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Magmatic and post-magmatic phenomena in the Karkonosze granite and its metamorphic envelope (West Sudetes, SW Poland)

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ABSTRACT:

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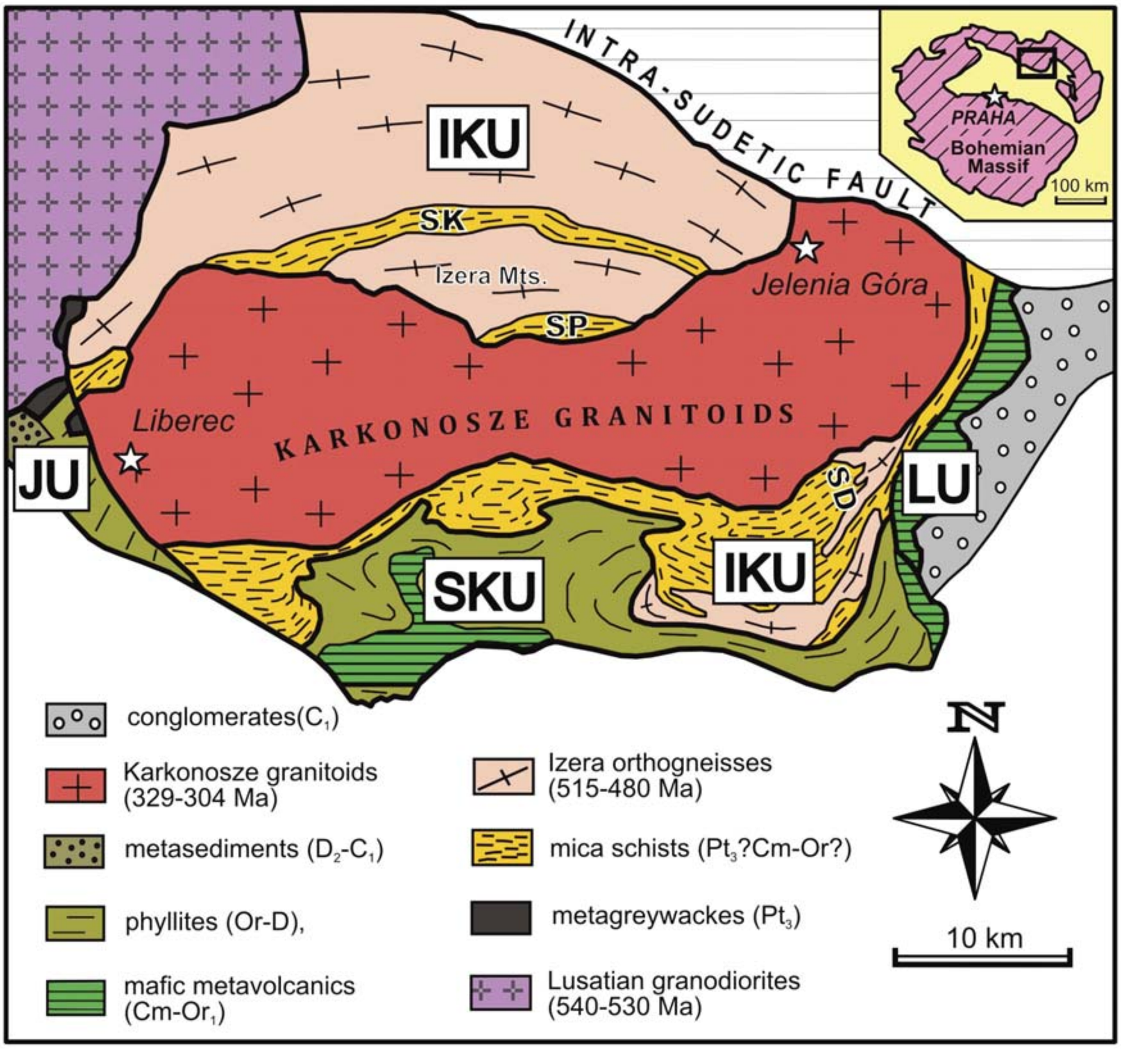
Mineralogical studies of the Karkonosze granite (ca. 322–312 Ma) and its surroundings in West Sudetes (SW Poland) have provided data on Nb-Ta-REE minerals from pegmatites in the NE part of the pluton and several new finds of Ag minerals and 15 oxygenic Bi phases, hitherto not reported from the massif. The Karkonosze pegmatites are enriched in HREE as fergusonite-(Y) or xenotime-(Y) appear in almost every studied pegmatite, together with a subordinate assemblage of the aeschynite, euxenite or columbite group. The abundance of LREE minerals such as allanite-(Ce) and the monazite group, correlates inversely with the Nb-Ta-Ti minerals, whilst an early generation of monazite-(Ce) revealed an exceptionally high amount of Nd (up to 22 wt.% of Nd_2O_3). The physical and chemical conditions during the magmatic and post-magmatic processes were reconstructed and the effects of contact metamorphism in amphibolites from hornfelsed zones examined. Changes in solution composition and concentration at the early magmatic stage (825–920ºC), pegmatitic stage overlapping with hydrothermal (560°C which ended at 160–90°C) and clearly hydrothermal stage (400 to 110°C) were studied in detail by means of melt and fluid inclusions in quartz. Furthermore, post-magmatic fluids, including some enriched in Li and B, were identified in rock-forming quartz from the whole pluton. In turn, study of the amphibolites indicates that the pair cummingtonite + anorthite or the presence of Ca-rich plagioclase with actinolite seem to be reliable mineral proxies of the thermal impact of the granitoid body on amphibolites in its envelope. The inferred conditions of the contact processes (450–550°C, 2.5–4.8 kbar) point to an elevated geothermal gradient (ca. 32–45°C/km) probably reflecting the heat flow induced by the Karkonosze intrusion. Moreover, despite the textural and mineral changes imposed by regional and contact metamorphism, the amphibolites have their pre-metamorphic (magmatic) geochemical features undisturbed.

Key words: Karkonosze pluton; Melt and fluid inclusions; Nb-Ta-REE pegmatites; Contact zone amphibolites.

INTRODUCTION

The Karkonosze granitoid, one of the biggest plutonic bodies in the Sudetes, is located in the marginal part of the present-day Bohemian Massif. Due to its internal complexity, textural diversity and abundance of mineral species, the pluton has intrigued and captured the interest of generations of geologists, mineralogists, petrologists and enthusiasts of Earth sciences. The intrusion belongs to a younger, late- to post-orogenic phase (325–290 Ma) of the intense granitoid magmatism in the Sudetes (ca. 340–290 Ma) which produced several large plutons (cf. e.g., Mazur *et al.* 2007; Oberc-Dziedzic *et al.* 2013). The formation of the intrusion is correlated with a relatively early stage of that phase in Late Carboniferous times (Awdankiewicz *et al.* 2010) due to coupled tectonic and magmatic processes involving both mantle and crustal sources (Mazur *et al.* 2007). As a consequence, the batholith is composite, situated in the core of the domal structure of the Palaeozoic rocks of the Karkonosze-Izera massif (Text-fig. 1) where several magma batches were emplaced in a dextral strike-slip regime during the initiated extensional collapse, uplift and unroofing of the host rocks initiated at ca. 335–337 Ma (Aleksandrowski *et al.* 1997; Mazur and Aleksandrowski 2001; Marheine *et al.* 2002). During the intrusion the envelope of the granite, comprising Palaeozoic metavolcanic-sedimentary successions, developed a pronounced, ca. 2.5 km contact aureole with hornfelses and spotted schists indicating a shallow level (<10 km) of emplacement (e.g., Borkowska 1966; Oberc-Dziedzic 1985; Fila-Wójcicka 2004; Ilnicki 2011; Žák *et al.* 2013).

Although several main varieties of the Karkonosze granitoid have been distinguished (Text-fig. 2; see also below), the distinctions are not trivial. Common small-distance changes of the granitoid features, many schlieren with very diffuse borders, and post-consolidation alteration of various intensity significantly hamper unequivocal subdivisions. Hence its petrographic and



Text-fig. 1. Geological sketch map of the Karkonosze-Izera massif (after Mazur and Aleksandrowski 2001, modified). Inset shows the Bohemian Massif. Radiometric age constaints after Borkowska *et al.* (1980), Duthou *et al.* (1991), Korytowski *et al.* (1993), Kröner *et al.* (1994, 2001), Kryza *et al.* (2014a, b), Linnemann *et al.* (2000), Machowiak *et al.* (2007), Marheine *et al.* (2002), Oberc-Dziedzic *et al.* (2010), Oliver *et al.* (1993), Tikhomirova (2002), Żelaźniewicz *et al.* (2004). Abbreviations: IKU – the Izera-Kowary unit, JU – Ještěd unit, LU – the Leszczyniec unit, SD – Sowia Dolina (the Owl Valley), SKU – the South Karkonosze unit, SK – the Stara Kamienica belt, SP – the Szklarska Poręba belt geochemical features, the isotope age of the distinguished varieties, the position, tectonics, structure and relationships with the cover were studied intensively (see e.g., Berg 1923; Cloos 1925; Borkowska 1966; Klomínský 1969; Chaloupský *et al.* 1989; Mierzejewski 2007; Słaby and Martin 2008; Žák *et al.* 2013; Kryza *et al.* 2012, 2014a, b). Nevertheless, almost the entire massif is built of a biotite granite with accessory allanite, zircon and apatite, at places with small amounts of hornblende. The geochemical features of the granite indicate a peraluminous composition, classified as a K-rich calc-alkaline type (KCG) with a complex, multistage origin (e.g., Mazur *et al.* 2007; Słaby and Martin 2008; Awdankiewicz *et al.* 2010; Žák *et al.* 2013 and references therein).

For decades, the wealth of mineral species occurring in the granitoid body and its envelope has attracted the attention of mineralogists, resulting in a large number of scientific contributions. Nonetheless, many of the most recent data on post-magmatic fluids and minerals in the Karkonosze pluton remain unpublished. Therefore the scope of this paper is to review mineralogical studies carried out on the Karkonosze granite and its immediate surroundings at the Faculty of Geology, University of Warsaw. The results of extensive research on melt inclusions characterizing the early stages of magma crystallization and on fluid inclusions in the granite rock-forming quartz, pegmatites and veins revealing the evolution of the post-magmatic fluids are summarized. Moreover, new data concerning the Nb-Ta-REE accessories in pegmatites from the NE part of the pluton and rare Ag, Bi minerals are presented. Also reported is a record of the thermal impact of the granite on rock-forming mineral assemblages in the amphibolites from the contact zones located along northern and south-eastern border of the intrusion. Additionally, geochemical features and the palaeotectonic position of these amphibolites are discussed.

