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ZIRCON U-Pb DATING OF IGNEOUS ROCKS IN THE RADZIMOWICE AND WIELISŁAW ZŁOTORYJSKI AURIFEROUS POLYMETALLIC DEPOSITS, SUDETES, SW POLAND

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Abstract: A rhyolite porphyry in the Radzimowice deposit at Bukowinka Hill has a SHRIMP zircon U-Pb age of 314.9 ± 3.1 Ma. This is consistent with previous zircon dating of a monzogranite and a rhyodacite (ca. 315 Ma) in the Żeleźniak sub-volcanic intrusion (ZI), considered to be the igneous rocks, representing the oldest magmatic pulses in the region. First-stage mesothermal auriferous sulphide mineralization in the deposit was connected to hydrothermal processes, associated with the rhyodacite intrusions. This was followed by tectonic activity and younger alkaline magmatism in a post-collisional geotectonic setting. The first-stage Au-bearing sulphide mineralization was cataclased and overprinted by younger epithermal base-metal sulphides with microscopic Au, associated with Bi-Te-Ag minerals. The younger magmatic pulses are represented by porphyritic andesites and lamprophyric dykes, which cut the ZI. Zircon from these dykes yielded ages of 312.8 ± 2.8 Ma for an andesite porphyry and 312.4 ± 4 Ma for a lamprophyre. All these magmatic pulses, evidenced in the Radzimowice deposit, are considered to be the oldest post-orogenic sub-volcanic magmatism cutting the basement of the intramontane basins in the Sudetes, on the NE margin of the Bohemian Massif. A rhyolite porphyry in the famous "Organy" exposure at Wielisław Złotoryjski (WZ) on the SE margin of the North-Sudetic Basin is younger, 297.5 ± 2.8 Ma. Vein-type auriferous ore mineralization, hosted by Early Palaeozoic graphitic schists in intimate contact with rhyolite porphyry in WZ, is also correlated with this magmatism. The auriferous ore mineralization at Radzimowice and Wielisław Złotoryjski formed at different times, during different magmatic pulses and successive hydrothermal stages, despite several similarities in geologic setting and country- and host-rock compositions. There was a transition from a post-collisional to a within-plate setting over about 20 Ma in Late Carboniferous–Early Permian times, with the older Żeleźniak and Bukowinka sub-volcanic intrusions in the uplifted part of the Kaczawa Metamorphic Complex (ZI) and the younger Wielisław Złotoryjski sub-volcanic intrusion in the metamorphic basement of an intramontane basin.

Key words: zircon, SHRIMP geochronology, gold deposit, porphyries, Variscides, Sudetes.

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INTRODUCTION

There are several abandoned small- and medium-size Au-bearing As-polymetallic deposits in the Sudetes, most of which formed as a result of multiple hydrothermal processes associated with Variscan (Carboniferous–Permian) magmatism (Mikulski, 2001). The Sudetes are part of the Central European province of Late Palaeozoic (Carboniferous–Permian) bimodal volcanism that extends about 400 km from Germany to Poland. This volcanism occurred in intramontane basins and neighbouring crystalline blocks in the eastern parts of the Rheno-Hercynian and Saxo-Thuryngian Zones (Dziedzic, 1996; Awdankiewicz, 1999, 2004; Ulrych *et al.*, 2004; Machowiak *et al.*, 2008). Moreover, in the Saxo-Thuryngian Zone, the successive volcanism caused by silica-rich magmas took place in the early Permian. This widespread post-orogenic volcanic activity was in general preceded by the intrusion of I- and/or S-type granitoids during the Variscan orogeny, mostly in the Carboniferous (ca. 345–300 Ma; Mazur *et al.*, 2007 and references therein). However, the current radiometric data of the authors and other published ages of the granitoids overlap with the volcanic activity (e.g., Awdankiewicz *et al.*, 2014).

The timing of the succession of igneous events of different geochemical characters in the Sudetes and the bimodal volcanism that followed remain the subject of contro-

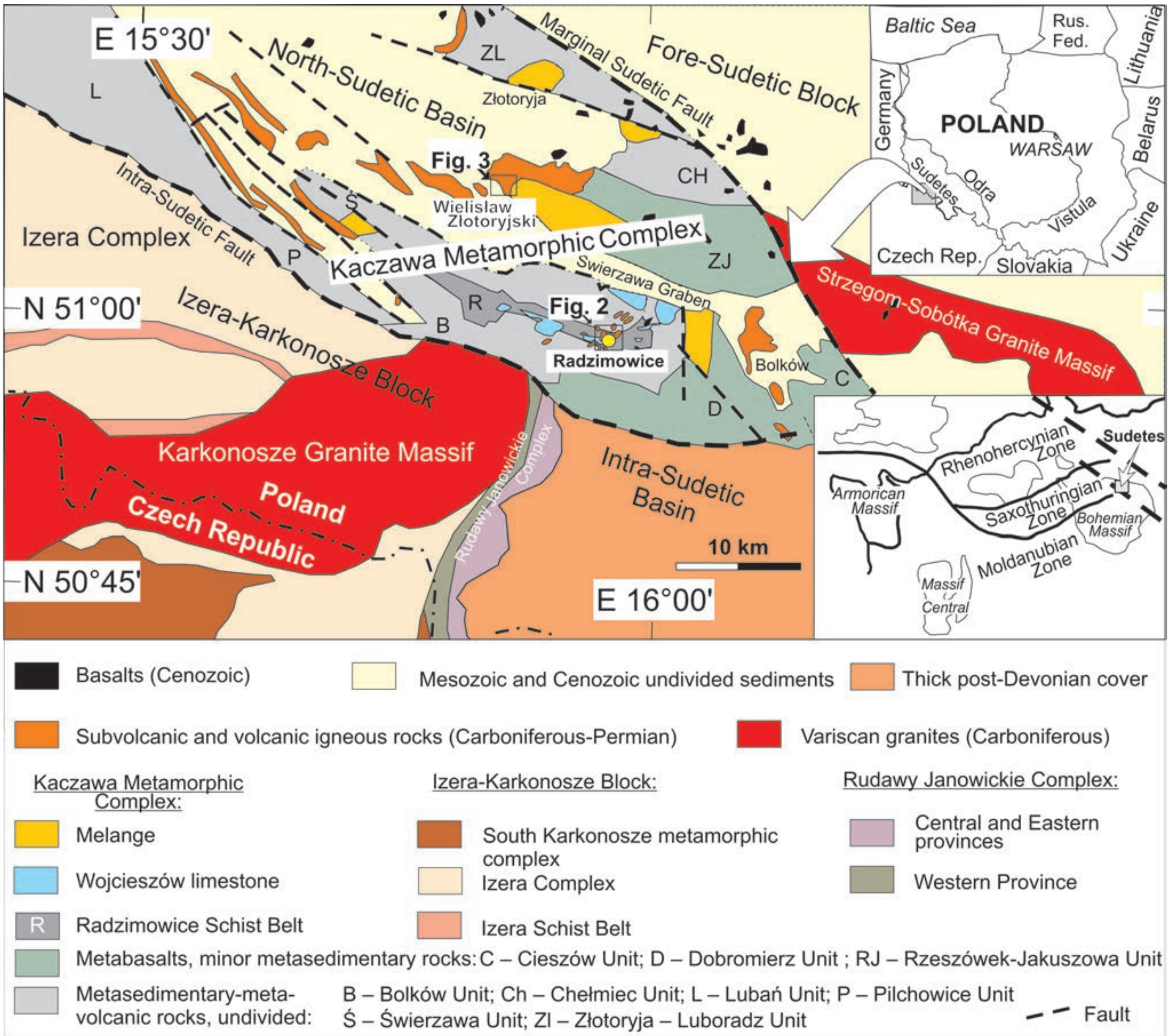

Fig. 1. Tectonic structural subdivisions of the Kaczawa Complex and adjacent geological units (after Jerzmański, 1965; Baranowski *et al.*, 1990; Seston *et al.*, 2000; Cymerman, 2002) showing the distribution of Late Palaeozoic igneous rocks and Cenozoic basalts, and the locations of the Radzimowice and Wielisław Złotoryjski gold deposits. Inset maps show location of the study area in Poland (upper) and in the European Variscan Belt (lower).

