunia, 1996). Dubińska (1995) identified two types of rodingites within the massif:

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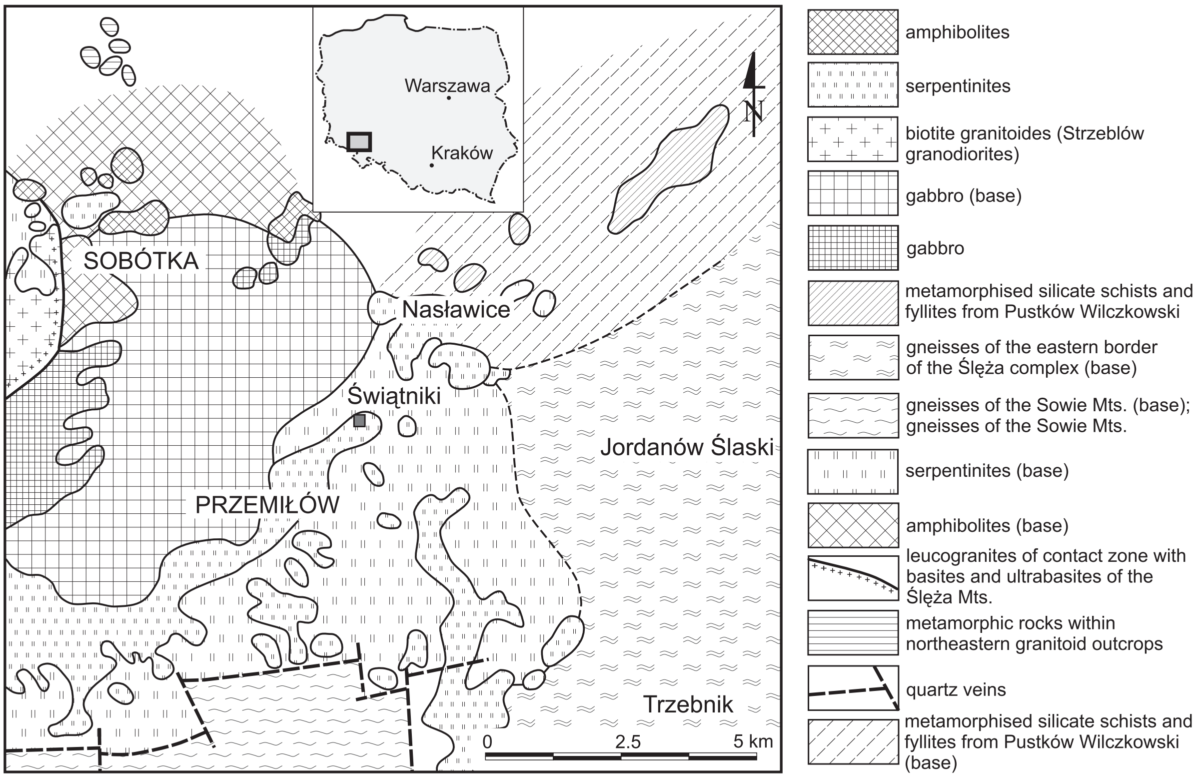

Fig. 1. The localization of Nasławice Quarry within the Ślęża complex (modified after Majerowicz, 1984)

boninitic rodingite and plagiogranite rodingite. More detailed geology and a geological sketch map of this region was presented by Dubińska (1995) and Dubińska et al. (2004).

METHODS

Microscopic and Raman spectroscopy investigations were carried out at the laboratories of the Faculty of Geology, Geophysics and Environmental Protection, AGH University of Science and Technology in Kraków, Poland. Standard optical examinations were carried out with an *Olympus BX 51* polarizing microscope. Backscattered electron observations were conducted on polished sections using a *FEI Quanta 200 FEG* scanning electron microscope with an EDS detector. The system of SEM operated at 20 kV accelerating voltage, 50 μA current, in a high vacuum mode, i.e. $6 \times 10^{-5} - 7 \times 10^{-6}$ Torr.

Raman spectra of selected rodingite components were recorded with a *Raman Thermofisher Scientific* spectrometer coupled with a DXR microscope equipped with 50×, 20× and 10× magnification lenses. The samples were excited with the 514.5 nm line of a *Spectra-Physics* Ar^+ laser. The laser power and excitation time was accommodated to the optical character of the samples. It should be noted that no sample preparation was performed. Unfortunately, the vast majority of rock regions could not be used due to the laser-induced sample fluorescence.