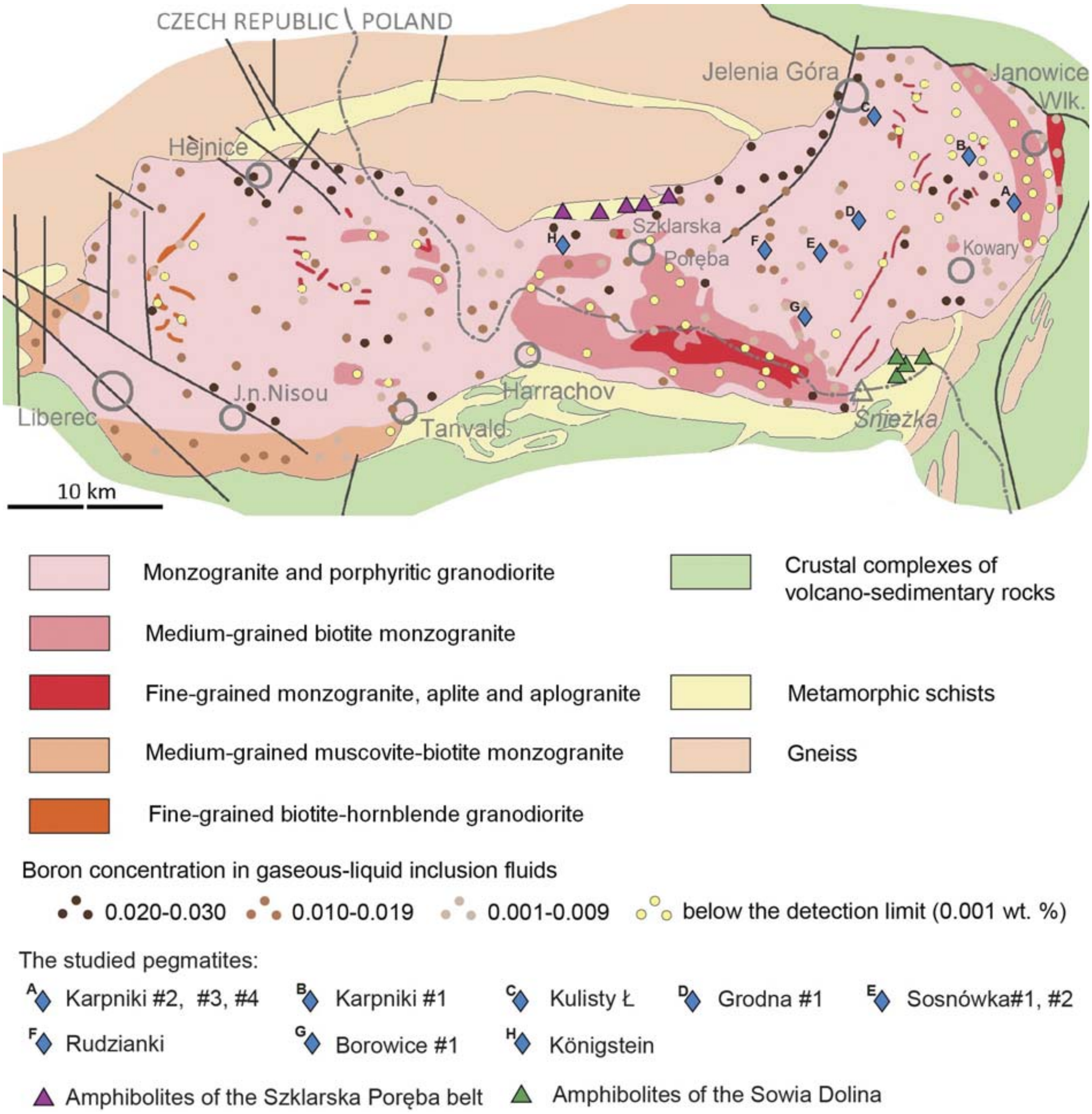
OUTLINE OF GEOLOGICAL SETTING

The Karkonosze-Izera massif is situated at the NE margin of the Bohemian Massif in West Sudetes which comprise also the neighbouring Kaczawa metamorphic unit, the Görlitz slate belt and the eastern part of the Lusatian massif (e.g., Mazur *et al.* 2006). This part of the Sudetes is associated with the Saxothuringian zone (e.g., Franke and Żelaźniewicz 2002) which is believed to plunge eastward beneath the Teplá–Barrandian domain, now buried below the infill of the intra-Sudetic basin, only to be re-exposed within an accretionary wedge in front of the Brunia domain (East Avalonia; e.g., Mazur and Aleksandrowski 2001; Chopin *et al.* 2012; Mazur *et al.* 2015; Szczepański and Ilnicki 2014).

The majority of the Karkonosze-Izera massif consists of metamorphic rocks of Neoprotorozoic-Palaeozoic age which host the Late Carboniferous Karkonosze granite (Mazur *et al.* 2007 and references therein). Different tectonic and lithostratigraphic subdivisions were proposed for the metamorphic series (for interpretations and overviews see, e.g., Chaloupský *et al.* 1989; Mierzejewski and Oberc-Dziedzic 1990; Mazur 1995; Seston *et al.* 2000; Smulikowski 1999; Kozdrój *et al.* 2001). The northern part of the massif (the Izera complex) is built predominantly of orthogneisses and metasediments. The former are derived from the ca. 480–515 Ma continental, rift-related Izera granites (Borkowska *et al.* 1980; Oliver *et al.* 1993; Kröner *et al.* 2001; Pin *et al.* 2007) emplaced within Cadomian crust of NW Gondwana affinity represented by Lusatian greywackes and arc-related granitoids (587–569 Ma) intruded by post-tectonic (540–530 Ma) granodiorites (e.g., Żelaźniewicz *et al.* 2009; Žačková *et al.* 2012 and references therein). During the Variscan orogeny the Izera granites were transformed into gneisses and due to the present position of the Karkonosze intrusion now are divided into the Izera gneisses (to the north of the granite) and their equivalents to the SE and S of the granite, i.e. the Kowary- and Krkonoše gneisses (Text-fig. 1). The Izera orthogneisses are embedded in a metasedimentary succession (mica schists with paragneisses, quartzofeldspatic rock, amphibolites, calc-silicates, crystalline limestones) and together they were interpreted as a single tectonic entity, the Izera-Kowary unit (Mazur and Aleksandrowski 2001). The succession is also split by the Karkonosze pluton and its major part is located to the south (the Velká Úpa group of Chaloupský *et al.* 1989), whilst to the north it forms four, roughly sub-parallel and narrow belts (Text-figs 1, 2) with the southernmost (the Szklarska Poręba belt) hornfelsed by the intrusion. Mica schists were interpreted as the Neoproterozoic cover of the Izera granite (Żelaźniewicz *et al.* 2003) metamorphosed during Variscan times. However, on the SE flank they are intimately associated with ca. 500–525 Ma quartzofeldspathic metavolcanics suggesting that the Izera gneisses and the metasediments were juxtaposed during the Variscan orogeny (Oberc–Dziedzic *et al.* 2010; Žačková *et al.* 2010, 2012).

The southern and eastern parts of the Izera-Karkonosze massif comprise a Cambrian–Devonian succession of metasediments deposited in a large marine basin with a bimodal suite of metavolcanics (Chaloupsky *et al.* 1989; Chlupáč 1997; Mazur and Aleksandrowski 2001; Patočka and Hladil 1998; Patočka *et al.* 2000; Dostal *et al.* 2001; Patočka and Pin 2005) and meta-igneous felsic and mafic rocks of roughly similar age emplaced in an extensional setting (ca. 500 Ma; Oliver *et al.* 1993; Bachliński and Smulikowski 2005; Kryza *et al.* 1995; Winchester *et al.* 1995). These rock series were combined into the South Karkonosze and the Leszczyniec units, respectively, and along with the Izera-Kowary unit now form an inverted metamorphic nappe pile stacked in the Late Devonian – Early Carboniferous (Mazur and Aleksandrowski 2001). The NW-directed nappe stacking followed the SE subduction of the an oceanic domain (ca. 360 Ma, Maluski and Patočka 1997) and Saxothuringian passive margin, presumably beneath the Teplá–Barrandian terrane prior to the Early Carboniferous, SE-directed extensional collapse and late- to post-orogenic Carboniferous intrusion of the Karkonosze granite (Mazur and Aleksandrowski 2001; Mazur *et al.* 2007).

The Karkonosze pluton occupies the central position of the Karkonosze-Izera massif. The canonical study of Borkowska (1966) recognized four rock varieties located in various parts of the intrusion: porphyritic coarse-grained granite with oligoclase- or al-