versy in many places, owing to the lack of modern geochronology. Auriferous ore mineralization in the Radzimowice Au-As-Cu deposit (Fig. 1) is considered to be transitional between a porphyry- and an epithermal-type deposit around the Carboniferous Żeleźniak porphyry intrusion (ZI), a composite sub-alkaline to alkaline body emplaced in a post-collisional setting (Mikulski, 2005a). The age relationship between the magmatic events and the successive stages of ore mineralization has not been defined precisely. A six-point Re-Os isochron age of 317 ± 17 Ma, obtained for auriferous sulphides (Co-arsenopyrite) in sheeted quartz-veins, for example, represents only the first stage of ore precipitation in the Radzimowice deposit (Mikulski *et al.*, 2005a). The major uncertainty in this estimate is due to the fact that the sulphides contain very little radiogenic Os (Mikulski *et al.*, 2005b). This result is in broad agreement with preliminary SHRIMP zircon U-Pb ages of a fine-grained rhyodacite and a medium-grained granite from the ZI, which date the main magmatic event at about 315 Ma (Muszyński *et al.*, 2002; Machowiak *et al.*, 2008). There are no previous geochronological data for other igneous rocks in the deposit. Preliminary results of SHRIMP zircon dating of sub-volcanic rocks from the Wielisław Złotoryjski area are 293 ± 2 Ma for porphyritic rhyolites and 294 ± 3 Ma for associated flows (Szczepara *et al.*, 2011) and 292.8 ± 2.1 Ma for Wielisławka rhyolites, as indicated in the recent publication of Awdankiewicz *et al.* (2014).

Here, the authors present new SHRIMP zircon U-Pb ages for igneous rocks in the abandoned Au-polymetallic deposits at Radzimowice and Wielisław Złotoryjski. The objective was to define and compare more precisely the sequence of magmatic processes and correlate them with the post-magmatic hydrothermal processes, responsible for the auriferous polymetallic mineralization. The geochemical and petrographic characteristics of the rocks studied also are documented.

GEOLOGICAL SETTING OF THE KACZAWA MOUNTAINS

The Kaczawa Mountains are located in the Sudetes that constitute the north-eastern part of the Bohemian Massif, an exposed part of the eastern European Variscides that includes parts of Poland, the Czech Republic, Austria and Germany (Fig. 1; Franke and Żelaźniewicz, 2000; Kozdrój *et al.*, 2001). The Kaczawa Mountains are separated on the north by the Marginal Sudetic Fault from the Fore-Sudetic Block, and on the south from the Izera-Karkonosze Block by the Intra-Sudetic Fault. Two structural complexes have been distinguished (Teisseyre *et al.*, 1957): 1) a lower basement complex (Kaczawa Metamorphic Complex, KMC), composed of Palaeozoic epimetamorphosed, folded volcanic and sedimentary rocks; and 2) an unconformably overlying upper complex, consisting of unmetamorphosed, weakly deformed Late Carboniferous, Permian, Triassic and Late Cretaceous platform-type sedimentary rocks and volcanics (Kryza and Awdankiewicz, 2012).

The KMC has been divided into thirteen nappe-like tectonic units, most of which consist of various smaller tectonic elements, such as thrust sheets, thrust folds and/or bodies of mélange (Teisseyre, 1963; Haydukiewicz, 1987a, b; Baranowski *et al.*, 1990, 1998; Kryza and Muszyński, 1992; Seston *et al.*, 2000; Cymerman, 2002). The KMC underwent polyphase deformation and metamorphism, ranging from very low-grade to greenschist-facies metamorphism, with peaks during the Mid-Late Devonian and Early Carboniferous (Viséan). Late Carboniferous and Permian extension within the eastern part of the European Variscan Belt (the Central European province) resulted in volcanism, a product of the late- to post-collisional tectonic setting (Awdankiewicz, 1999; Karnkowski, 1999). The location of several volcanic centres and their successive eruptive products in the Sudetes was controlled by fault zones aligned NNW–SSE to NW–SE. Those faults border Hercynian depressions, filled with Early Carboniferous to Early Permian intramontane late- to post-orogenic sediments, accompanied by acidic to intermediate volcanics (Dziedzic, 1996). The molasse deposits and minor volcanic rocks occur mainly in graben structures, such as the North Sudetic Basin, with its eastern part represented by the Świerzawa Graben, and the Intra-Sudetic Basin, which partly developed also on the KMC basement. Two volcanic cycles, each beginning with predominantly trachyandesite and dacite and ending with rhyolite, have been described (Kozłowski and Parachoniak, 1967). The Sudetes, owing to subsequent tectonic movements, underwent basin inversion in the Mesozoic (Oberc, 1972). This was followed by strong Cretaceous–Cenozoic tectonics during the Alpine orogeny and the rocks of the lower complex were exposed (Teisseyre *et al.*, 1957).

GEOLOGICAL SETTING OF THE DEPOSITS

The abandoned Au deposit at Radzimowice is located in the southeastern part of the Kaczawa Mountains and the Wielisław Złotoryjski gold mining area is in the central part of the Kaczawa Foreland (Fig. 1). The Radzimowice deposit and the surrounding rocks form a horst between the North Sudetic Basin to the northwest and the Intra-Sudetic Basin to the southeast. The Wielisław Złotoryjski deposit also occurs in a horst (Świerzawa Horst) that forms the eastern part of the North Sudetic Basin. The Świerzawa Horst is separated from the Jerzmanice Graben to the north by an ENE–WSW-oriented fault, and from the Świerzawa Graben to the south by the NE–SW-trending Sędziszowa Fault (Milewicz and Kozdrój, 1994). In both deposits, auriferous polymetallic-sulphide mineralization in quartz (with and without carbonate) veins is hosted by rocks belonging to two different structural stages, a lower unit, consisting of folded and metamorphosed Variscan basement (Kaczawa Metamorphic Complex – KMC), and an upper unit, comprising Late Carboniferous igneous rocks (Mikulski, 2007). The lower structural stage is composed of Lower (Middle?) Cambrian–Lower Carboniferous assemblages of pelitic flysch with Lower Palaeozoic volcanic interbeds. The rocks have been metamorphosed under greenschist facies conditions and tectonized (Cymerman, 2002), producing quartz-sericite-graphite schists, albitized phyllites with thin intercalations of siliceous and graphitic slates, metagreywackes, quartzites, and greenstones, belonging to different tectonic units (Fig. 1).

The oldest of these units at the Radzimowice deposit are the Radzimowice schists in the south and the Chmielarz schists in the north (Fig. 2). The Radzimowice schists unit formed a rock belt which is up to 2 km wide and extends from the West to the East for a distance of about 17 km. This unit has thickness over 1 km and consists predominantly of mudstones over sandstones. The mode of the primary sediment deposition as the turbidite sequences is consistent with sedimentation in a trench-floor or trench-slope basin setting (Baranowski, 1988). Uncertainty remains as to the tectonic and stratigraphic position of the Radzimowice schists within the KMC sequence (Teisseyre, 1963; Urbanek and Baranowski, 1986; Baranowski *et al.*, 1990; Kryza and Muszyński, 1992; Cymerman, 2002; Tyszka *et al.*, 2008). The Chmielarz schists consist of volcaniclastic sediments of Cambrian or Ordovician age (Kozdrój *et al.*, 2001).

The upper structural stage of the Radzimowice deposit is represented by Carboniferous sub-alkaline and alkaline igneous rock suites and minor granites, forming the Żeleźniak (ZI) and Bukowinka (BI) intrusions. The upper structural unit of the Wielisław Złotoryjski deposit consists of younger (Early Permian) sub-alkaline rhyolites, associated with rhyolitic tuffs (Kozłowski and Parachoniak, 1967). These Permian igneous rock suites of the North-Sudetic Basin represent high-K calc-alkaline magmas, erupted in an extensional, intracontinental, post-collisional setting in the eastern part of the Variscan belt of Europe (Awdankiewicz, 2003). In the Radzimowice area among the intrusive rock bodies the largest is the Żeleźniak intrusion, which has a laccolith shape. The other intrusive rocks form a few