FORMER AND PRESENT STUDIES OF SUDETIC RODINGITES

JORDANÓW-GOGOŁÓW SERPENTINITE MASSIF

Mineralogical and petrographic studies of serpentinites from this massif have been conducted since the end of the 19th century. The possibility of occurrence of rodingites in Sudetic ophiolites, especially within the Jordanów-Gogołów Massif, was first mentioned by Traube (1885, 1888), and then by Sachs (1902) who connected these rocks with *Weisssteins* (term used by German geologists for white aplite veins intersecting various, dark coloured rocks from the Niemcza Zone). An interest in this problem was subsequently continued by Gaweł (1957) and Heflik (1967). Investigating the altered leucocratic zone in Jordanów Śląski, Heflik (1967) found that there is an association of grossular with vesuvianite, diopside, zoisite and prehnite, which was later recognized as rodingite (Heflik and Żabiński, 1980). At Jordanów Śląski, rodingite occurs in the northwestern and eastern walls of the quarry, in the form of irregular lenses, 1 × 0.25 m in size. In the vicinity of Jordanów Śląski, a similar mineral paragenesis was also observed in both the serpentinite quarry in Nasławice (Heflik, 1968; Gunia, 1996) and a small quarry located south of the village of Świątniki (Majerowicz, 1979, 1984). Within the Jordanów-Gogołów Massif, rodingites were also observed between Glinica and Jordanów Śląski, near Uliczna (Czernica Hill; Gunia, 1996).

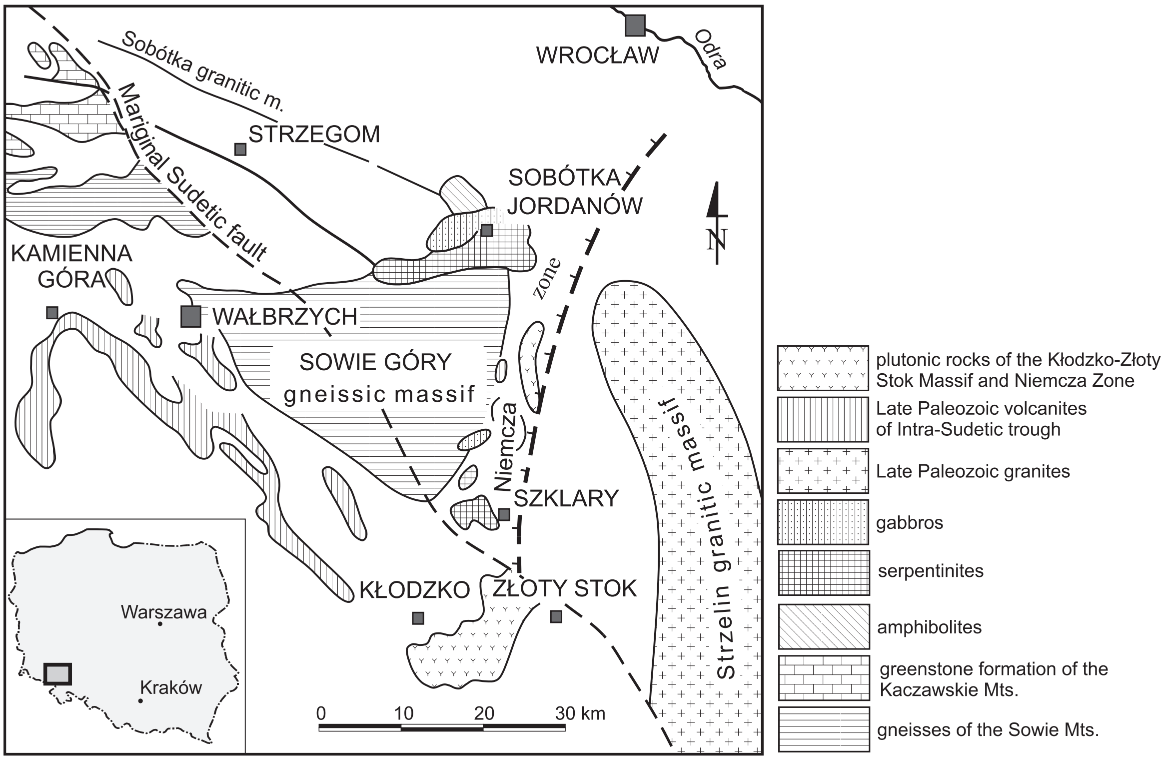

Fig. 2. The distribution of basic and ultrabasic rocks within the Niemcza Zone (modified after Smulikowski and Teisseyre, 1957)

Rodingite from Jordanów Śląski is white in colour and contains garnet (grossular) with saponite (Heflik and Żabiński, 1965). Locally, it can also be composed of garnets with pyroxenes (diopside), locally intergrown with tremolite, forming aggregates with a radial texture (Fig. 3). Crystallisation of this association took place in stages. Decreasing temperature led to the crystallisation of the following phases: first diopside and grossular, and then tremolite. Rodingite of this massif is locally cut by thin magnesite-talc veins (Fig. 4). Mineral composition of rodingites from other localities in Lower Silesia is very similar to that of Jordanów-Gogołów metasomatic rocks.