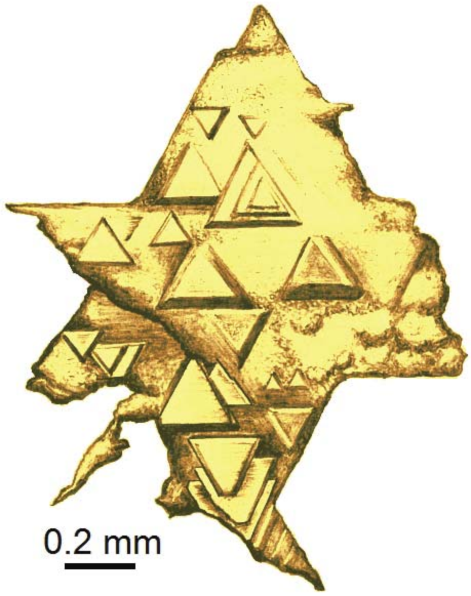


Text-fig. 2. Localities of the studied samples. Circles denote samples in the Karkonosze pluton in which secondary fluid inclusions in rock-forming quartz were investigated; the map presents the occurrence of boron in the fluid inclusions in wt. % of the inclusion fluid. Blue diamonds show localities of the studied pegmatites. Triangles denote outcrops of the studied amphibolites in the Szklarska Poręba belt (purple) and in the Sowia Dolina (green). Map after Kozdrój *et al.* (2001), modified bite-mantled potassium feldspar phenocrysts, equigranular granite composed of fine to medium crystals of potassium feldspar, acid plagioclase, quartz and biotite, medium-grained granite containing the same components as the previous variety, and granophyric granite. In turn, Kozdrój *et al.* (2001) presented monzogranite and porphyritic granodiorite, medium-grained biotite monzogranite, fine-grained monzogranite, aplite and aplogranite, medium-grained muscovite-biotite monzogranite, and fine-grained biotite-hornblende granodiorite (Text-fig. 2). The recent report of Žák *et al.* (2013), combining field, spatial, textural relationships with U-Pb zircon geochronology, distinguished the separately evolved and the oldest (317.3 ± 2.1 Ma) S-type, equigranular leucocratic two-mica Tanvald granite, followed by at least two I-type voluminous batches of the medium- to coarse-grained porphyritic Liberec granite (319.5 ± 2.3 Ma) and the overlying medium-grained, strongly porphyritic Jizera granite (320.1 ± 3.0 Ma and 319.3 ± 3.7 Ma) and the uppermost minor intrusions of the medium-grained equigranular Harrachov granite (315.0 ± 2.7 Ma) and fine to medium-grained equigranular Krkonoše granite. The structural and petrological studies of Žák and Klominský (2007) and Słaby and Martin (2008) showed the dominant role of mixing–mingling, hybridization and fractional crystallization in the genesis of the pluton. Progressive injection of mafic melts derived from an enriched mantle source into fractionating crustal acidic magma represented by the equigranular granites led to the formation of the dominant porphyritic granite facies. Furthermore, Žak *et al.* (2013) emphasized the progressive strain accumulation during multistage magma emplacement, whilst Gros (2016) recognized the vital role of fluids in magma evolution. However, Kryza *et al.* (2014a) in their comprehensive report on up-to-date geochronological studies of the Karkonosze pluton argued that the equigranular biotite granites represent the most evolved melts, postdating the porphyritic-type granites. Their own results of an age study of chemically abraded zircons (322 ± 3 and 319 ± 3 Ma for a porphyritic granite and 318 ± 4 Ma for an equigranular granite) confirmed the temporal succession proposed by Žak *et al.* (2013), thus supporting the view that the Karkonosze Pluton underwent a protracted igneous evolution, possibly spanning a 15–20 Ma duration (Kryza *et al.* 2014a). In contrast, the high-precision CA-ID-TIMS zircon crystallization ages obtained by Kryza *et al.* (2014b) indicate that the two main granite types of the Karkonosze pluton formed during a relatively short time span at around 312 Ma corroborating the hypothesis that the formation of the batholith was a short episode.

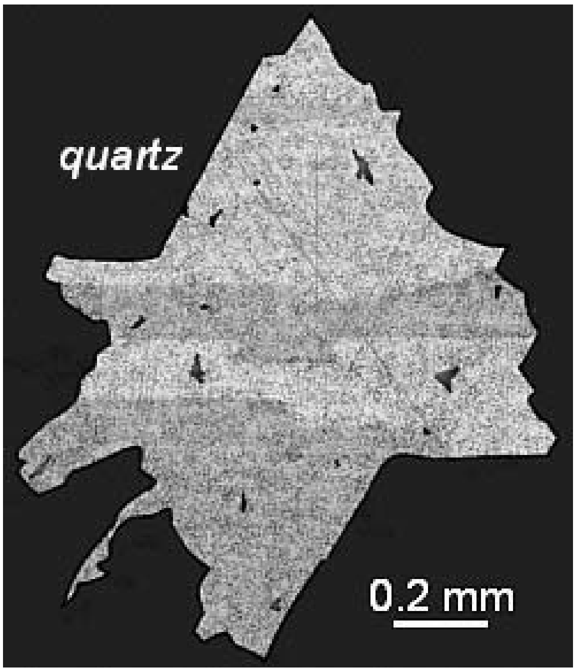
MINERALOGICAL STUDIES OF THE KARKONOSZE GRANITE

The studies of magmatic and post-magmatic phenomena in the Karkonosze pluton started in the Faculty of Geology in the 1950s. The geochemical behaviour of many elements was investigated in the granitoid and pegmatitic feldspars (Kowalski 1967), and a wide range of trace elements was determined in Sudetic quartz, including that coming from the Karkonosze pluton (Waleńczak 1959, 1969). Starting in 1968, fluid inclusion studies in the Institute of Geochemistry, Mineralogy and Petrology yielded a number of data, which gave an outline of the conditions of post-magmatic mineralization in this area (Karwowski and Kozłowski 1972; Kozłowski 1973, 1978; Kozłowski and Karwowski 1974). On the other hand, previously unknown tin-tungsten-molybdenum mineralization was recognized in the northern part of the Karkonosze pluton (Karwowski *et al.* 1973; Kozłowski *et al.* 1975; Olszyński *et al.* 1976). An evolution of the chemical composition of plagioclase by metasomatic replacement of calcium by sodium in pegmatites was also studied (Nowakowski and Kozłowski 1983). Investigations in this pluton (and the others) suggested more extensive problems, like a metasomatic formation of the pegmatites (Kozłowski 2002), a general outline of the post-magmatic activity with the determined evolution of temperature, pressure and fluid composition (Kozłowski and Marcinowska 2007) or completion of the minerals, occurring in the pegmatitic assemblages (Kozłowski and Sachanbiński 2007).

Furthermore, the research effort focused on diverse issues of mineral genesis in the Karkonosze-Izera massif and beyond. That includes occurrences of native gold (Text-figs 3, 4) from the Karkonosze pegmatites and gold-bearing veins (Kozłowski 2011a), but also elsewhere in the Sudetes (deposits in Taczalin, Radzimowice, Klęcza, Czarnów, etc.; see Kozłowski and Metz 1989; Mikulski *et al.* 2003; Mikulski *et al.* 2005; Mikulski *et al.* 2007; Mikulski and Kozłowski 2011), at Miedzianka in the Holy Cross Mts. (Kozłowski 2011b) or even in the Scandinavian quartz of pebbles found in the West Pomeranian Baltic shore (Kozłowski 2011c). Hydrothermal (metasomatic inclusively) activity in metamorphic rocks was also studied, e.g., the formation of tourmaline and complex metasomatites from the Izera complex (Kozłowski and Metz 1995; Słaby and Kozłowski 2005; Fila *et al.* 1996; Kozłowski *et al.* 1997), silicification in the tectonic zone of Garby Izerskie at the northern contact zone of the Karkonosze granite (Kozłowski and Metz 2004), multistage vein crystallization in Izera gneisses (Kozłowski and Marci-



Text-fig. 3. Native gold found on quartz and its surface polished and etched with aqua regia, revealing cluster of crystals, Cicha Równia, Karkonosze pluton



Text-fig. 4. BSE image of native gold specimen shown in Text-fig. 3, Cicha Równia, Karkonosze pluton, Cicha Równia, Karkonosze pluton

nowska 2004), the formation of rock crystal from Jegłowa in East Sudetes (Karwowski and Kozłowski 1975) and beryl from both Karkonosze and Columbia (Kozłowski *et al.* 1986, 1988).

Melt inclusions in quartz

The magmatic stage of the Karkonosze granitoid was investigated by means of melt inclusion studies. The appropriate inclusions were found in euhedral magmatic quartz. The fillings of the inclusions were crystallized to potassium feldspar, plagioclase, quartz, biotite, and a mixture of fine grains of silicates, probably with muscovite; the small volatile bubble was deformed (flattened). On heating the inclusion fillings melted and then homogenized at temperature between 825 and 920ºC; these values may be attributed to the early stage of magma crystallization, when the quartz crystals selected for the study formed (Kozłowski 2007).

Rock-forming quartz

Insights into the composition of fluids in the whole pluton were obtained by analyses of fluids in secondary inclusions in rock-forming quartz of the granitoid. The investigation of 552 samples (years of collection 1968–1999) at 229 collection sites (Text-fig. 2), each containing 2 or 3 samples, yielded data on total concentrations of salts in fluids (usually ≤15 wt. %) and contents of K, Ca, Mg, Fe, Li, S, F, B, CO_2 and CH_4. In these fluids NaCl is the main dissolved salt, KCl also occurs, but with concentrations usually lower than 1 wt. %; Ca, Mg and Fe are common, however, their concentrations are low. The solutions are distinctly Li-bearing, B is common, but in low though variable concentrations. CO_2 is common, however, in scarce amounts and methane occurs exceptionally. Anions other than Cl^- are subordinate; distinct solution changes appear close to the pluton contacts and along some dislocations.

Post-magmatic activity

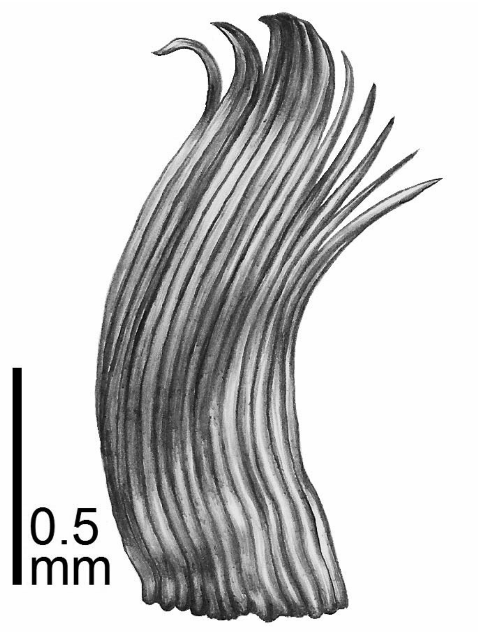
The evolution of the post-magmatic fluids in the Karkonosze pluton have been investigated even more thoroughly in pegmatitic and vein quartz. The samples in this study were collected from 26 pegmatitic bodies and 33 veins in the Polish part of the pluton. The size of the sampled pegmatitic nests ranged from several centimeters to 1 meter, and the vein thicknesses ranged from 0.5 cm to ca. 85 cm. The veins formed in open fractures as well as by metasomatism of the wall rock along a thin crack, and the vein quartz was mostly milky to pale gray, rarely with amethyst zones (e.g., from Szklarska Poręba–Marysin). In the pegmatites the oldest quartz was dark gray and opaque, then covered by morion, next by smoky quartz, rock crystal and pale amethyst.