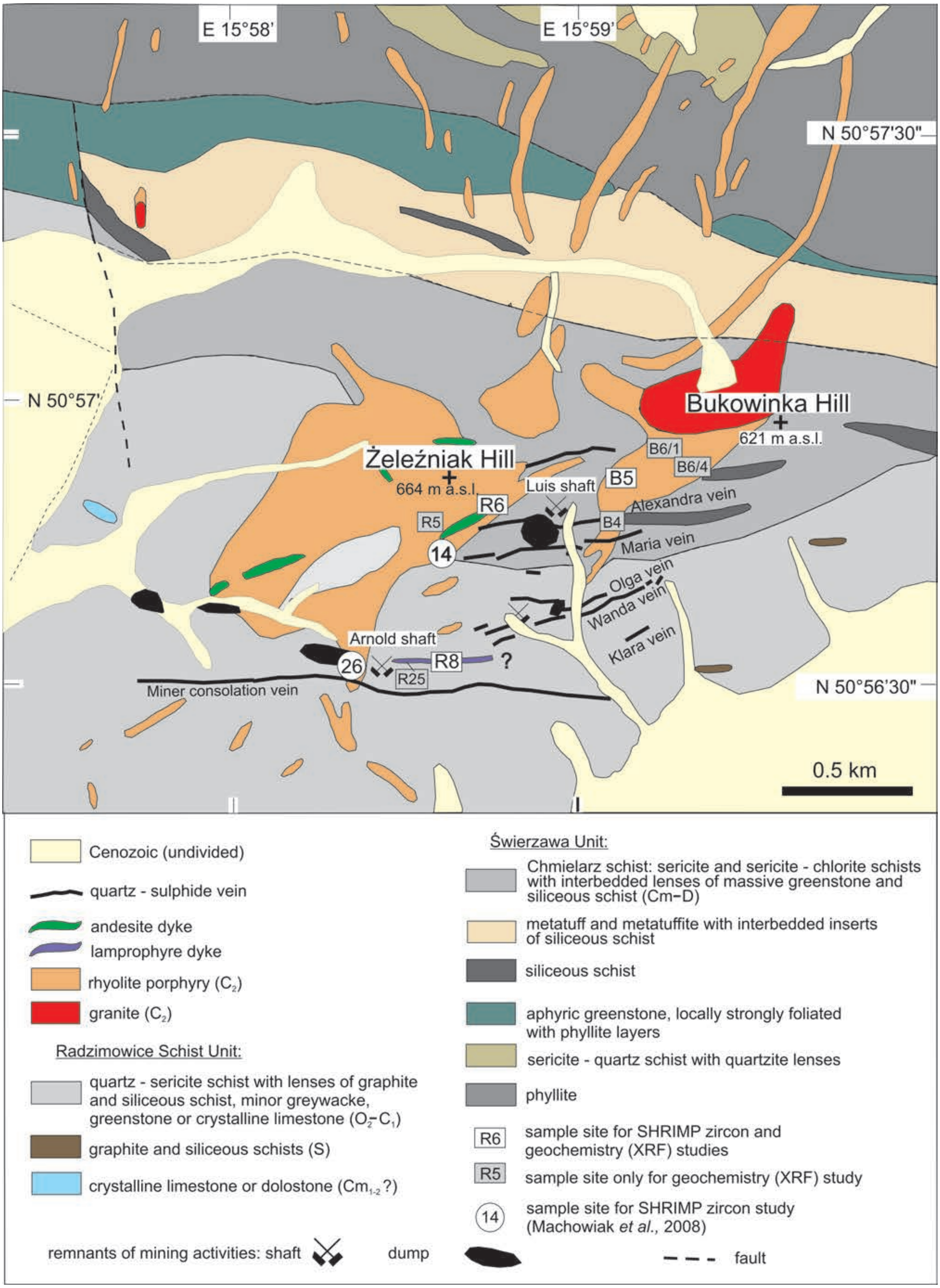

Fig. 2. Location of sampling sites for SHRIMP zircon and geochemical studies on a geological background of area of Au-Cu-As Radzimowice deposit (after Cwojdziński and Kozdrój, 1994). Ore vein locations after Mikulski (2007).

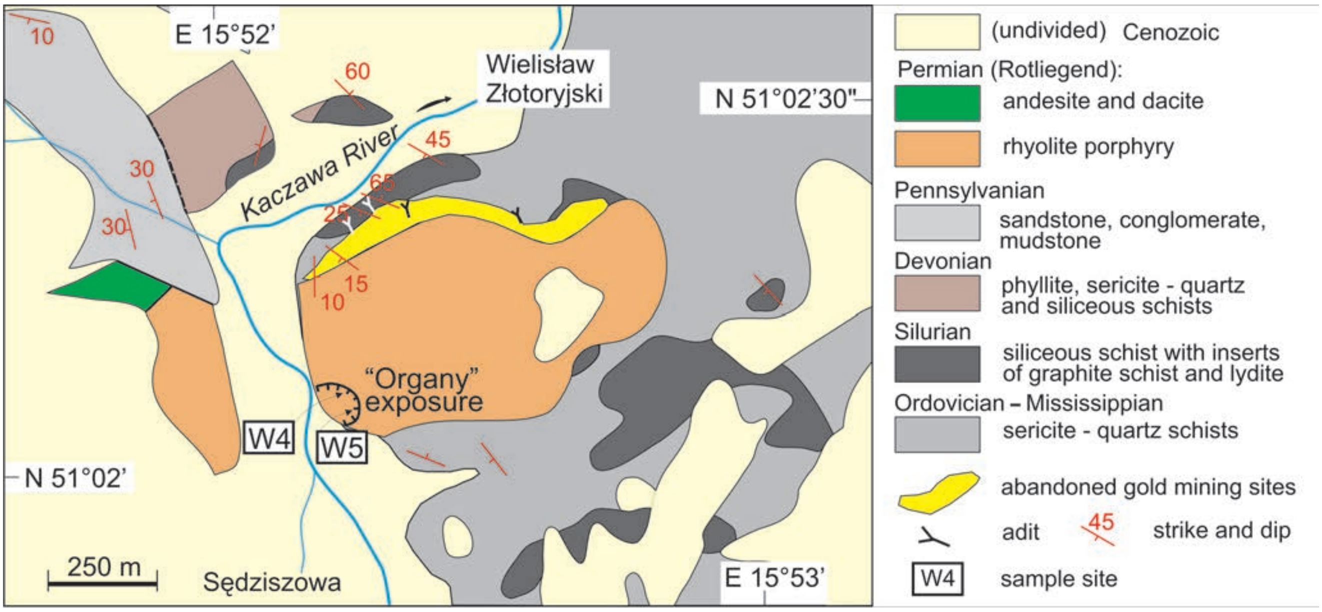

Fig. 3. Location of sampling sites for SHRIMP zircon and geochemical studies on a geological background of abandoned gold mining areas near the "Organy" exposure at Wielisław Złotoryjski, modified after Milewicz and Kozdrój (1994).

smaller bodies and a swarm of dykes and radial apophyses. They are usually discordant to the surrounding bedding and other structures. The Żeleźniak intrusion, is composed of felsic rocks (mostly of rhyolite, dacite and rhyodacite composition) of various textures, containing xenoliths, and cut by mafic and felsic dykes, and quartz veins (Skurzewski, 1984; Kozdrój, 1995; Mikulski, 2005a). The ZI and BI magmas intruded along W–E-oriented faults, but the exact succession is not yet clearly defined. The Żeleźniak intrusion is irregularly shaped. A central body 3–4 km^2 in area is surrounded by several radial rhyodacite dykes (Fig. 2), ranging in thickness from several to hundreds of meters, and in length up to 6–7 km (Cwojdziński and Kozdrój, 1994). Lamprophyric rocks usually have been found in the waste from the southern part of the Radzimowice deposit and they were recorded in unpublished mining reports as diorite porphyry or as kersantite that intruded the Radzimowice Schist (Manecki, 1965; Zimnoch, 1965; Paulo and Salamon, 1974; Mikulski, 2007). The main lamprophyre dyke, with an E–W trend and over 0.5 km in length, was marked on the detailed geological map of the Radzimowice area (Cwojdziński and Kozdrój, 1994). In addition, a few andesite dykes of various strikes and lengths that cut the Żeleźniak intrusion were also recognized and mapped (Fig. 2).

Most rocks in the ZI body are aphanitic, some porphyritic (Skurzewski, 1984). They are strongly altered, as manifest by sericitization of plagioclase and chloritization of biotite. Moreover, these rocks host ore mineralization (Mikulski, 2005a). Emplacement of the ZI post-dates the regional metamorphism (blueschist and subsequent greenschist facies) and the main deformation events in the KMC.