In the early 1980s, the senior author mentioned the presence of mineralogical paragenesis in Nasławice, which are identical to those from Jordanów Śląski (Heflik, 1982). In 2009, in the southeastern part of the Nasławice Quarry, he found an about 20-cm-thick vein composed of intensely altered fine-grained gabbro, which contained green-white rodingite enclaves. Samples collected from these rocks are the object of the present studies. The rocks are commonly porphyritic, consisting of diallage and strongly altered hornblende phenocrysts set in the fine-grained diopside and amphibole (tremolite–actinolite) groundmass. The phenocrysts are also repre-

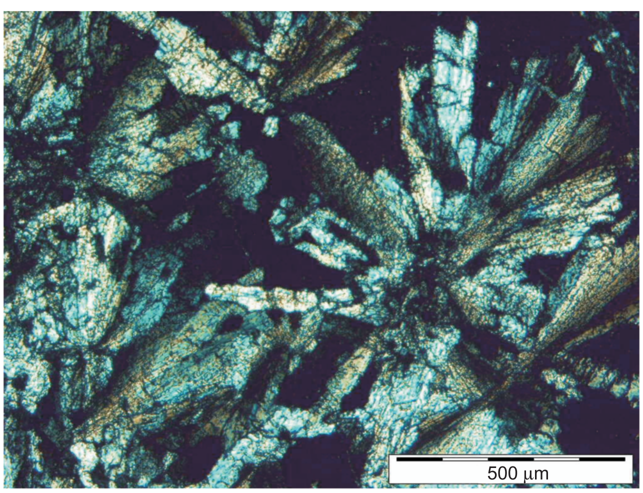

Fig. 3. Pyroxenes with radial texture in rodingite from Jordanów Śląski (crossed polars)

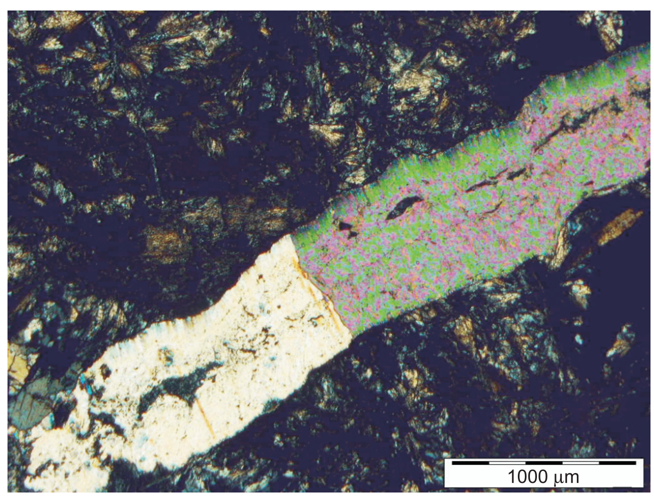

Fig. 4. Carbonate vein in rodingite from Jordanów Śląski, (crossed polars)

sented by numerous tabular forms, which are most probably fine-grained aggregates of pyroxene with garnet crystalised probably after primary basic plagioclase. The majority of phenocrystals are strongly altered, only the diallage is relatively fresh; although the peripheral parts of some of the crystals are amphibolitized to some extent.

The presence of main components of this rock, i.e. grossular and diopside was confirmed by micro *Raman* spectroscopy (Fig. 5). The presence of grossular is manifested by the bands at 370, 423, 545, 819 and 876 cm^{-1}. The bands 423, 546 and 819 and 876 cm^{-1} are related to Si-O bending and stretching vibrations, respectively (Kolesov and Geiger, 1998, 2005). tigations revealed that the pyroxene composition is variable, from diopside (single crystals) to augite (spherical aggregates). The latter also shows a variable composition between individual domains of crystal, i.e. in the core, Al dominates over Mg, whereas in the rim, the content of Al decreases and the content of Mg increases (Fig. 7). Similarly, garnets show variable compositions of Al, Cr and Fe, typical of the ugrandite group.

The veins that intersect rodingites are filled with garnets (Fig. 8) or pyroxenes. Hence, it is assumed that in addition to rodingite that resulted from eins (dykes) of augite/diopside and basic plagioclase, there is also another (younger) generation of rodingite.