In the pegmatitic quartz both primary and secondary inclusions were studied. Gray quartz contained primary inclusions from less than 1 to 100 µm long and 8 to 10 generations of secondary inclusions. Usually secondary inclusions in the older parts of the crystals had their equivalent primary inclusions in the younger growth zones. The primary inclusions yielded data on the growth conditions of the appropriate host crystal zones. The earliest inclusions were filled by low-density fluid, that homogenized to a gas phase at 560 to 410°C. Dissolved salt concentrations were difficult to determine, and the freezing data yielded only approximate values of 3 to 5 wt. % in the liquid phase (hereafter of NaCl equivalent, if not stated otherwise) for the inclusions of Th 560–490°C, 4–6 wt. % for 490-440°C and 6–7 wt. % for 440–410°C. These data may be the basis of a rough estimate of total salt concentration in the gaseous fluids at the given temperatures as tenths to ca. 3 wt. %. The concentrations of CO_2 determined by means of microreactions (Krogh 1911; Roedder 1970) in individual inclusions ranged from 3 to 11%; the remainder was aqueous vapor. The inclusions of the next generation in gray quartz homogenized to a liquid phase at 410–320°C; the solutions had total salt concentrations from 3 to 14 wt. %, and NaCl was the main dissolved component with a decreasing content of KCl and increasing $CaCl_2$. The morion zone that crystallized on gray quartz had inclusions of Th 350 to 260°C; it changed gradually to smoky quartz with primary inclusions with Th decrease to 190°C. Solutions in inclusions had concentrations up to 30 wt. % at ca. 300°C, when a high participation of $CaCl_2$ was found, even 18 wt. % in inclusion solution. This compound concentration decreased at ca. 200°C, as well as that of the total salt. Primary inclusions in rock crystal had Th from 230 to less than 100°C, and the inclusion solution concentration decrease from 16 to 4 wt. %. This was accompanied by a distinct decrease of the $CaCl_2$ content, especially at temperature below 160°C; the NaCl concentration was almost stable, but at ca. 180°C almost 10% of the total salts dissolved was KCl. Pale amethyst was the last quartz growth zone in some pegmatites. It contained fluid inclusions of Th 160-90°C and dissolved salts similar to those in inclusions in rock crystal, with, however, the distinct presence of the carbonate ion. In the temperature interval 410-130°C several small-scale events of existence of the gaseous fluid was stated due to finding of the inclusions, homogenizing in the gas phase.

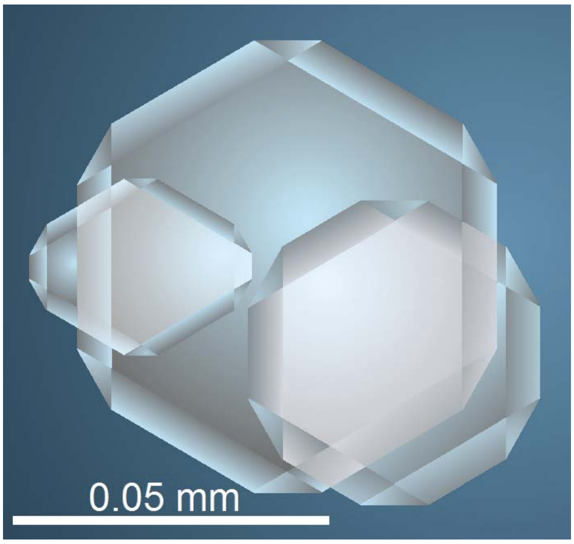
Vein quartz contained inclusions that had Th from 400 to 110°C and were filled mainly by liquid solutions. The episodes of gaseous solution were short and local, most probably caused by formation of cracks and fractures in the wall rock and in the vein itself. Concentrations of the hydrothermal fluids at Th 400-340°C increased from 3 to 11 wt. %, then a concentration increase to ca. 25 wt. % was found, followed by a decrease to ca. 10 wt. % at 220°C. At temperature 220–130°C the total salt concentrations were in the range 14–8 wt. %, decreasing even to 2 wt. % at 130–120°C. The early solutions were of the K-Na type, changing gradually to the Na-type at ca. 330°C. Later inflow of Ca was distinct, with the Na:Ca ratio as high as 1 at 180–160°C. The late stage of vein quartz formation was characterized by sodic solutions with one or two short episodes of potassium ion inflow. Chloride ion was the main anion; however, the presence of the carbonate ion was quite common, found in ca. 40% of the studied inclusions with the latter temperature interval. Though CO_2 was found in gas phase frequently, two intervals of methane presence (220–210 and 180–170°C) were noted. The presented evolution of the post-magmatic fluids in the Karkonosze pluton was pertinent to all the studied pegmatites and veins.

New occurrences of Ag, Bi minerals and studies of accessories

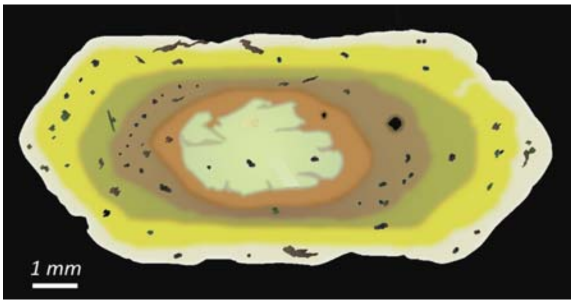
New localities of a number of minerals have also been found – such as native silver (Text-fig. 5) and its compounds: acanthite, paramorphs of acanthite after argentite, matildite, stromeyerite (Text-fig. 6), proustite and chlorargyrite. Chemical analyses of these minerals (trace elements in native silver inclusively) were made, as well as fluid inclusion studies in paragenetic quartz. Moreover, 15 oxygenic minerals of bismuth were indentified, most of them until the present not known from the Karkonosze pluton. The group includes bismite, sillénite, kusachiite, russellite, koechlinite, bismoclite, bismutite, beyerite, kettnerite, ximengite (Text-fig. 7), pucherite, walpurgite, schumacherite, namibite and eulytite. All these minerals were analysed chemically and by the X-ray method, and documented by thorough drawings and SEM images. Homogenization temperatures of fluid inclusions pertinent to crystallization of native silver, investigated in paragenetic quartz, yielded values of 90 to 137°C and pressure not exceeding 0.5 kbar. The parent liquid solution had total salt concentration 3.0–5.2 wt.% and NaCl as the main dissolved component plus low amounts of Ca and carbonate (hydrocarbonate) ions. Other silver minerals formed in two temperature ranges: the lower one (proustite 73–77°C, stromeyerite 96–130°C, acanthite 117–125°C) and the higher one (argentite 224–240°C and matildite 225–231°C). Solution composition and concentrations, and pressure values were similar to those given here for native silver. Chlorargyrite formed



Text-fig. 5. Native silver, Łomnickie Rozdroże, Karkonosze pluton



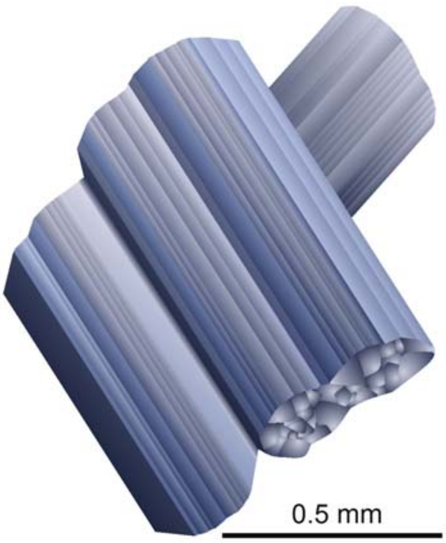
Text-fig. 7. Ximengite crystals, Szklarska Poręba Huta quarry, Karkonosze pluton



Text-fig. 8. Zoned grain of clinozoisite-allanite-epidote, Michałowice quarry, Karkonosze pluton

apparently under supergene conditions or from very low-temperature solutions evolved from post-magmatic fluids. The oxygenic bismuth minerals are mostly of supergene origin however, except for eulytite and ximengite, where the temperature of crystallization could even have been close to 50°C.

Moreover, although preliminary studies of allanite from the Karkonosze pluton were published (e.g., Kozłowski and Metz 1994), new specimens were found and are now under investigation (Text-fig. 8). Additional



Text-fig. 6. Stromeyerite, Hutniczy Ridge, Karkonosze pluton

aspect of this mineral study was presented for specimens from Spitsbergen (Smulikowski and Kozłowski 1994). One may include here the investigation of gadolinite from the Michałowice pegmatite (Kozłowski and Dzierżanowski 2007).