The rhyolites from the Bukowinka intrusion are barren, contain more biotite and have a more uniform equigranular texture. Light grey-pink porphyritic microgranite is present between the quartz-sericite schists and the rhyolite in the northern part of Bukowinka Hill (Majerowicz and Skurzewski, 1987; Cwojdziński and Kozdrój, 1994). Medium- to fine-grained monzogranites, composed of quartz, plagioclase, alkali feldspar, biotite and accessory zircon and apatite, represent the first episode of late-Variscan magmatic activity in the Radzimowice deposit. They are calc-alkaline, peraluminous, and were derived from inhomogeneous crustal sources (Mikulski, 2007). Medium-grained monzogranite and fine-grained rhyodacite from the ZI previously have yielded SHRIMP zircon ages of 316.7 ± 1.6 Ma and 315.0 ± 2.1 Ma, respectively (Machowiak *et al.*, 2008).

Gold mineralization in the Wielisław Złotoryjski deposit occurs in the contact zone between the Palaeozoic metasedimentary rocks of the KMC and the Permian quartz rhyolite porphyry (Fig. 3). The rhyolites from Wielisław Złotoryjski represent part of the Permian volcanic sequence in the second diastrophic-sedimentary cycle of the middle Rotliegende in the North-Sudetic Basin (Milewicz, 1987; Awdankiewicz, 2006). Previous preliminary SHRIMP zircon U-Pb dating of rhyolites and tuff indicated Early Permian ages (Szczepara *et al.*, 2011). The Permian rhyolites, with effusive or sub-volcanic structures, are best exposed in a section 35 m high in the Organy rhyolite quarry, on the southwestern slope of Wielisławka Hill. There flow foliation defines a concentric structure about 100 m wide, the axis of which plunges gently (0–35°) to the NE–E (Awdankiewicz and Szczepara, 2009). The Wielisław Złotoryjski rhyolites possibly represent a gently inclined plug or the inner part of a lava dome (Awdankiewicz, 2006).

The abandoned small-scale mining area is in direct contact with the open-pit quartz porphyry quarry, where there is a famous example of rare columnar jointing in felsic rocks. In the northwestern part of the quarry, the columns plunge at angles of 50–70° NW and in the southern part, they plunge to the SW. Upwards, the dip decreases to 20°. The columns are 20–30 cm in diameter, commonly 4- or 5- sided, and rarely 3- or 6-sided. The rhyolites are associated with grey-brown and greenish rhyolitic tuffs (up to 30–40 cm thick) that were found in some places, but also by breccias with ash. The tuffs were albitized during post-eruptive fluid migration. The tuff breccias consist of numerous fragments of rhyolite, andesite, and minor quartzite and schists from the Palaeozoic basement within a fine-grained felsic matrix (Milewicz and Frąckiewicz, 1988).

GOLD-BEARING ORE MINERALIZATION

The Au-bearing As-polymetallic mineralization of the Radzimowice deposit is in six major sulphide-bearing quartz veins or lodes (with and without carbonate), accompanied by sulphides disseminated in the country rock (Manecki, 1965; Zimnoch, 1965; Paulo and Salamon, 1974; Mikulski, 1999). These lodes trend E–W and dip steadily (60–85°) to the N or S, extending down-dip 0.2–2.1 km, with a thickness of 6 cm to 1.4 m. The economic ore-mineralization is the result of successive hydrothermal stages of ore precipitation. Early quartz with paragenetic Co-arsenopyrite (with and without pyrite mineralization) with refractory Au was cataclased and overprinted by carbonates, associated with base-metal sulphides (chalcopyrite, galena, sphalerite and fahlore), followed by a late association of Te-Bi-Au-Ag minerals and sulphosalts with sub-microscopic Au (Fig. 4A–F; Mikulski, 2007). The sulphide ores form either massive aggregates of various sizes, or veins and disseminations within a gangue, dominated by crystalline white quartz with carbonates. Gold contents in the polymetallic ores vary between veins, ranging from several up to hundreds of ppm (mostly 3–10 ppm Au). The main sources of refractory Au were Co-bearing arsenopyrite and pyrite (about 70 ppm Au and 5 ppm Au, respectively) and microscopic Au-electrum and maldonite. Electrum occurs as inclusions and micro-veinlets, associated with pyrrhotite or chalcopyrite filling fractures in Co-arsenopyrite. Electrum grains (up to 0.5 mm) are also present in quartz fibres or as intergrowths with Te (hessite) and Bi minerals (Mikulski, 2005b, 2014). Metal contents also vary, for example, As 1.0-ca. 20 wt.%, Cu 0.8–8.2 wt.% and Ag 40-ca. 400 ppm. It is estimated that the total production from the Radzimowice deposit in the 19th and 20th centuries was ca. 0.5 Mt of metal ores and ca. 4.2 t of gold (Mikulski, 2007).

The Radzimowice deposit is commonly assumed to be a hydrothermal deposit, strongly associated with late-stage sub-volcanic rhyolite intrusions. Hydrothermal alteration is widespread, especially in the ZI dacite porphyries and in the vicinity of the ore shoots. Strong early acidic and argillitic alteration (sericitization, pyritization, and kaolinitization in vein selvages) was followed by alkalic hydrothermal alteration of propylitic character (illitization and chloritization), with albitization and carbonatization (Manecki, 1965; Mikulski, 2007). The geological setting and ore structures, low Au/Ag ratios, and significant Cu contents in the Radzimowice deposit indicate its formation in a continental setting. The type of mineralization is transitional between porphyry and low sulphidation epithermal (Mikulski, 2005a). Continuous syn-mineralization uplift of the region, containing the deposit, in the Late Carboniferous to Early Permian times resulted in superposition of low sulphidation epithermal mineralization over relics of higher-temperature, deeper-seated mineralization.

At Wielisław Złotoryjski, Au mineralization is present in a few small quartz veins with Au-bearing sulphides hosting by Palaeozoic metasedimentary rocks along the contact with the Permian quartz rhyolite porphyry. There was intermittent, small-scale Au exploration on the northern slopes of Wielisławka Hill in the 16th and 19th centuries (Zöller, 1936). The western area of Au-bearing veins was explored by three adits, penetrating down-dip to only 70 m below the ground surface. Mining activity was very limited. Extraction of Au and Ag has been reported, but the amount of production is unknown.

Sulphide mineralization is present as disseminated impregnations and nests in veins, striking NW–SE, dipping 50–60° to the NE. The host rocks are argillaceous and graphitic schists. The quartz veins contain coarse-grained euhedral pyrite, in association with rare arsenopyrite and base-metal sulphides (chalcopyrite, galena and sphalerite). Gold occurs as inclusions in pyrite, which is present in quartz veins and as impregnations in the schists. The pyrite ore contains an average of about 18 ppm Au. Galena contains about 60 ppm Ag (Zöller, 1936). The argillaceous and graphitic schists are silicified and may contain Au from trace levels up to 0.5 ppm. Single, fine grains of Au are also found in chalcedony fillings in fractured quartz-graphite schists (Mikulski, 2007).

The blistered (porous) rhyolites and volcanic tuffs in the immediate area of Wielisław Złotoryjski are agatiferous. In the Nowy Kościół–Różana–Sokołowiec region, there are numerous agate balls and ellipsoids from 3 to 30 cm diameter. Hydrothermal processes and fluid migration associated with Early Permian volcanism were responsible for precipitation of ore, chalcedony, quartz and iron oxides.

METHODS AND MATERIALS

Samples of igneous rocks (porphyritic andesites, dacites, rhyolites and lamprophyres) were collected for geochronological, geochemical and petrographic study from the Radzimowice deposit and from the "Organy" exposure of rhyolite porphyry at Wielisław Złotoryjski (Figs 2, 3). Major element contents were measured on glass beads at the Polish Geological Institute by wavelength dispersive X-ray fluorescence and minor and trace elements were measured on powder pellets by WDS-XRF, using a PW-2400 Philips, and by digestion ICP-AES. Analytical conditions for major oxides and trace elements were radiation – X-ray tube with Rh anode (3 kW); crystals – LiF 200, PE, Ge, PX1; collimators – 0.15 mm, 0.30 mm; detectors – scintillation counter, flow proportional counter (Ar/CH_4) and Xe-sealed proportional counter. The analyses were plotted on geochemical diagrams along with data from 44 whole-rock major element analyses, compiled from Manecki (1965), Pendias (1965); Skurzewski (1984), Majerowicz and Skurzewski (1987), and Mikulski (2007).