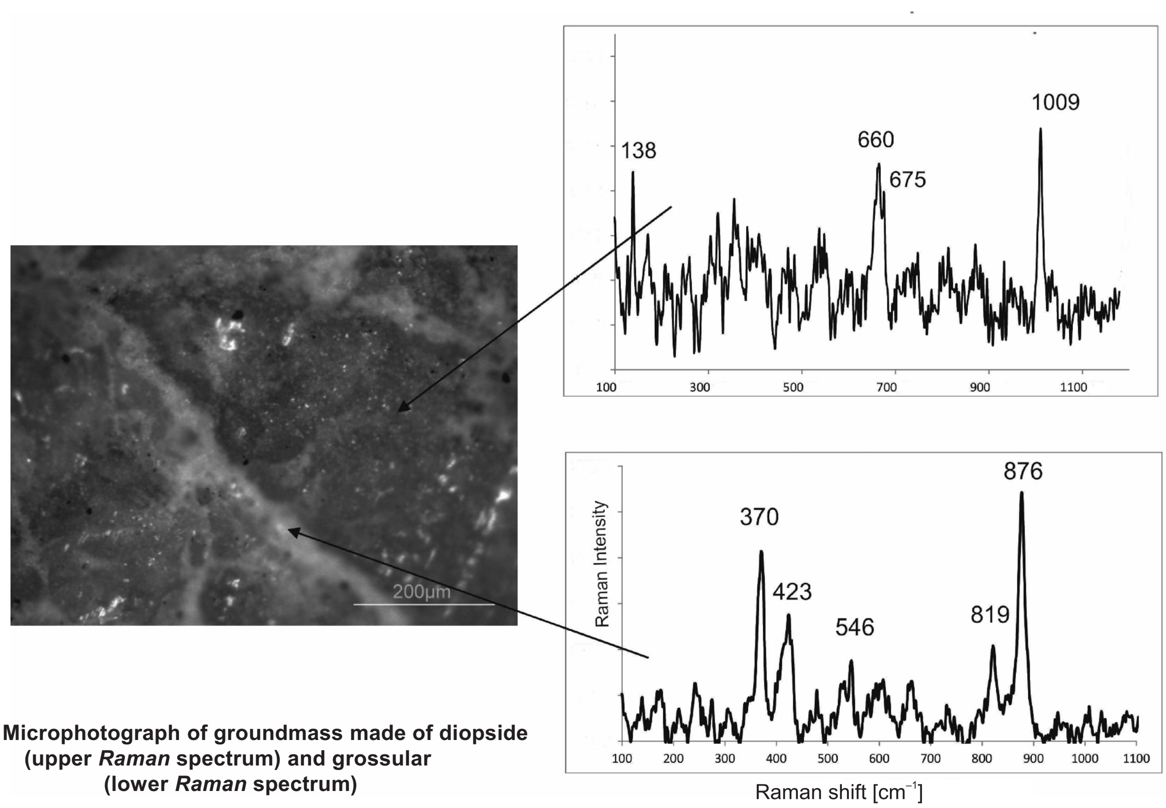

Fig. 5. Microphotograph of groundmass made of diopside (upper *Raman* spectrum) and grossular (lower *Raman* spectrum)

The band at 370 cm^{-1} could be mixed T/R(O_4H_4) and T/R(SiO_4) vibrations. The characteristic bands at 138, 660, 675 and 1009 cm^{-1} can be attributed to diopside. Richet et al. (1998) assigned bands 660–675 cm^{-1} and 1009 cm^{-1} to a mixed stretching bending mode of the Si-O-Si bridging bond and Si-O stretching vibrations with non-bridging oxygen, respectively. The band of 138 cm^{-1} is associated with the deformation mode of the silicate chain.

The main components of the rocks are accompanied by accessory minerals of vesuvianite and adularia with characteristic hour-glass zoning (Fig. 6). Locally, single crystals of basaltic hornblende and picotite (Fe, Mg)(Al, Cr)$_2$O$_4$ also occur in the rock. This type of hornblende is often found in fine-grained gabbro; Heflik and Żabiński (1970) described it in the rock from Słupiec in the Nowa Ruda gabbro-diabase massif. It was most likely formed as a result of iron oxidation under the influence of hot gases in the last stage of magma differentiation.

In SEM images, rodingite enclaves from Nasławice form a pyroxene-garnet conglomerate intersected by numerous thin veins. The matrix is made of pyroxenes forming well-developed thin columns as well as spherical aggregates. SEM-EDS inves-

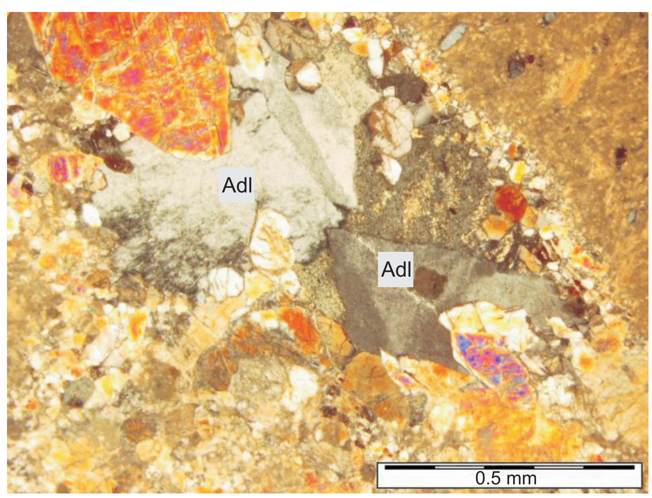

Fig. 6. Adularia (Adl) crystals in rodingite from Nasławice (crossed polars)