Nb-Ta-REE mineral assemblages from pegmatites in the Karkonosze pluton

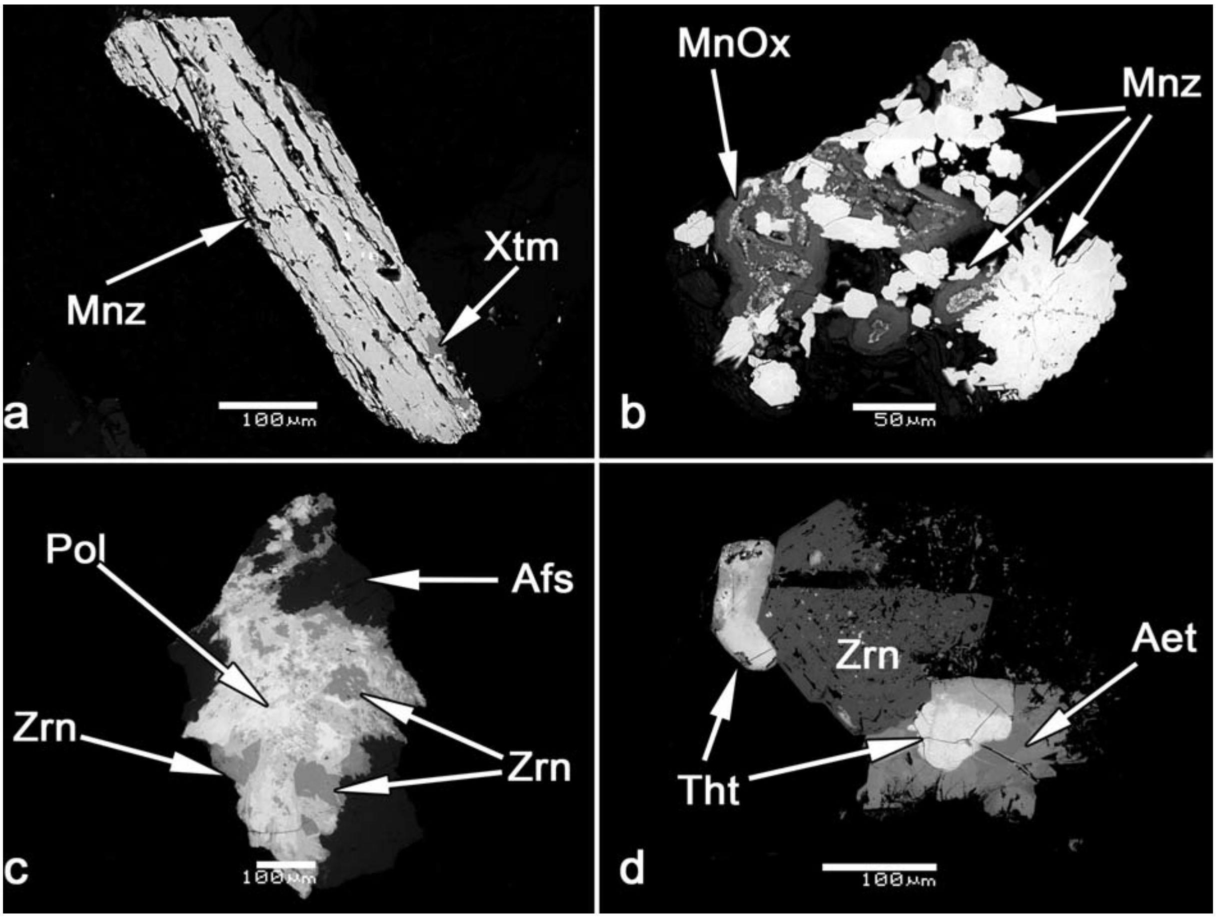
Recent advancements in the study of Karkonosze pegmatites carried out in the Institute of Geochemistry, Mineralogy and Petrology has permitted the description of more than 15 minerals containing significant amounts of niobium, tantalum and rare earth elements. An interesting study of was performed by Matyszczak (2007, 2008). Pegmatites located mostly in the NE part of thepluton were examined and also single bodies situated in the middle part of the pluton, to the W from the Szklarska Poręba, were the subject of investigation (Text-fig. 2). Based on accessory minerals, as well as on contemporary knowledge of the Karkonosze pegmatites (Sachanbiński 2005; Kozłowski and Sachanbiński 2007 and references therein, Aleksandrowski *et al.* 2013) the bodies were classified as NYF (niobium, yttrium, fluorine) family pegmatites (Černý and Ercit 2005), with, however, very low contents of fluorine.

Based only on the chemical composition determined by means of electron microprobe, the following accessory minerals have been identified: aeschynite-(Y), nioboaeschynite-(Ce), polycrase-(Y), fergusonite-(Y), minerals with compositions of the pyrochlore subgroup, microlite, uranobetafite, liandratite, cerianite-(Ce), monazite group minerals, xenotime-(Y), xenotime-chernovite and xenotime-thorite solid solutions, and allanite-(Ce).

Monazite group minerals

The monazite group minerals are rather common accessory minerals, although there are pegmatites in which only single or even no crystals were found. Monazite-(Ce), monazite-(Nd) and cheralite have been identified. They occur in many morphological variations, but based on morphological, textural and chemical features they were divided into two varieties: early and late (probably hydrothermal).

Early variety of monazite (Text-fig. 9a) occurs as relatively large single crystals, up to 0.8 mm in size, but sometimes as very small inclusions in biotite up to several dozen μm long. The grains are often cracked or porous and sometimes with zonal textures. Generally they are well chemically preserved (absence of non-formula elements such Al or Fe) and analytical totals vary mostly around 100%. Although early monazite is monazite-(Ce), crystals of this variety which formed later than the others have increased amounts of Nd, up to about 22 wt. % Nd_2O_3. It is worth mentioning that this is one of the highest contents of Nd_2O_3 in monazite-(Ce) presented in the literature (Förster 1998). Even the monazite-(Nd) described by Matyszczak (2013) has a lower



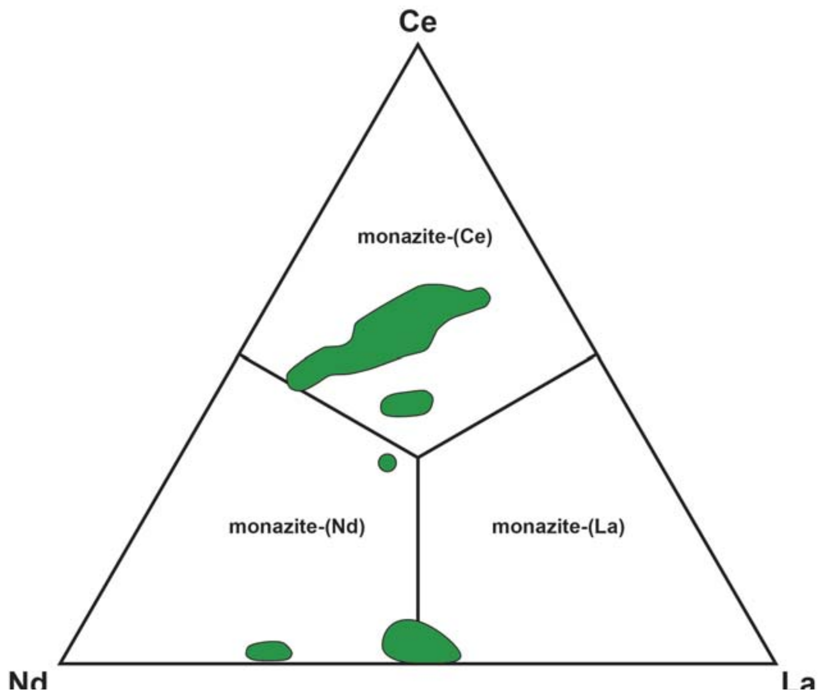
Text-fig. 9. BSE images of minerals from the monazite group, aeschynite-(Y) and polycrase-(Y): a – primary (early) monazite-(Ce) from the Königstein pegmatite; b – late monazite-(Nd) together with manganese oxides from Karpniki #4 pegmatite; c – irregular intergrowth of polycrase-(Y) in K-feldspar from Grodna #1 pegmatite; d – aeschynite-(Y) in paragenesis with zircon and thorite from the Kulisty Ł pegmatite. Xtm – xenotime-(Y), Mnz – monacite-(Ce), MnOx – manganese oxides, Afs – K-feldspar, Pol – polycrase-(Y), Zrn – zircon; Tht – thorite; Aet – aeschynite-(Y). For pegmatite location see Text-fig. 1. See text for details content of Nd_2O_3. Only the Alpine monazite-(Nd) has a higher amount of this element (Greaser and Schwander 1987; Demartin *et al.* 1991). As a result, their projection in the ternary diagram for monazite falls close to the monazite-(Nd) – monazite-(Ce) sideline (Text-fig. 10). Based on the xenotime-monazite geothermometer (Pyle *et al.* 2001) the lower temperature limit formation of this variety was estimated as above 500°C.

The late variety of monazite group minerals is represented by monazite-(Ce), monazite-(Nd) and cheralite. It occurs usually as fine acicular crystals forming massive clusters (intergrowths). An exception to this is monazite-(Nd) from the pegmatite Karpniki #3 and Karpniki #4 where it forms relatively large (up to 50 μm) crystals (pseudomorphic after rhabdophane?, Text-fig. 9b). A late variety of monazite is chemically heterogeneous compared to the early variety in being enriched in Ca, Al or Fe and depleted in Th and U (with the exception of cheralite). The analytical total of this variety rarely exceeds 94%, which is probably due to a very fine grained intergrown phase, porosity, increased electron beam susceptibility, partial cerium oxidation from Ce^{3+} to Ce^{4+} and hydration, a common process related to metamictisation. Minerals of this variety are often replaced by cerianite, and they themselves often replace earlier monazite-(Ce), xenotime and possibly rhabdophane. Based on the xenotime-monazite geothermometer an approximate upper temperature formation of this variety of 300–400°C was estimated. Some minerals of this group occur together with manganese oxide, which presumably indicates especially low temperature conditions of formation (Text-fig. 9b).

Minerals of the aeschynite and euxenite groups

Based on the canonical discrimination proposed by Ewing (1976) and developed by Ercit (2005), aeschynite-(Y), nioboaeschynite-(Ce) from the aeschynite group and polycrase-(Y) from euxenite group minerals were identified. Minerals of these groups are seldom accessory phases in the Karkonosze pegmatites. Their presence was recently reported by Matyszczak (2012a, 2012b). With the exception of the Grodna #1 pegmatite, where polycrase-(Y) is the main Nb-Ta-Ti mineral, single grains of this mineral were found in four other examined localities. Special attention should be paid to the Borowice #1 pegmatite, in which only one grain of nioboaeschynite-(Ce) was found. Minerals of the aeschynite and euxenite groups usually form grains or intergrowths of irregular habit, up to 400 μm in size. They are always altered to various degrees which is clearly visible on the BSE images (Text-fig. 9c). Unaltered grains occur exceptionally rarely (Text-fig. 9d).

The aeschynite group seems to be the most diverse in terms of chemical composition. The A-site in minerals of this group is occupied mainly by Y+HREE in the case of aeschynite-(Y), whilst nioboaeschynite-(Ce) is enriched in LREE and Ca. In the case of the B-site the situation is similar: analyses fall close to the Ti and Nb



Text-fig. 10. Composition of monazite in Ce-La-Nd system from the investigated Karkonosze pegmatites corners of the ternary diagram (Text-fig. 11).Intermediate phases are present as well. They are represented by aeschynite-(Y) enriched in Ca and U+Th in the A-site and Nb and Ta in the B-site.