Representative samples of outcropping quartz porphyries and lamprophyre were selected for SHRIMP zircon dating: porphyritic andesite (R6) from the eastern slope of Że-

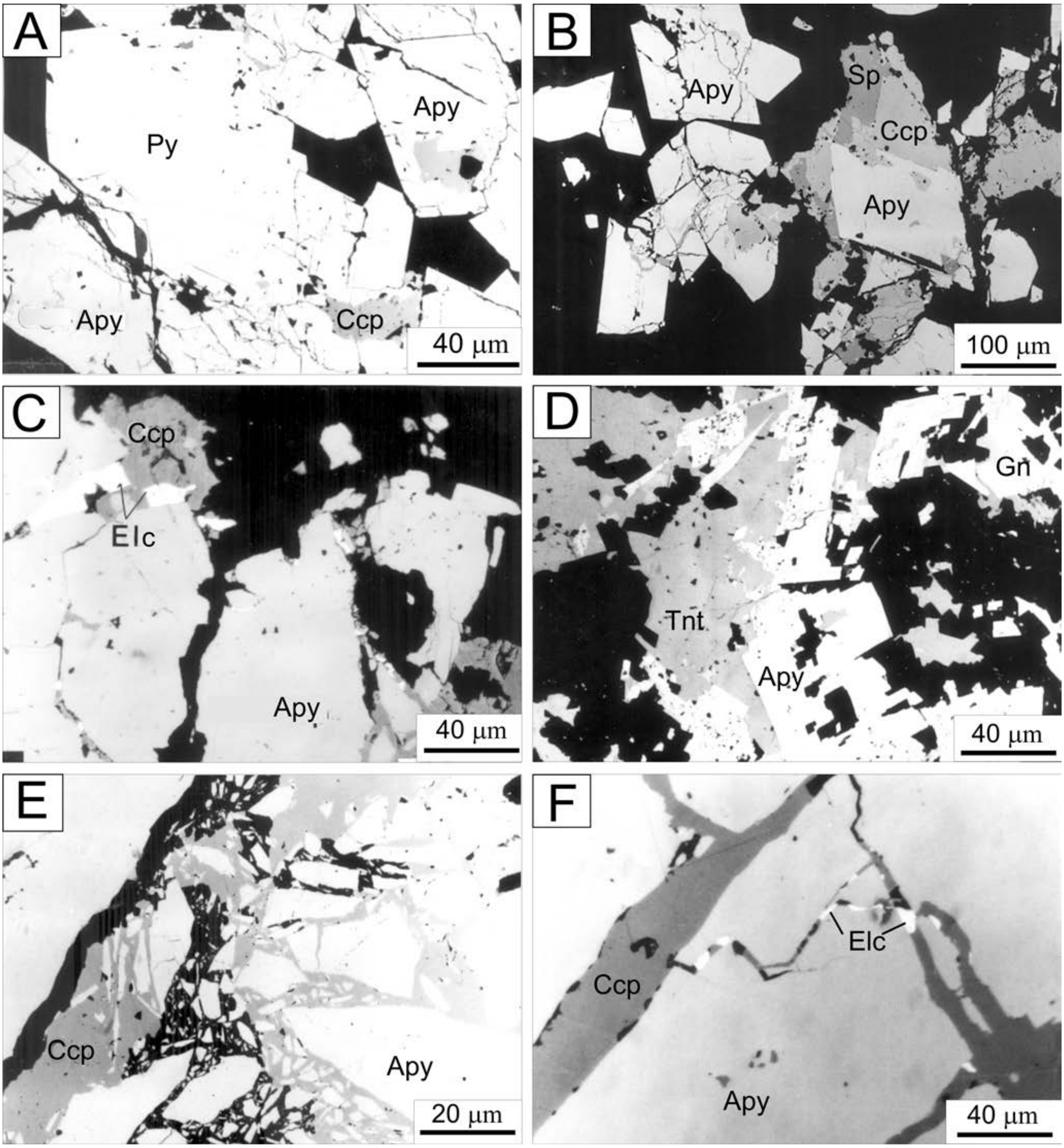

Fig. 4. Reflected light photomicrographs of auriferous ore mineralization from Radzimowice Au-As Cu deposit. **A–D**. Strongly fractured and cataclased Co-arsenopyrite (Apy) and pyrite (Py) are cemented by the second generation of ores – base metal sulphides (chalcopyrite – Ccp; sphalerite – Sp; galena – Gn; tennantite – Tnt) and quartz and carbonates (black); **E, F**. Fractured aggregate of Co-arsenopyrite (Apy) cemented by chalcopyrite (Ccp), electrum (Elc) and quartz (black).

leźniak Hill, near the Radzimowice settlement north of Mysłów, rhyolite porphyry (B5) from the southwestern slope of Bukowinka Hill, lamprophyre (R8) from a dyke in the southern part of the deposit from the area of the Miner Consolation vein near the Arnold shaft, and rhyolite porphyry (W4) from the "Organy" exposure at Wielisław Złotoryjski. Approximately 5 kg of each rock specimen were crushed and the heavy-mineral fraction (60–250 μm) separated, using standard low-contamination heavy-liquid and magnetic separation procedures. Zircon grains were handpicked, mounted in epoxy resin with reference zircon SL13 (U = 238 ppm) and TEMORA 2 ($^{206}Pb^{*}/^{238}U = 0.06683$), polished and Au-coated for SHRIMP analysis at the Research School of Earth Sciences, ANU, using procedures described by Williams and Claesson (1987). The data were processed, following methods described by Williams (1998, and refer-

Table 1

Chemical analyses of igneous rocks samples from the Żeleźniak and Bukowinka intrusions in the Radzimowice deposit and from the "Organy" exposure at Wielisław Złotoryjski

Major oxides and element [wt.%]	Żeleźniak intrusion				Bukowinka intrusion				Wielisław Złotoryjski	
	andesite	andesite	lamprophyre		rhyolite				rhyolite	
	R6	R7*	R8*	R25*	Bu 5	Bu 4	Bu 6/4	Bu 6/1	W4	W5
SiO_2	60.09	61.80	44.32	45.06	70.67	73.11	72.31	72.65	74.62	75.30
Al_2O_3	13.04	15.16	11.28	13.80	15.32	14.08	15.44	14.96	12.77	12.64
Fe_2O_3	6.96	3.74	8.29	8.97	2.31	2.15	0.81	1.09	1.56	1.59
TiO_2	0.80	0.37	0.79	1.04	0.42	0.26	0.32	0.32	0.13	0.14
MnO	0.02	0.13	0.20	0.19	0.01	0.00	0.01	0.02	0.01	0.01
MgO	0.50	1.63	8.36	8.58	0.81	0.22	0.49	0.93	0.61	0.43
CaO	0.45	2.70	7.16	6.84	0.51	0.24	3.34	2.97	0.28	0.23
Na_2O	0.09	2.66	0.97	1.56	3.55	2.89	5.74	5.55	1.67	1.16
K_2O	3.49	3.77	1.84	2.49	4.19	4.78	0.41	0.69	6.70	7.52
P_2O_5	0.07	0.13	0.32	0.31	0.14	0.08	0.12	0.13	0.05	0.05
S	1.20	1.08	0.20	0.25	0.00	0.01	<0.001	0.00	0.01	0.01
Cl	0.21	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.05	0.05
F	0.07	0.13	0.02	0.03	0.01	0.01	0.02	0.02	0.10	0.13
LOI	1.87	5.57	12.13	10.25	1.95	1.38	0.58	0.74	1.39	0.69
Total	88.84	98.89	95.90	99.40	97.94	97.81	99.59	100.07	99.95	99.94
Trace element [ppm]										
Cu	1407	134	105	59	280	19	54	128	<5	<5
Pb	1034	27	62	48	25	14	17	31	30	15
Zn	551	82	178	186	34	35	14	46	44	31
As	62494	191	1070	597	178	48	18	32	80	80
Au	1.38	0.005	0.001	0.003	<0.002	<0.002	<0.002	0.003	0	<0.002
Ag	45	4	4	7	0.8	0.5	<0.3	<0.3	<3	<3
Ba	480	352	656	576	842	1073	116	210	223	285
Ce	83	95	106	41	34	51	31	69	98	100
Co	4	7	38	30	2.5	2.3	0.8	1.4		
Cr	36	9	802	510	13.9	9.3	12	15	<5	<5
Hf	4	5	3	0.7	5.3	4.2	5	5	5	4
La	36	40	24	23	17.7	32.6	15.8	44.1	49	46
Mo	<2	4.2	<2	<2	5	3	2	4	<2	<2
Nb	11	12	12	9	13	11	8	10	19	19
Ni	4	7	247	133	9	8	6	7	4	4
Rb	143	152	177	79	129	136	<10	20	218	248
Sr	118	122	395	297	289	328	501	481	26	20
Th	15	19	12	7	15.5	13.3	14.3	13.7	22	22
U	4	7	5	2	4.4	2.2	3.6	3.8	<2	<2
V	30	29	146	162	38	22	21	24	8	12
Y	19	20	33	19	20	19	12	12	33	31
Zr	201	191	155	100	147	104	148	144	130	141

* Data after Mikulski, 2007.

ences therein), using PRAWN and LEAD software written by T. Ireland. Concordia diagrams were prepared, using ISOPLOT software written by Ludwig (2008). Individual analyses were plotted with 1σ error ellipses, and uncertainties in the mean ages, which include the uncertainty in the standardization, are quoted at the 95% confidence level (tσ, where 't' is Student's t).