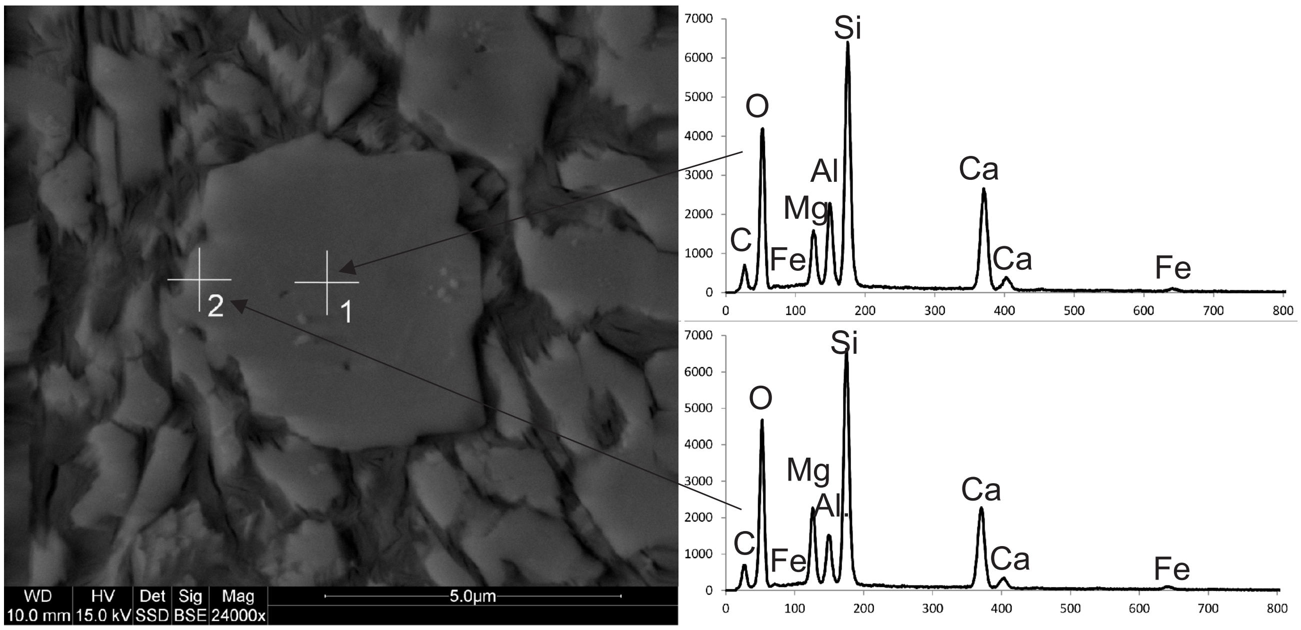

Fig. 7. Variable composition of a pyroxene crystal: 1 – core, 2 – rim (BSE image)

The SEM-EDS studies, revealed the presence of numerous accessory phases in rodingite from Nasławice, i.e. apatite, millerite? (Fig. 9A), sphalerite (Fig. 9B), galena and iron sulphides (Fig. 9C). The latter compounds contain also traces of Cu and Ni. Besides the sulphides, Ni arsenates with Bi traces were found in the rock matrix (Fig. 9D). Polymetallic compounds, rich mainly in nickel, form tiny crystals (Fig. 10A). In the peripheral parts, they are represented by nickel sulphides with Pb traces, whereas in the central part – by nickel arsenates with Fe and Pb admixture. Locally, Ni sulphides with Bi, Co and Pb, are also observed (Fig. 10B). In the vicinity of Nasławice, pitticite (hydrous ferric arsenate sulphate) was reported from serpentinites of Jordanów Śląski (Traube, 1888).

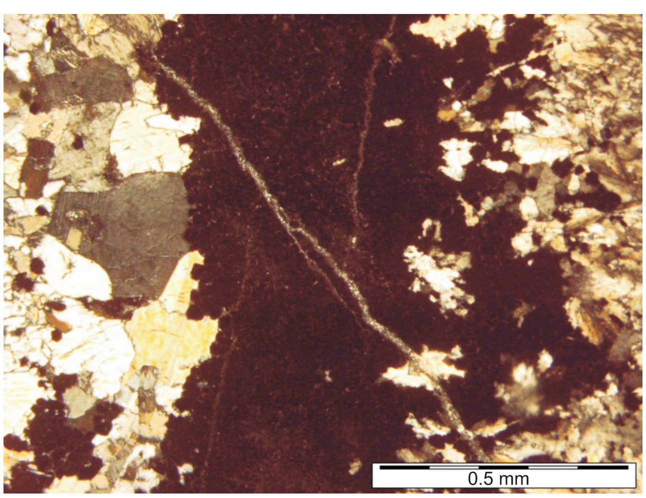

Fig. 8. Garnet vein intersecting rodingite from Nasławice (crossed polars)

The presence of native elements of the Cu-Au series and their compounds in rodingites was described by Spiridonov et al. (1997). In Poland, native copper in rodingitizated gabbro was reported by Gunia (1986b) from serpentinites of the Braszowice-Brzeźnica Massif. Similarly, the mineral paragenesis was also found by Gałuskin and Szełęg (2003) in rodingites from Nasławice. They found amalgamates of silver in association with Cu and Ag sulphides, Ag and Cu selenides, and Cu, and native copper oxides.

SZKLARY SERPENTINITE MASSIF

In the 1980s, detailed geological investigations were carried out in the Marta' nickel mine in Szklary near Ząbkowice Śląskie (*vide* Heflik and Natkaniec-Nowak, 1989). The aim of these investigations was to study serpentinites and other products of serpentinization, formed as a result of alteration of ultramafic (dunite, peridotite) and mafic rocks (gabbro) (*vide* Natkaniec-Nowak and Pitera, 1986). During those studies, lenses of rocks resembling nephrite with the association of leucocratic rocks were found in Szklary (Heflik et al., 1988). A similar phenomenon of paragenesis of rocks was described by Heflik (1967) from the Jordanów Śląski serpentinite quarry near Sobótka.