The euxenite group is more homogeneous. Generally the A-site is predominantly occupied by HREE, whilst the B-site is dominated by Ti, but with a significant contribution of Nb and Ta (Text-fig. 11). The grain from the Rudzianki pegmatite is exceptionally enriched in U+Th and Ta, which causes a shift of its position toward the border of classification on ternary diagram for both sites (Text-fig. 11)

The cation exchange vectors defining solid solutions in both groups are ambiguous and difficult to specify. However, it seems that the dominant exchange directions are close to these given below, and proposed by Škoda and Novák (2007), or their combinations:

(i) $Y\mathit{REE}^{3+} + Ti^{4+} \leftrightarrow Ca^{2+} + (Nb, Ta)^{5+}$

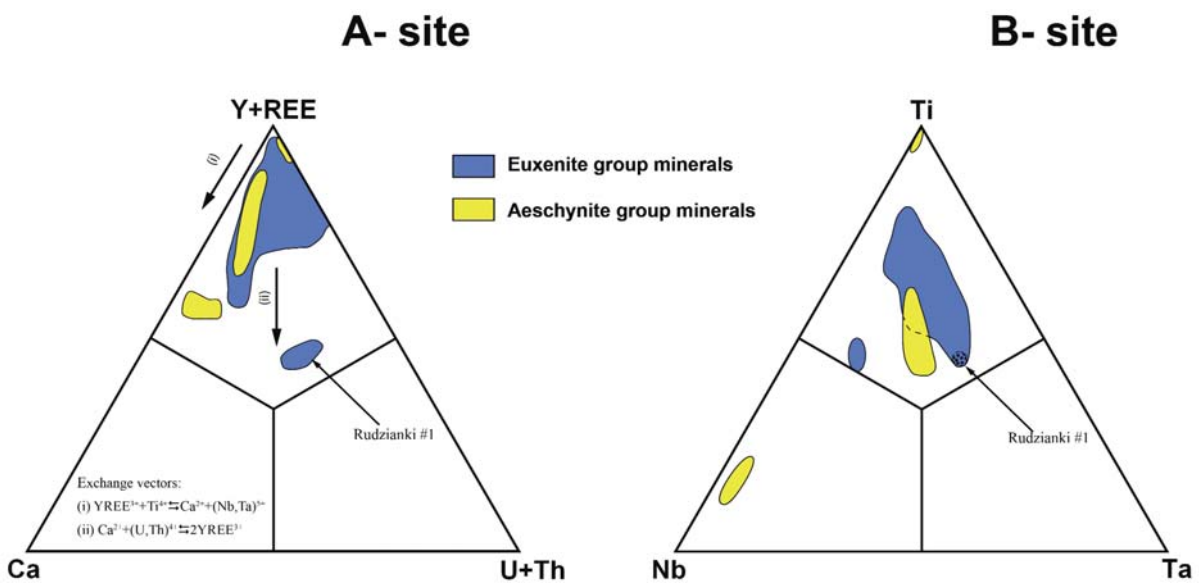
(ii) $Ca^{2+} + (U+Th)^{4+} \leftrightarrow 2Y\mathit{REE}^{3+}$

The studied Karkonosze pegmatites are most often enriched in heavy REE minerals as well as in Nb-Ta-Ti phases. The main carriers of HREE are interchangeably very common fergusonite-(Y) and xenotime-(Y). In places, due to their absence their role is taken over by polycrase-(Y). Light REE minerals, represented mainly by the monazite group, rarely together with allanite-(Ce), are usually common but it seems that their amount is inversely correlated with Nb-Ta-Ti minerals. In two pegmatites, Sosnówka #2 and Königstein, in the absence of Nb-Ta-Ti phases, monazite is the main REE mineral together with allanite-(Ce) and xenotime-(Y), respectively. Primary minerals containing Nb,Ta and Ti as their main components are common in the pegmatite bodies, very often being dominant accessory minerals. The most widespread mineral of this group is fergusonite-(Y), present (in variable amounts) in almost every pegmatite. The other phases – minerals of the aeschynite and euxenite or columbite group – play a very subordinate role, with the previously mentioned exception of the Grodna#1 pegmatite.

Fergusonite and other Nb-Ta-Ti phases are to various degrees altered. The products of their alteration are phases with the composition of the pyrochlore group and liadratite.

GRANITE IMPACT ON THE COVER ROCKS: AMPHIBOLITES FROM THE CONTACT ZONE

The thermal influence of the Karkonosze granite was studied along the northern border of the pluton in the hornfelsed schist belt of the Szklarska Poręba and in the south-eastern section of the contact zone in the Sowia Dolina (the Owl Valley), both belonging to the Izera-Kowary unit (Text-figs 1, 2). The research focused on the mineral composition of amphibolites affected by the pluton and on the record of metamorphic conditions. Nevertheless, the abundance of metabasic rocks in the Karkonosze-Izera massif allowed for comparisons to be made between the thermally affected rocks and their counterparts located at distance from the intrusion, thus stimulating a detailed study of their chemical features, origin and paleotectonic significance.



Text-fig. 11. A- and B-site cation occupancy for aeschynite and euxenite groups minerals. Arrows indicate main substitution vectors

Origin of protoliths to the amphibolites

Mafic bodies present in the Karkonosze-Izera massif were commonly metamorphosed during the Variscan orogeny, which resulted from collisional events related to the closure of the Rheic oceanic domains and seaways located between the parts of the Armorican archipelago (e.g., Aleksandrowski and Mazur 2002; Winchester and PACE 2002). Despite the variable degree of metamorphic and tectonic involvement, their primary geochemical features are still discernible and contributed to the reconstruction of the geotectonic position of the constituent units of the Karkonosze-Izera massif prior to the onset of the Variscan metamorphism. Metabasites of the Leszczyniec unit dated at ca. 500 Ma (Oliver *et al.* 1993) have a typical N-type MORB affinity (Text-fig. 12; e.g., Kryza *et al.* 1995; Winchester *et al.* 1995). They were associated with an extensional setting and are considered a part of obducted oceanic floor (Mazur and Aleksandrowski 2001). Dated at ca. 500 Ma mafic and felsic volcanics of the South Karkonosze unit (Bendl and Patočka 1995), embedded in a succession of Ordovician–Devonian metasediments, display the more variable geochemical characteristics of within-plate affinity, ranging from that of OIB- to P-MORB type (Text-fig. 12). They are interpreted as rocks formed prior to early sea-floor spreading in a propagating intracontitnental rift of Cambro-Ordovician to Silurian age (Patočka *et al.* 2000).

Given that diversity, the amphibolites of the Izera-Kowary unit are quite homogeneous in their geochemical characteristics. Although the unit is now dismembered by the Karkonosze granite (Text-fig. 1), metabasites from its northern part (i.e. the Izera complex, including the Szklarska Poręba belt) and from its south-eastern part are a coherent series of rocks compositionally equivalent to mildly alkaline, transitional-to-tholeiitic basalts and have OIB-like trace element patterns, with enrichment in HFSE, LREE and depletion in HREE. Unlike the mafic metavolcanics in adjacent units, the rocks did not display typical N-MORB features. Moreover, amphibolites from the contact zones show a consistent and limited variation in their chemical composition (Text-fig. 12). As a matter of fact, it is even more limited than that of the other metabasites from the unit, thus attesting to the lack of substantial disturbance of their original or near-original magmatic elemental relationships during thermal activity of the Karkonosze pluton.

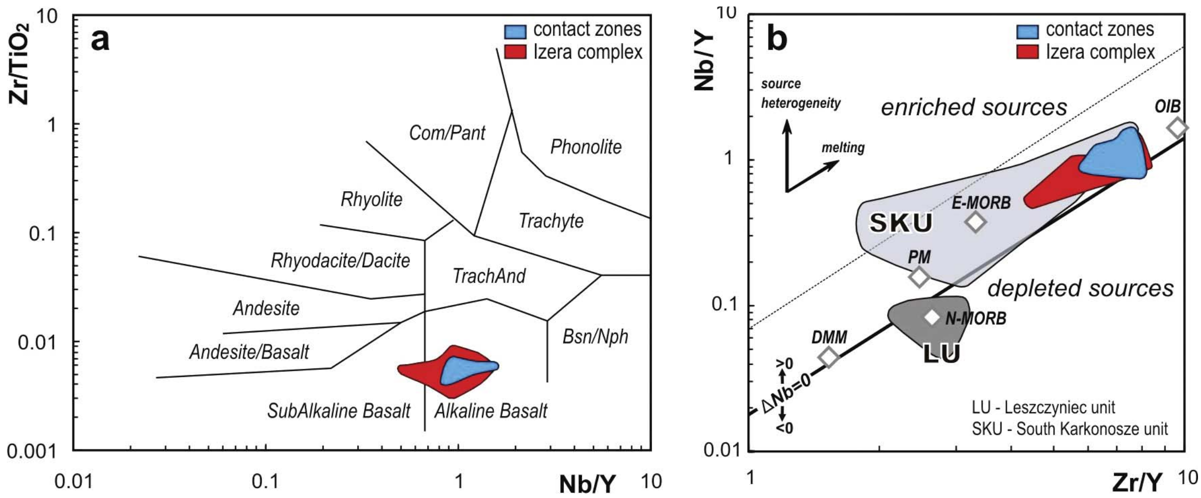
Geochemical parameters and trace element modelling suggest that the mafic magmas were formed due to variable degrees of partial melting (3–5%) of fertile, enriched (i.e. undepleted) garnet-bearing (7–8%) sublithospheric (asthenospheric) source. The observed chemical differences between the amphibolites from the contact zones and the metabasites of the Izera complex are attributable to the increasing degrees of partial melting (Text-fig. 12) which presumably involved more heterogeneous asthenosphere in the case of the latter. Despite these differences, all show systematic enrichment intrinsic to OIB-like sources, i.e., ΔNb>0 (Text-fig. 12).

Interestingly, in terms of geochemical characteristics, both the protoliths to metabasites from the South Karkonosze unit and the Izera-Kowary unit have positive ΔNb values, thus signalling derivation of melts from similar, enriched mantle sources. Although this does not corroborate a mutual spatial proximity at the time of the formation of the melts and protoliths, it does, however, indicate some geochemical affinity.

The amphibolites appear to have formed in a single tectonic setting and show chemical compositions most similar to that of modern magmas generated in an extensional setting (e.g., intra-continental rift). Furthermore, the lack of voluminous intra-plate mafic magmatism in the study area, the inferred characteristics of the mantle sources and estimated potential temperatures 1420–1550°C (slightly higher than those of an ambient mantle) suggest a lithosphere extension-controlled passive rift system accompanied by progressive decompression melting at gradually shallower levels rather than activity of an upwelling deep-mantle plume (Ilnicki 2012).