GEOCHEMICAL AND PETROGRAPHIC FEATURES OF THE STUDIED ROCKS

The igneous rocks from the Radzimowice deposit studied here are represented by porphyritic andesite and dacite (R5 and R6) and lamprophyres (R8 and R25) from the Żeleźniak intrusion, and rhyodacite porphyries from the Bukowinka intrusion (B5 and B4; Fig. 2). The rhyodacites from Bukowinka are massive, a characteristic violet-red colour, and have typical porphyritic textures with an allotriomorphic matrix. They are composed of plagioclase, K-feldspar, quartz, hornblende, biotite and small amounts of zircon, titanite, ilmenite, magnetite, pyrite, apatite, calcite and epidote (Fig. 5A, B). The average grain size of phenocrysts is 2–5 mm, but generally the K-feldspar and quartz are much finer than the plagioclase. Hornblende in places forms aggregates that are chloritized and calcified. Biotite commonly forms overgrowths on hornblende, and tiny aggregates in places intergrown with opaque minerals. Albite occurs mostly as a replacement of plagioclase or as microfracture fillings, due to hydrothermal activity.

The porphyritic andesite and dacite samples (R5 and R6) are light beige in colour and medium- and fine-grained (Fig. 5C). They are representative of the calc-alkaline felsic rocks with porphyritic to aphyric textures from the sub-volcanic facies of the Żeleźniak intrusion, which range in chemical composition from dacite to andesite. They are composed of K-feldspar, quartz and sodic plagioclase, phenocrysts (1–5 mm diameter; Fig. 5D) within an allotriomorphic matrix of quartz and potassic feldspar. Sericite, calcite, Ti-oxides and sulphides in the dacites commonly form pseudomorphs after biotite and feldspar phenocrysts. The dacites also contain abundant disseminated sulphides (mainly pyrite and arsenopyrite) and small amounts of zircon, apatite and epidote.

The lamprophyres sampled (kersantites) are dark grey, with porphyritic textures. Phenocrysts of biotite (< 0.5 mm) and secondary minerals (carbonate, chalcedony and chlorite) after primary olivine are present in a fine-grained, crystalline groundmass, containing sericitized plagioclase (andesine), quartz, biotite and carbonates (Fig. 5E, F). Locally, the lamprophyre is strongly affected by carbonatization and As contents are highly elevated (0.05–0.1 wt.% As), owing to hydrothermal processes.

The rhyolite sample from Wielisław Złotoryjski (W4) is massive, porphyritic, and violet-rose in colour (Fig. 5G, H). Phenocrysts of quartz, K-feldspar, sodic plagioclase, biotite (< 4–5 mm in diameter), are present in a spherolitic matrix of allotriomorphic quartz and potassic feldspar (mainly sanidine), containing also fine-crystalline hematite pigment. The phenocrysts in places represent up to 40 volume percent of the rock. The quartz phenocrysts have characteristic magmatic corrosion. The K-feldspar and biotite are completely weathered. Albite and kaolinite pseudomorphs after plagioclase are common. Biotite is mostly replaced by chlorite. Sulphides are absent.

The major-element oxide and trace-element contents of the 8 igneous rock samples from Radzimowice and Wielisław Złotoryjski are listed in Table 1. The igneous rocks from the Radzimowice complex can be divided into three groups (Mikulski, 2007): (1) hypabyssal calc-alkaline micro-, and medium-grained granites with porphyritic textures (tonalite, monzogranite and granodiorite), (2) calc-alkaline felsic rocks from the sub-volcanic facies (dacite, rhyolite, andesite and trachyte) with porphyritic to aphyric textures, and (3) dykes and veins of fine- and coarse-grained alkaline rocks (lamprophyre) with porphyritic textures. The samples for the present geochemical and isotopic study are from groups 2 and 3.

The compositions of the 8 samples are plotted on a chemical discrimination diagram in Figure 6, along with published whole rock data for 44 other samples from the region. Most of the igneous rocks from the Żeleźniak, Bukowinka and Wielisław Złotoryjski intrusions plot in the peraluminous field, except for lamprophyre samples from Żeleźniak, which fall in the metaluminous field on the diagram of Al/(Na + K) *vs.* Al/(Ca + Na + K). Most of these rocks are potassic on the plot of K_2O *vs.* Na_2O. On the (Na_2O + K_2O) *vs.* SiO_2 diagram (Fig. 6A), the rocks from the Żeleźniak intrusion plot in the fields of andesite (R6), transitional to dacite (R5), and tephrite, basanite (R8, R25). The samples from Bukowinka (B4 and B5) are in the dacite field and those from Wielisław Złotoryjski (W4 and W5) in the rhyolite field. This matches with the position of most of the ZI rocks in the fields of rhyodacite-dacite, trachyandesite and andesite on the Nb/Y *vs.* Zr/TiO_2 diagram. The rocks have Nb/Y ratios less than 0.67, a characteristic of the calc-alkaline series or rocks transitional between the calc-alkaline and tholeiitic series.

Porphyries from the Żeleźniak intrusion can be strongly mineralized, especially along the contacts with ore veins, but those from the Bukowinka intrusion are barren. The felsic porphyritic samples studied here have a range of SiO_2 (60–75.3 wt.%) and alkali element contents, and moderately high Al_2O_3 contents (up to 12.6–15.3 wt.%; Table 1). The Na_2O and K_2O contents in the ZI and BI are 0.1–3.6 wt.% and 3.5–4.8 wt.%, respectively. The rhyolite porphyries from Wielisław Złotoryjski have much higher contents of SiO_2 (74–76 wt.%) and K_2O (6.7–7.5 wt.%), but only moderate Na_2O (ca.1.5 wt.%).

The K_2O/Al_2O_3 ratios of the sub-volcanic rocks (excluding lamprophyres) from the ZI and the BI are ca. 0.2, but from Wielisław Złotoryjski are almost 3-times higher, at about 0.6. Both series have a range of magnesium numbers [$Mg\#$ = Mg/(Mg + Fe)] of 25–75, and low concentrations of mantle-compatible trace elements (e.g., < 36 ppm Cr, < 9 ppm Ni). They are characterized by high concentrations of large-ion lithophile elements (LILE; e.g., up to 7.5 wt.% K_2O (W5), up to 248 ppm Rb (W5), 328 ppm Sr (B5), and 0.1 wt.% Ba (B4)), moderate light rare-earth element concentrations (LREE; e.g., up to 49 ppm La, 100 ppm Ce), and low levels of high-field-strength elements (HFSE; e.g., < 1.0 wt.% TiO_2, < 141 ppm Zr, < 19 ppm Nb). Low to moderate HFSE (Nb, Ta, Zr, Hf, and Y) contents are typical of volcanic-arc rocks with I-type affinities. High contents of Th (up to 22 ppm) and U (up to 7 ppm) suggest some crustal contamination during magma ascent, which is a characteristic feature of continental arc associations (Müller and Groves, 2000).