In Szklary, the outcrops of leucocratic and nephrite-like rocks are located in the northern part of the mine, in the western wall (lens of 5 × 2 m in size), and about 200 m to the north in the eastern wall (zone of 12 × 2 m in size). Altered gabbro with inclusions of rodingites was observed in this region (*vide* Heflik and Natkaniec-Nowak, 1989). In its immediate vicinity, white-coloured, crumbly albitites (Muszyński and Natkaniec-Nowak, 1993, 1992) and crystalline schists (tremolite and biotite–actinolite–vermiculite) were also found. All these rocks occur within the intensely altered serpentinites. In this leucocratic zone, the mineral association includes grossular, augite/diopside, plagioclase (albite–oligoclase), tremolite, clinozoisite, clinochlore, serpentine, prehnite and talc.

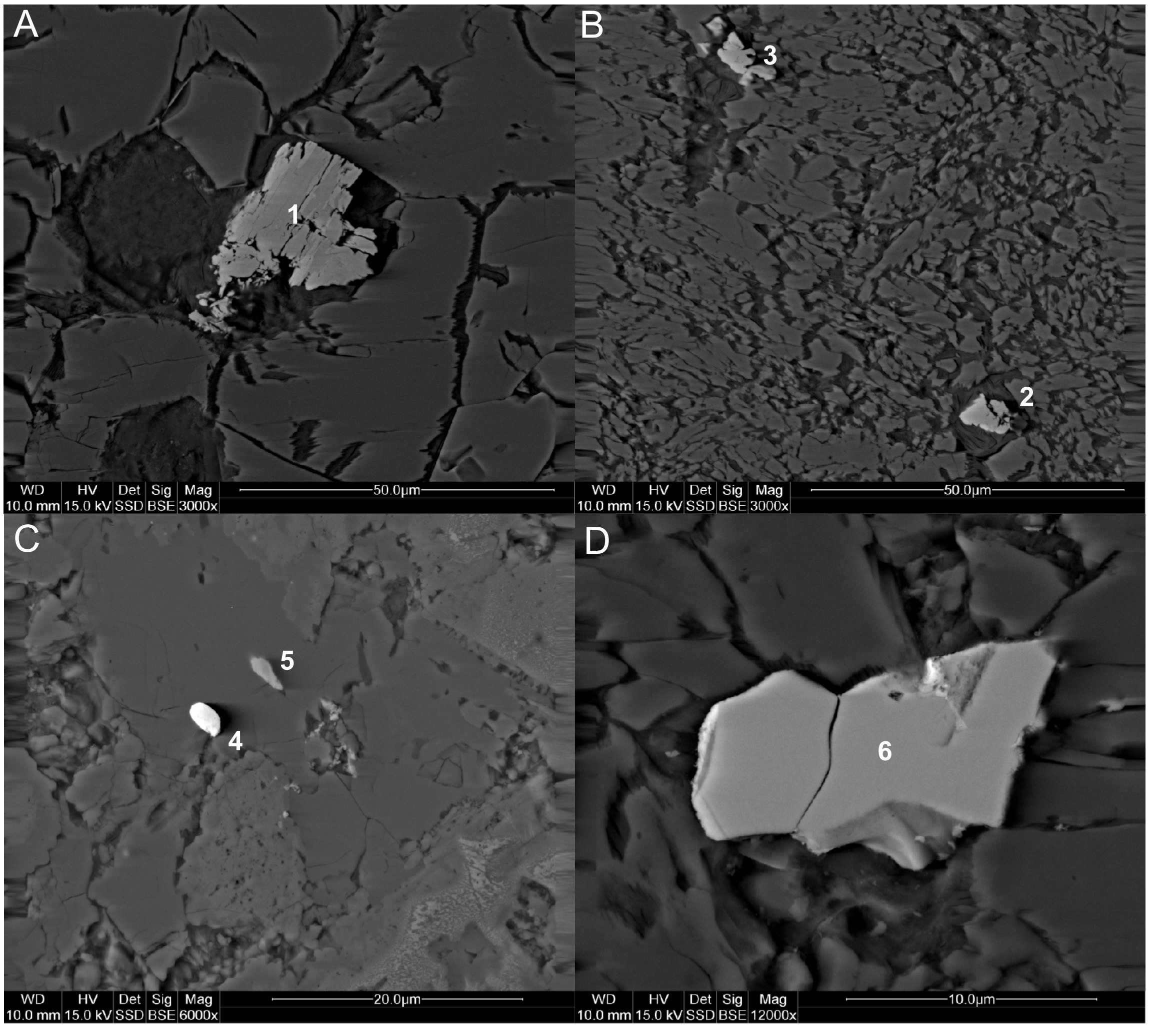

Fig. 9A–D – ore-bearing phases in rodingite from Nasławice (BSE image)

A – nickel sulphide (1); **B** – sphalerite (2, 3); **C** – galena (4), iron sulphide (5); **D** – Ni arsenates (6)