In the regional context, the origin of the amphibolite protolith introduces another facet of the the Early Palaeozoic event of Gondwana fragmentation – the generation of OIB-like magmas from fertile asthenospheric sources beneath extending continental crust. Yet, as indicated by the geochemical character of the amphibolites and of mafic dykes exposed in the northern part (the Izera complex; Ilnicki 2010) or in the eastern part of the Karkonosze-Izera massif, (western province of Winchester *et al.* 1995), locally the rifting process must have ceased earlier (immature rift). In contrast, the South Karkonosze and the Leszczyniec units document a more advanced extension, with the opening of a seaway from E to W (in recent co-ordinates) – and even generation of oceanic lithosphere (Kryza *et al.* 1995; Kachlík and Patočka 1998a, Crowley *et al.* 2000; Patočka and Smulikowski 2000; Patočka *et al.* 2000; Patočka and Pin 2005).

The age of the protoliths for the amphibolites in the contact zones is unknown. However, recent geochronological dating of quartzofeldspathic rocks from the SE part of the Izera-Kowary unit yielded an age of 498 ± 9 Ma (Oberc-Dziedzic *et al.* 2010). These rocks are associated with the amphibolites and were together inter-



Text-fig. 12. Chemical variation of amphibolites from the northern and south-eastern contact zones of the Karkonosze granite compared to metabasite rocks from the Izera complex and other parts of the Karkonosze-Izera massif. a. The Nb/Y versus Zr/TiO_2 diagram (after Winchester and Floyd 1977). Metabasite data from Ilnicki (2003, 2010, 2012). b. Nb/Y versus Zr/Y diagram. Parallel lines mark the limits of the Iceland array and the ΔNb=0 line separating enriched (E-MORB, OIB) from depleted (N-MORB) sources (after Fitton 2007). Vectors are from Escuder Viruete *et al.* (2009). Sources of data: the Leszczyniec unit – Kryza *et al.* (1995), the South Karkonosze unit – Patočka *et al.* (2000), Patočka and Smulikowski (2000), the Izera complex – Ilnicki (2010). See text for details

preted as a bimodal volcanic suite hosted by mica schists (Oberc-Dziedzic *et al.* 2010). Hence, the age of these amphibolites may be conjectured as Early Palaeozoic (early Ordovician), correlating with a significant and protracted (ca. 515–470 Ma) thermal event in the Izera-Kowary unit (Żelaźniewicz *et al.* 2009) represented by the Izera granites and, presumably, subsequent bimodal volcanic suites (Floyd *et al.* 2000; Oberc-Dziedzic *et al.* 2005; Pin *et al.* 2007). However, Nowak *et al.* (2011) reported much younger zircon ages of some metagabbros from the Izera complex (ca. 390–365 Ma, peaking at ~370 Ma) and proposed a different paleotectonic pattern of their genesis. The interpretation of Nowak *et al.* (2011) is at variance with previous local and regional interpretations (e.g., Crowley *et al.* 2000; Dostal *et al.* 2001; Timmerman 2008) and hitherto their ca. 370 Ma episode has not been confirmed by other studies carried out in the West Sudetes or in the NE part of the Bohemian Massif. In any case, the emplacement of the mafic protoliths of the amphibolites must have taken place not later than before the onset of the Variscan metamorphism (late Devonian to early Carboniferous, Maluski and Patočka 1997; Marheine *et al.* 2002; Mazur *et al.* 2006) to account for the observed textures and appearance of their amphibolite-facies mineral assemblages.

Metamorphic record of the amphibolites

In contrast to the geochemical features, metamorphic events have totally obliterated the primary textural characteristics of the protoliths to the amphibolites. A monotonous set of minerals including amphibole (bluish-green, green or colorless), plagioclase, Ti phases (ilmenite, rutile, sphene titanite?), epidote, biotite, chlorite, epidote and quartz have entirely replaced the magmatic phases. In the northern contact zone (the Szklarska Poręba belt) amphibolites developed a pronounced metamorphic foliation with a stretching lineation present. The rocks are fine-grained, granonematoblastic with green or bluish-green amphibole prisms a few tenths of a millimeter long and defining foliation planes. A coarse-grained, sometimes porphyroblastic, randomly textured or weakly foliated variety is also found (Ilnicki 2002). These features are ascribed to the prograde stages of metamorphism and the coeval deformation. Together with the onset of contact metamorphism the amphibolites in the northern zone underwent widespread and substantial changes in their textures. As a result, the prograde foliation is partly obscured due to recrystallization of the amphibole blasts and their often poikiloblastic appearance. It was observed that locally and very close to the granite contact a green pleochroic variety of amphibole is absent and only non-pleochroic monoclinic amphibole appears in the form of randomly oriented prismatic or acicular crystals (Text-fig. 13).

In the south-eastern contact zone amphibolites are most often porphyroblastic with a moderately developed metamorphic foliation and a stretching lineation both outlined by the parallel alignment of smaller amphibole prisms and by the elongation of the granular plagioclase ± quartz mosaic. The microtextural position of some porphyroblasts suggest synkinematic growth. In the

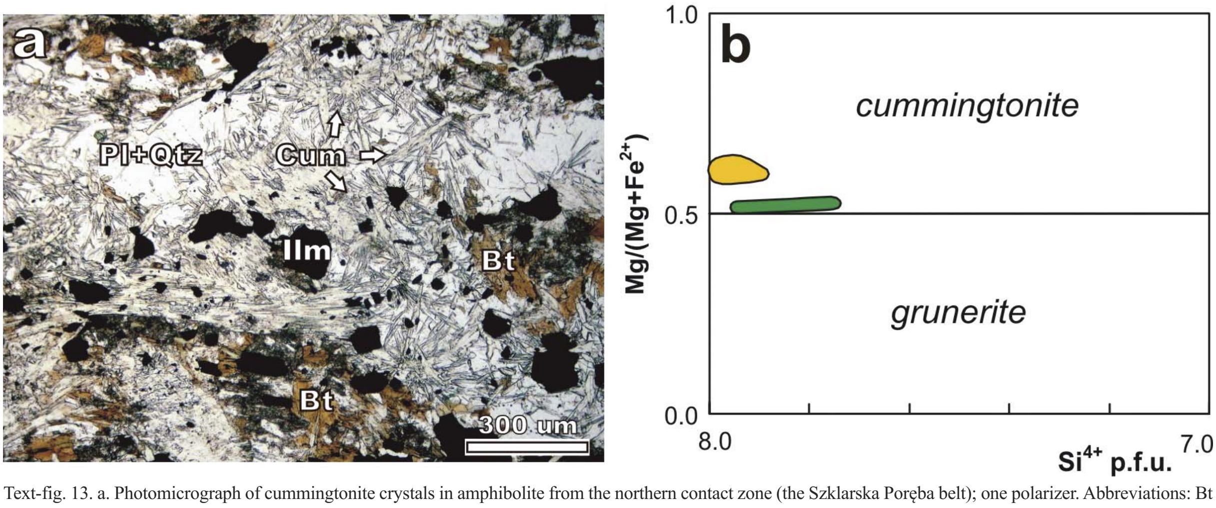
Sowia Dolina a schistose variety of amphibolites is rare and actually a range of transitional textures was noted. In microlithons of some schistose rocks, relics of an earlier foliation (S_1) were recognized (Ilnicki 2011). In rocks near the Karkonosze granite, acicular crystals of amphibole were noted along S_2 planes or in bundles on larger amphibole prisms parallel to the main schistosity. Also colourless blasts of monoclinic amphibole embedded in a groundmass of acicular crystals or small prism of green amphibole were found. As in the northern contact zone, they are most probably of syn- to post-kinematic origin.

The mineral inventory in the studied amphibolites is plain and most substantial changes in chemical composition are pertinent to amphibole and plagioclase. In particular, the compositional variation of the former coupled with its microtextural position was employed to reconstruct qualitatively and quantitatively the metamorphic path.

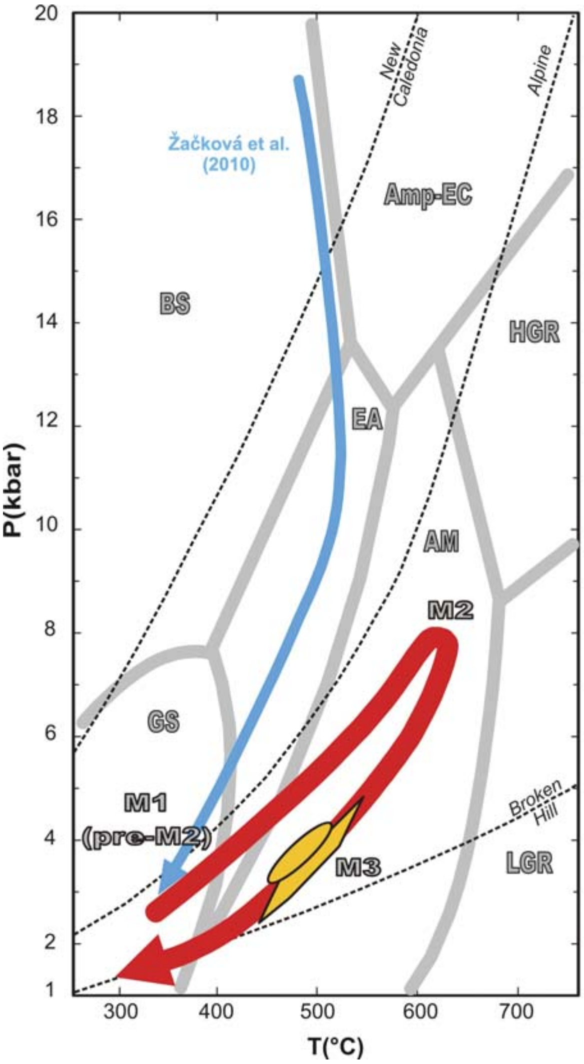
Amphibole crystals are commonly zoned with continuous core-to-rim zonation best expressed is variation of Si^{4+} a.p.f.u., but other mineral-chemical parameters (e.g., Al^{IV} vs. Al^{VI}, Al^{IV} vs $[Na+K]^A$, etc.) express the corresponding and consistent variation trends. In both studied areas prisms defining main foliation planes (S_2 on the regional scale) have tschermakitic or Al-rich magnesio-hornblende cores (6.1–6.9 Si^{4+} a.p.f.u.) and their composition changes to Si-rich magnesio-hornblende or actinolite (6.9–7.8 Si^{4+} a.p.f.u.) rimwards. In the Sowia Dolina, much often than in the northern zone, some relics of prograde amphibole documenting the initial stages of regional metamorphism were found, especially in samples more distant from the Karkonosze pluton. The relics occur in cores of porphyroblasts (actinolite and Mg-hornblende, 7.1–7.7 Si^{4+} a.p.f.u.) or of blasts inside D_1-related microlithons (Mg-hornblende, 6.5–6.7 Si^{4+} a.p.f.u.). Subsequently, these crystals follow rimwards the compositional patterns which are present in younger generation (S_2-related) of amphiboles. In turn, in samples close to the intrusion a colourless, monoclinic amphibole of cummingtonite composition appears (Text-fig. 13). The crystals are Si-rich (7.74–7.95 Si^{4+} a.p.f.u. in the Sowia Dolina, >7.90 Si^{4+} a.p.f.u. in the Szklarska Poręba belt) with no systematic core-to-rim variation.