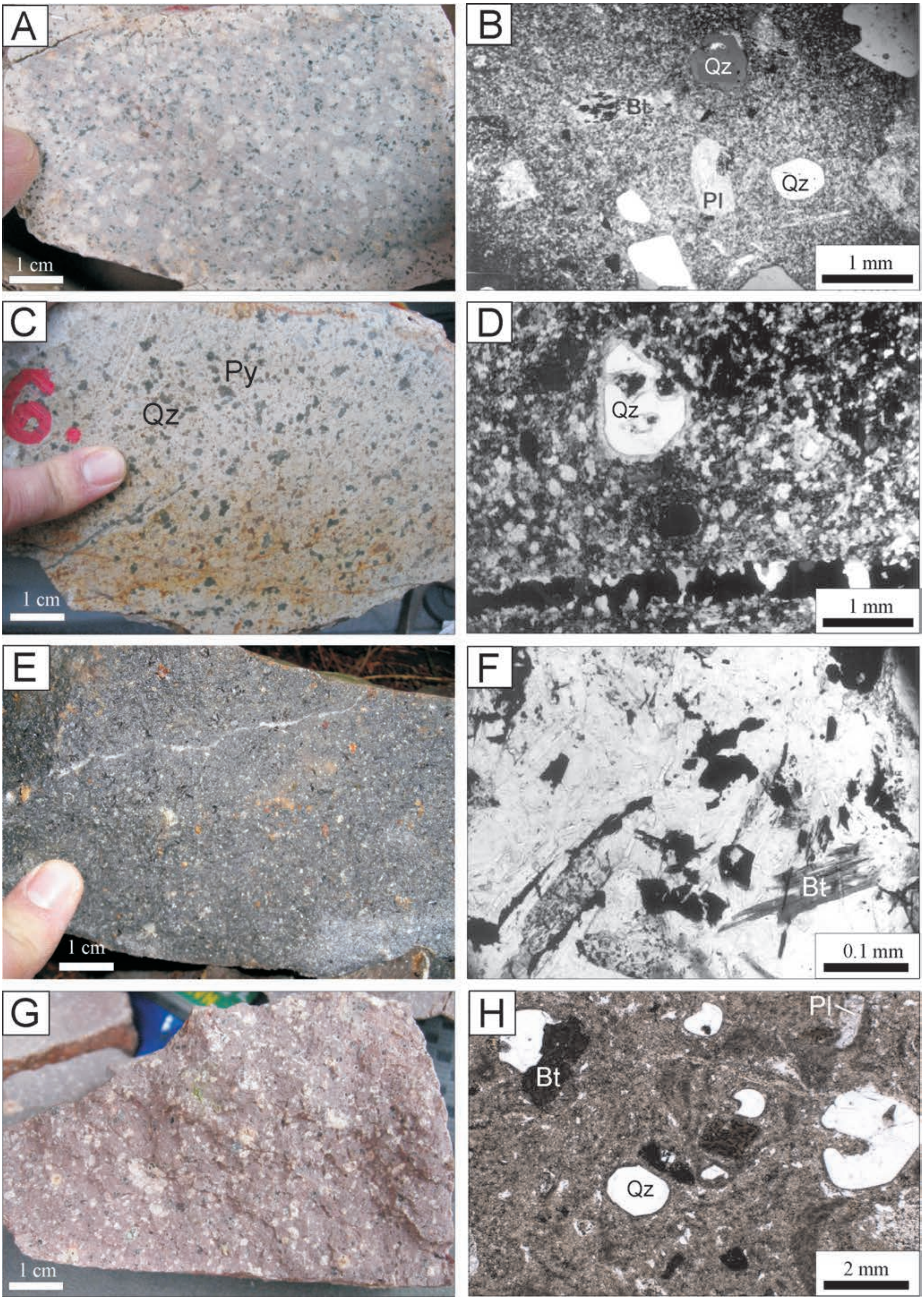
A
1 cm
B
Qz
Bt
Pl
Qz
1 mm
C
Py
Qz
1 cm
D
Qz
1 mm
E
1 cm
F
Bt
0.1 mm
G
1 cm
H
Pl
Bt
Qz
2 mm

Fig. 5. Photographs and photomicrographs (B, D, F, H; plane-polarized light) of sampled igneous rocks from Radzimowice and Wielisław Złotoryjski deposits. **A, B**. Rhyolite porphyry from the Bukowinka intrusion. Radzimowice deposit, sample B6. **B.** Quartz (Qz), plagioclase (Pl) and biotite (Bt) phenocrysts in an allotriomorphic matrix of quartz and potassium feldspar. Plagiocalse is partly replaced by sericite, and biotite by chlorite. **C, D.** Photographs of andesite porphyry (sample R6) and a thin section, respectively from the Żeleźniak intrusion with strong sulphide mineralization of veinlet-impregnation type. **D.** Pseudomorphs of sericite and calcite after plagioclase phenocrysts. Note also euhedral crystals of arsenopyrite and the quartz-sulphide veinlet cutting dacite (black) and an embayed quartz phenocryst. **E, F.** Lamprophyre specimen from Radzimowice deposit, sample R8. **F.** Pseudomorphs of pyrite and titanite (black) after biotite (Bt) and hornblende crystals in lamprophyre. **G, H.** Rhyolite porphyry from the "Organy" exposure at Wielisław Złotoryjski, sample W4. Quartz (Qz), plagioclase (Pl) and biotite (Bt) phenocrysts in an matrix of rhyolites.

On the K_2O *vs.* SiO_2 diagram (Peccerillo and Taylor, 1976) the lamprophyres plot in the field of shoshonites and ultrapotassic rock. The lamprophyres have low SiO_2 (43–44.3 wt.%), high Na_2O (up to 1.6 wt.%), and high MgO (ca. 8.5 wt.%) contents (Table 1). Their K_2O/Na_2O ratios range from 1.5 to 1.6, typical of the shoshonitic association (Müller and Groves, 2000). They have *Mg#* of 77–79 and high concentrations of mantle-compatible trace elements. When compared with other published data summarized by Mikulski (2007), these samples represent different types of sub-volcanic calc-alkaline rocks.

Considering geotectonic setting diagrams, on the Y-Nb diagram and on the Y + Nb - Rb diagram of Pearce *et al.* (1984) the samples studied plot in the island-arc (VAG; Fig. 7A) field and in the VAG and syn-collisional field (syn-COLG; Fig. 7B), close to a triple-boundary point that is characteristic of post-collisional granites, transitional to the within-plate granite field (WPG). On these two diagrams the rhyolite samples from Wielisław Złotoryjski plot in the transition to the field of within-plate granites. On the diagrams of Müller and Groves (2000), also based on simple ratios of 'immobile' elements (Zr/Al_2O_3 *vs.* TiO_2/Al_2O_3), it is possible to distinguish the potassic igneous rocks of continental (CAP) and post-collisional areas (PAP) from those of a within-plate setting. The samples from Radzimowice and Wielisław Złotoryjski fall into the continental and post-collisional fields. On the basis of the geochemical results, continental crust played a dominant role in the process of rhyodacitic magma genesis, with contributions from mafic calc-alkaline magmas (lamprophyre).

SHRIMP ZIRCON U-Pb DATING

Rhyolite porphyry from the Bukowinka intrusion

The zircons from the Bukowinka rhyolite porphyry (B5) consisted of a relatively uniform population of clear, reddish, elongate grains with few mineral inclusions, but some axial cavities (Fig. 8). Most grains were ≤ 50 µm diameter, with aspect ratios of 2–6. Many of the longer grains