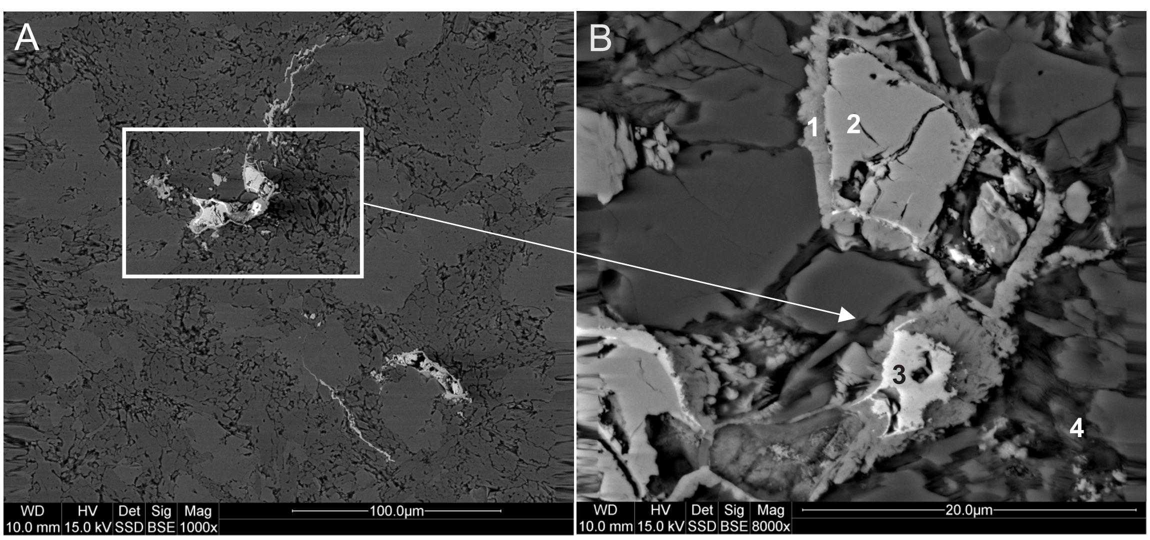

Fig. 10A and B – polymetallic compounds in rodingite from Nasławice i.e. nickel sulphides with Fe and Pb traces (1), nickel arsenates with Fe and Pb admixture (2), Ni sulphides with Bi, Co and Pb (3, 4) (BSE image)

Heflik and Natkaniec-Nowak (1989) thoroughly described lenses of strongly and weakly altered gabbro with rodingite inclusions. Greenish (light type) and grey (dark type) rodingites form spherical bodies within the intensely altered gabbro. They show heteroblastic (grano-, poikiloblastic) and massive, locally relict texture. Rodingites are mainly composed of garnet (grossular), which is intergrown with pyroxene crystals (augite/diopside). The texture of these mineral intergrowths is characteristic of eutectic systems, described e.g. from gabbro pegmatites (Heflik and Żabiński, 1970). Garnets are the most probable products formed as a result of garnetization of basic plagioclases, the main components of protolithic gabbroid. The main phases of this rock are accompanied by elongate crystals of tremolite, locally forming radial aggregates. Rodingite is intersected with thin veins of prehnite and clinozoisite.

BRASZOWICE-BRZEŹNICA SERPENTINITE MASSIF

Rodingite from serpentinites near Mikołajów was first described by Gunia (1986a, b), even though many years before, Traube (1889) found grossular in this massif at the Mnich Hill. The possibility of rodingite occurrences in this region was also considered by Dziedzicowa (1979) and Jamrozik (1981).

Rodingites crop out in the upper part of the wall of the serpentinite quarry, on the southwestern slope of the Mnich Hill (Kozie Chrzepty). In strongly fractured serpentinites, pink-grey mylonitized rodingite forms enclaves, 3 × 0.4 m in size. Between the rodingite and the serpentinite, there is a chlorite contact rim of the “black-wall”. Locally, in the immediate proximity to the occurrences of rodingites, single opal-chalcedony veins can be observed. Rodingites show grano-, porphiroblastic and massive textures. Grossular appears as a main component of these rocks, while diopside, chlorite and vesuvianite are secondary phases. Garnets reach sizes of up to 0.15 mm, and they are a little bit larger (ca. 0.5 mm) only in the contact zone with chlorite rocks. Single chlorite crystals occur also in the garnet matrix of the rock. Diopside forms idiomorphic crystals up to several cm in size. Vesuvianite fills interstices in the grossular groundmass (Gunia, 1986a).

INTERPRETATION AND DISCUSSION

Rodingites from Lower Silesia seem to be similar in form, texture, and mineral composition to the other Ca-rich, SiO_2-undersaturated rocks formed as a result of serpentinization (e.g., Sivell and Waterhouse, 1986; Kobayashi and Kaneda, 2010). They form veins (in the NW and E wall of the Jordanów Śląski Quarry and the SE wall of the Nasławice Quarry) or irregular lenses (in the W and E walls of the abandoned Szklary mine). The largest isolated enclave of rodingite (2.5 × 3 m) was noted on the NW wall of the Jordanów Śląski Quarry. Similarly, smaller enclaves were observed in the western part of the Szklary mine and on the western wall of the serpentinite quarry near Mikołajów.

All of them show complex, heteroblastic (grano-, poikiloblastic), massive, locally cataclastic or relict texture. They are composed mainly of garnets (grossular), pyroxenes (augite/diopside) and vesuvianite. Tremolite and Fe-rich chlorite are secondary phases. This mineral paragenesis is characteristic of a Ca-rich medium genetically related to basic magma (Gaweł, 1957; Heflik, 1967).