The second mineral of principal importance in the amphibolites, plagioclase, is calcium-rich and shows a rimward increase of anorthite in zoned blasts. In the northern zone it is bytownite-to-anorthite (An_{80-100}) with occasional relics of oligoclase or andesine. In the Sowia Dolina bytownite ($<An_{89}$) was found only in cummingtonite-bearing samples, whilst in the rest of the samples plagioclase rims have mostly a labradorite composition (An_{48-67}). Exclusively in samples more distant from the pluton plagioclase retained albitic cores surrounded by oligoclase rims (An_{18-30}, Ilnicki 2011).

Out of several mineral assemblages distinguished in the amphibolites, a syn-D_2 paragenesis tschermakite/Mg-hornblende + oligoclase-andesine + epidote + quartz + Ti-phase ± biotite and a subsequent, syn- to post-D_2 paragenesis Mg-hornblende/actinolite ± cummingtonite + labradorite-bytownite + quartz + Ti-phase ± epidote ± biotite ± chlorite are the most common and are essential in the reconstruction of metamorphic conditions. Together with relics of actinolite + albite they define a clockwise P-T trajectory with prograde path from greenschist- to amphibolite facies conditions and retrogression coinciding with the onset of contact metamorphism induced by the emplacement of the Karkonosze pluton. Thermobarometric estimates de-



Text-fig. 13. a. Photomicrograph of cummingtonite crystals in amphibolite from the northern contact zone (the Szklarska Poręba belt); one polarizer. Abbreviations: Bt – biotite, Cum – cummingtonite, Ilm – ilmenite, Qtz – quartz, Pl – plagioclase. b. Chemical composition of cummingtonite from the northern contact zone (Szklarska Poręba belt, yellow field) and the south-eastern contact zone (Sowia Dolina, green field). Mineral data from Ilnicki (2002, 2011) rived from amphibole-based geothermobarometers (Zenk 2001; Gerya *et al.* 1997; Triboulet 1992; and Triboulet *et al.* 1992) indicate metamorphic peak conditions at values not exceeding 610–640°C and 6.9–8.2 kbar followed by the final thermal episode at 450–550°C, 2.5–4.8 kbar (Text-fig. 14). Thus the pair cummingtonite+anorthite or presence of Ca-rich plagioclase with actinolite turn out a useful mineral proxy of the thermal impact of the granitoid body on the amphibolites of its envelope signaling the hornfels-amphibolite facies conditions of LP-HT metamorphism. Indeed, the samples of the studied amphibolites which are the farthest from the pluton are devoid of Ca-rich plagioclase, did not form Mg-hornblede–actinolite rims on tschermakite cores and lack cummingtonite. In turn, thermally affected metabasites from the contact aureole along the southern border of the Karkonosze granite have developed a similar assemblage to those reported here (Klominský *et al.* 2004; Šida and Kachlik 2009).



Text-fig. 14. A generalized tentative pressure-temperature path for the amphibolites with plotted conditions of contact metamorphism inferred from mineral-chemical variation of amphiboles from the south-eastern contact zone in the Sowia Dolina (rectangle; after Ilnicki 2011, modified) and the northern contact zone (ellipse) and compared to that of metapelites from the SE part of the Izera-Kowary unit (Žačková *et al.* 2010, blue arrowed line). Metamorphic facies boundaries after Liou *et al.* (2004): AM – amphibolite, BS – blueschist, EA – epidote-amphibolite, Amp-EC – amphibole-eclogite, GS – greenschist, HGR – high-pressure granulite and LGR – low-pressure granulite facies. Representative geotherms for subduction metamorphism (New Caledonia), convergent continental metamorphism (Alpine) and high-temperature low-pressure metamorphism (Broken Hill) after Vernon and Clarke (2008). See text for discussion

The reconstructed PT trajectory provides interesting implications on the regional scale. Its retrograde segments show an elevated geothermal gradient (ca. 32–45°C/km) which conceivably may illustrate the heat flow induced by the Karkonosze intrusion. And whilst the metamorphic peak conditions reflect an intermediate P/T gradient (ca. 22–25°C/km) corollary to continental collision orogens (Spear 1993), the initial stages correspond to a geothermal gradient of 35°C/km (Ilnicki 2011). This is at variance with the recent report of Žačková *et al.* (2010) on metapelites from the same Izera-Kowary unit as those studied here amphibolites from the Sowia Dolina (south-eastern contact zone) and actually collected within a few kilometer-distance from them. Žačková et al. (2010) argued that the metasediments underwent blueschist facies conditions (≥18–19 kbar at 460–520°C) prior to isothermal decompression (to 10.5–13.5 kbar) and retrogression (<8.5 kbar at <480°C; Text-fig. 11) thus suggesting definitely higher field geotherm (ca. 7–8°C/km) for the prograde path. Taking into account the close proximity of the sampled sites, such a contrast in the assessment of the initial stages of Variscan metamorphism obviously requires further study and debate.

FINAL REMARKS

The extended mineralogical studies carried out by the authors in recent years substantially contribute to the widening of the state of knowledge about the granitic intrusion of Karkonosze and the related post-magmatic and exocontact processes. There are several genuinely new findings and localities, including those of native silver, six silver-bearing sulphides and sulphosalts or 15 oxygenic Bi minerals hitherto not reported from the pluton. The investigations also increase the inventory of accessory minerals recognized in the Karkonosze pegmatites. More than 15 species of Nb-Ta-REE minerals were identified with fergusonite-(Y) present in almost every pegmatite and subordinate minerals of the aeschynite, euxenite or columbite group. The Karkonosze pegmatites are most often enriched in

HREE, sequestered interchangeably by very common fergusonite-(Y) and xenotime-(Y). In turn, LREE are enclosed in common monazite group minerals and allanite-(Ce), although their amount seems to correlate inversely with that of Nb-Ta-Ti minerals. It should be also noted that in an early generation of monazite-(Ce) an increased amount of Nd (up to about 22 wt.% of Nd_2O_3) was ascertained. To the best of our knowledge, this is one of the highest contents of Nd_2O_3 in monazite-(Ce) hitherto published.

Furthermore, studies of melt inclusions and primary fluid inclusion in quartz have allowed for the reconstruction of the changes in physical and chemical conditions during the magmatic and post-magmatic stages of development of the Karkonosze pluton. The conditions of early stages of magma crystallization were recorded by melt inclusions which yielded temperatures 825–920ºC. It was established that fluids (total salinity up to 15 wt.% NaCl) recognized in the whole of the pluton were Li-bearing with common although low concentrations of B, Ca, Mg and Fe. The inclusions from crystals of quartz formed at the pegmatitic stage (temperatures from 560 to 160-90°C) show that the fluids which crystallized pegmatite minerals had variable total concentrations and the composition of salts. The stage commenced at 560 to 410°C with an increasing salinity of fluids reaching up to 6-7 wt. % and CO_2 content up to 11%. The solutions reached maximum salt concentrations during the morion crystallization stage (up to 30 wt. % ca. at 300°C), asdid the Ca content of the solutions (up to 18 wt. % of $CaCl_2$), otherwise dominated by NaCl with minor and decreasing amount of KCl. The latest batches of pegmatites formed from increasingly diluted fluids with total salinity dropping from 16 to 4 wt. %.

Liquid solutions locked in inclusions from vein quartz showed a corresponding although not identical evolution of the conditions pertinent to the hydrothermal stage (temperatures from 400 to 110°C). Similarly, at first (i.e. above 340°C) the salinity of fluids increased from 3 to 11 wt. % and peaked at 25 wt.%, only then to fall to ca. 10 wt. % at 220°C and remain at moderate values between 8 and 14 wt.%. In the final stages (130-120°C), the solutions became very diluted (down to 2 wt.%). Like the changes in chemical composition of fluids during pegmatite formation, the hydrothermal solutions were gradually impoverished in KCl with an increasing role for NaCl. An influx of Ca-rich liquids was also observed, although at lower temperatures (180–160°C) than in the pegmatites. At lower temperatures the carbonate ion was present in the fluids, but the latest solutions remained Na-rich, episodically supplied by KCl inputs.

The mineralogical and petrological study reported here of amphibolites indicates that the pair cummingtonite + anorthite or the presence of Ca-rich plagioclase with actinolite are reliable mineral proxies for the thermal impact of the granitoid body on the amphibolites of its envelope, signaling the hornfels-amphibolite facies conditions of LP-HT metamorphism. In the case of the northern and south-eastern sections of the contact zone of the Karkonosze pluton it was inferred that the thermal metamorphism was limited to temperatures of 450–550°C at pressures 2.5–4.8 kbar. Hence the retrograde stage of P-T path point to an elevated geothermal gradient (ca. 32–45°C/km) probably reflecting the heat flow induced by the intrusion. Moreover, despite the obvious textural and mineral changes imposed not only by regional metamorphism, but also by the heat released from the intruding granite, the studied amphibolites seem to have their pre-metamorphic (magmatic) geochemical features undisturbed.

The new data presented here blend with the results which in the past few decades were systematically supplied by researchers of the Faculty of Geology, including the first report on Sn-W-Mo mineralization in the northern part of the Karkonosze pluton, metasomatic phenomena inside the pluton (pegmatites) or in adjacent metamorphic areas, a description and documentation of the pegmatite mineral assemblages and gold-bearing veins, and pioneering geochemical studies on feldspars or trace elements in quartz. Despite much effort, the mineralogical and petrological issues concerning the emplacement and activity of the Karkonosze pluton still need study and further clarification. Even taking into account the new findings reported here, there is still a wide open and promising perspective for further, undoubtedly rewarding mineralogical pursuits in the Karkonosze-Izera massif.

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