Rodingites from Nasławice are enriched in polymetallic phases. Compounds of Fe, Ni, and Co are associated with an ultramafic protolith, even though the presence of phosphorus seems to be related to mafic rocks, as a maximum amount of P_2O_5 is characteristic of gabbro magma. Cu and Ag compounds are also typical of a mafic protolith (gabbro, basalt). It should be noted that in the vicinity of Nasławice, in Pustków Wilczkowski, there are occurrences of Cu phosphates (turquoise) (e.g., Heflik et al., 1976). Hence, it is assumed that copper compounds are quite widespread in the rocks of the region and the presence of Cu must be associated with the host, ultramafic and mafic rocks of Lower Silesia. However, Cu and Ag sulphides could crystallise also during the hydrothermal stage of magma differentiation at a much lower temperature range. Gałuskin and Szełęg (2003) suppose that crystallisation of Cu-Ag minerals from sulphides begins at 200°C, then, under the low sulphur activity, they are substituted by selenides and, finally, native Cu is substituted by oxides, whereas Ag remains in a native state.

During the hydrothermal stage, also Fe and Pb compounds could crystallise. However, Zn, Pb, As and Bi compounds are associated rather with acid pneumo-hydrothermal emanation. Bismuth with copper and nickel are frequently incorporated into Pb-Ag compounds. In rodingites from Nasławice, Bi occurs in arsenates. Adularia is also a hydrothermal product.

Based on our studies and literature data (Dubinska et al., 2004), it was noted that rodingites from Nasławice are enriched mainly in Ca and Mg, and show some contents of Fe and Ti (Dubińska et al., 2004), which suggests that their origin could be related to a mafic protolith. The presence of main mineral phases, accessory polymetallic compounds of Fe, Ni, Co, Zn, Pb, Cu, Ag, As, Bi and P and the texture of these rocks could also support this thesis. It is assumed that rodingites from the other occurrences in Lower Silesia could contain similar polymetallic compounds (e.g., Gunia, 1986b, noted the presence of copper in rodingites from the Braszowice-Brzeźnica Massif).

Lis and Sylwestrzak (1981) noted that pegmatite-pneumatolitic products affected the leucocratic zone within the serpentinites of the Nasławice Hills. In the Jordanów Śląski Quarry, they found pegmatites and aplites. The pegmatite was composed of albite, quartz, muscovite, K-feldspar, beryl, garnet (almandine–grossular), tourmaline (dravite), gahnite, columbite, fluorite, zircon and cassiterite, whereas the aplite contained quartz, K-feldspar, plagioclase, biotite, beryl and garnets (almandine–spessartine). The rocks with such mineral paragenesis were also found within the adjacent granitoids of the Strzegom-Sobótka Massif. Thus, aplites and pegmatites from Nasławice could be genetically associated with granitoides of this massif. Similarly, in Szklary near the occurrences of rodingite, pegmatites with gem quality tourmaline crystals are found (Pieczka, 1987). Sachanbiński et al. (2000) associated them with acidic rocks of the Strzegom-Sobótka Massif. However, based on new SHRIMP zircon age, Kryza (2011) suggested that aplites and pegmatites from these massifs show similar age as granitoids from the Niemcza Shear Zone, dated at 338 +2/–3 Ma.

CONCLUDING REMARKS

In Nasławice, the mafic protolith is represented by fine-grained gabbro. This rock exhibits different texture than gabbro from the Sobótka region (e.g., diallage gabbro in the upper part of Ślęża Mt.). It forms an intrusion resembling a dyke. It is assumed that these rocks are genetically related to the ophiolite suites of the Góry Sowie Block. However, it is not clear which magmatic stage of the ophiolitic system the dykes are associated with. According to the sequence of the Troodos Ophiolite in Cyprus (Varga and Moores, 1985), the fine-grained gabbro from Nasławice most probably belongs to the sheeted dyke complex, which in Troodos is built mainly of diabases that experienced greenschist- or amphibolite-facies alteration. The thickness of these dykes ranges from 0.5 to 5.0 m with 0.3–3.0 m in length. The fine-grained gabbro from Nasławice is probably genetically associated with orthoamphibolites from Sobótka, which could originate from the alteration of diabase under amphibolite-facies conditions.

To sum up, the rodingites occurring around the Góry Sowie Block are related to a mafic protolith (fine-grained gabbro). During the formation of rodingites and other co-existing leucocratic rocks (Heflik, 1967), pneumo-hydrotermal post-granitic products, associated with acidic rocks of the Strzegom-Sobótka Massif or the Niemcza Shear Zone, played a negligible role. Rodingites from Lower Silesia resemble the rocks from New Zealand described by O'Brien and Rodgers (1973), Leach and Rodgers (1978) and Sivell and Waterhouse (1986), as well as those found in the Sartuohai chromium deposit in China (Kobayashi and Kaneda, 2010).

The authors of this paper suppose that the rodingites from the Sudetic serpentinite massifs share a common origin, and the variability between them could result only from local events. Moreover, the problem of genesis of these interesting decorative rocks is still open. Nevertheless, the authors hope that the investigations presented herein will be fruitful to the discussion of rodingites from Lower Silesia.

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