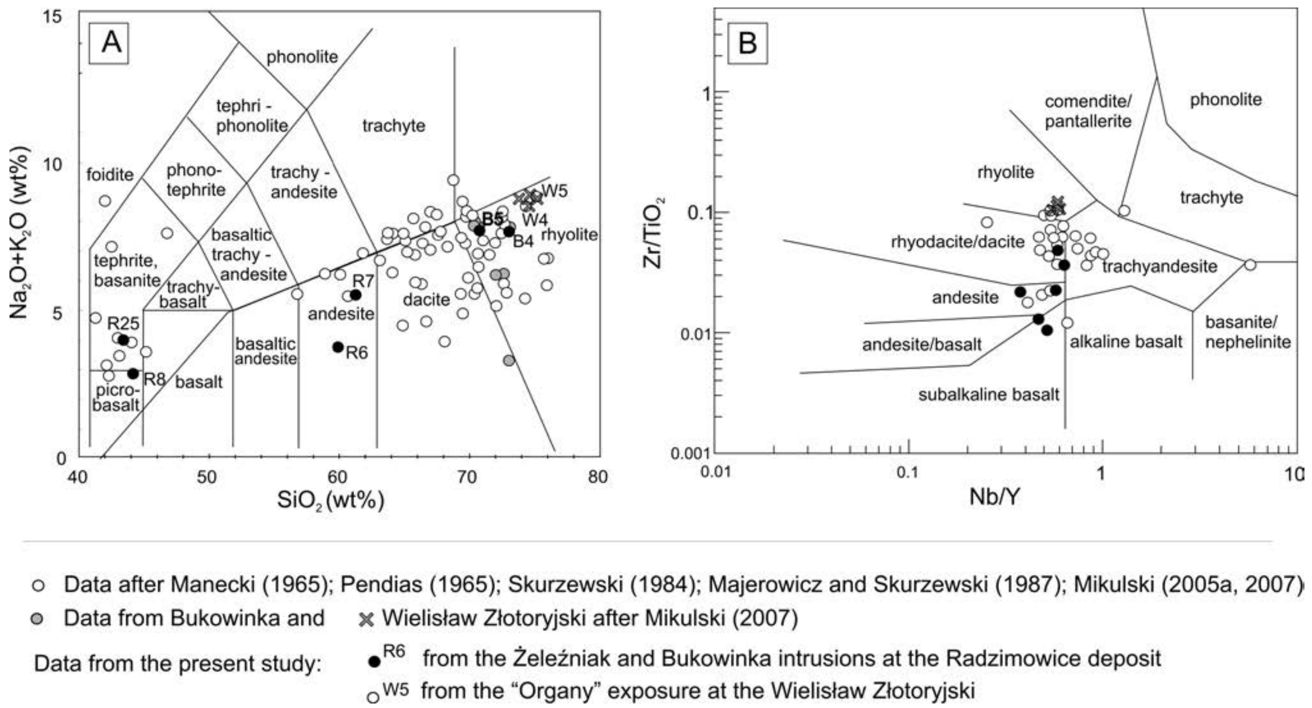

Fig. 6. Chemical classification of Late Carboniferous and Permian igneous rock suites of the Żeleźniak and Bukowinka intrusions from the Radzimowice Au-Cu-As deposit and from Wielisław Złotoryjski. **A.** $Na_2O + K_2O$ *vs.* SiO_2 diagram after Le Maitre *et al.* (1989). **B.** Zr/TiO_2 *vs.* Nb/Y diagram after Winchester & Floyd (1977).

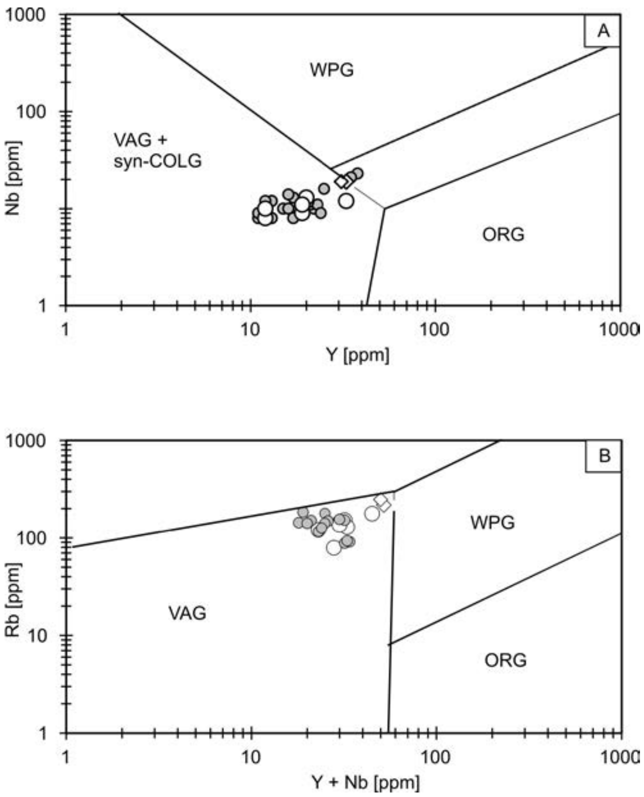

Fig. 7. Position of samples studied on the discrimination diagrams of Nb *vs.* Y (**A**) and Rb *vs.* Y + Nb (**B**), after Pearce *et al.* (1984). Data from the present study (open circle and rhomboedr (from Wielisław Złotoryjski), and after Mikulski (2007; gray circle). Abbreviations: syn-COLG – syn-collisional granites; WPG – within-plate granites; VAG – volcanic arc granites; ORG – ocean-ridge granites.

were lacking their terminations, probably because of damage caused during crushing in preparation for mineral separation. CL imaging showed a consistency in zoning textures, the elongate grains having banded zoning and the stubby grains having concentric zoning. These textures are consistent with the zircons being a single igneous population. Seven of the 10 zircon grains analyzed had banded zoning; the remainder had concentric zoning. All grains had moderate U contents (ca. 290–720 ppm), but the grains with concentric zoning were those with the highest U (ca. 600–720 ppm) and lowest Th/U (0.27–0.32, c.f. 0.36–0.94 for the banded grains; Table 2). All the isotopic analyses fall in a single concordant cluster, however, with no systematic difference in radiogenic $^{206}Pb/^{238}U$ as a function of crystal texture or U-Th content (Fig. 9). Two of the 10 radiogenic $^{206}Pb/^{238}U$ measurements (analyses 1.1, 9.1) are significantly lower than the rest. Omitting these assuming radiogenic Pb loss leaves 8 analyses with the same radiogenic $^{206}Pb/^{238}U$ within analytical uncertainty, giving a weighted mean age of 314.9 ± 3.1 Ma (95% c.l.), the uncertainty including uncertainty in the Pb/U calibration.

Porphyritic andesite from the Żeleźniak intrusion

The zircon grains from porphyritic andesite R6 were clear, colourless, slightly fractured and had few inclusions. The crystals were 30–100 µm in diameter, mostly sharply euhedral, and with aspect ratios ranging from 1 to 7. Most of the longer grains lacked terminations, presumably owing to breakage. CL imaging showed that the shorter grains mostly had fine concentric growth zoning and relatively weak luminescence, while the longer grains had broader-banded zoning and strong luminescence contrast (Fig. 8). Very few grains contained a texturally discordant core. The U contents were moderate to high (ca. 200–1600 ppm; n = 13), correlating with the strength of luminescence rather than the zoning texture (Table 2). Th/U ranged from 0.21 to 1.06, but again with no correlation with zoning texture. The isotopic analyses, with three exceptions, form a tight cluster within analytical uncertainty of concordia (Fig. 10). The exceptions are two analyses with high common Pb contents (6.1, 7.1), and one with a significantly lower radiogenic $^{206}Pb/^{238}U$ than the main group (1.1), all affected by radiogenic Pb loss. The remaining 10 analyses have the same radiogenic $^{206}Pb/^{238}U$ within the analytical uncertainty (MSWD = 0.6), giving a weighted mean age of 312.8 ± 2.8 Ma (95% c.l.).

Lamprophyre from the Żeleźniak intrusion

The zircon grains extracted from lamprophyre R8 were a mixed population of euhedral to subrounded short-prismatic to normal prismatic crystals, 50–100 µm in diameter (Fig. 8). The internal texture of the crystals was varied, ranging from CL-dark unzoned to moderate CL-bright, with simple igneous zoning. All dated grains (n = 11) had igneous zoning. All the dates are Palaeozoic (ca. 565–305 Ma) and the analyses are mostly concordant within uncertainty (Fig. 11). Seven analyses define the youngest group, five of which have the same ^{206}Pb-^{238}U within uncertainty, giving a weighted mean age of 312.4 ± 4 Ma (95% conf.). Given the range in zircon morphologies and measured dates, it is possible that even the youngest grains are contaminants from the country rock. The mean age of ca. 312 Ma is therefore a maximum for the age for the lamprophyre dyke; it might well be younger.

Rhyolite porphyry from the "Organy" exposure at Wielisław Złotoryjski

The zircon from rhyolite porphyry sample W4 occured as medium to fine (50–100 µm diameter), mostly clear, reddish and somewhat fractured euhedral grains with low aspect ratios (≤ 4), simple crystal shapes and few inclusions. CL imaging showed a range of zoning textures (Fig. 8). About 60% of the grains had weak luminescence and broad concentric or sector zoning, 30% of the grains had stronger luminescence and fine concentric zoning, and the remaining grains had banded zoning with strong luminescence contrast. Of the 12 grains dated, 3 were weakly luminescent, 5 had concentric zoning, and 4 had banded zoning. The weakly luminescent grains had consistently higher U contents (ca. 700–800 ppm) than the remaining grains (ca. 90–370 ppm) and much more uniform Th/U (0.55–0.58, c.f. 0.28–1.08 for the rest; Table 2). Except for the analysis of one CL-dark grain with a high common Pb content (2.1), the

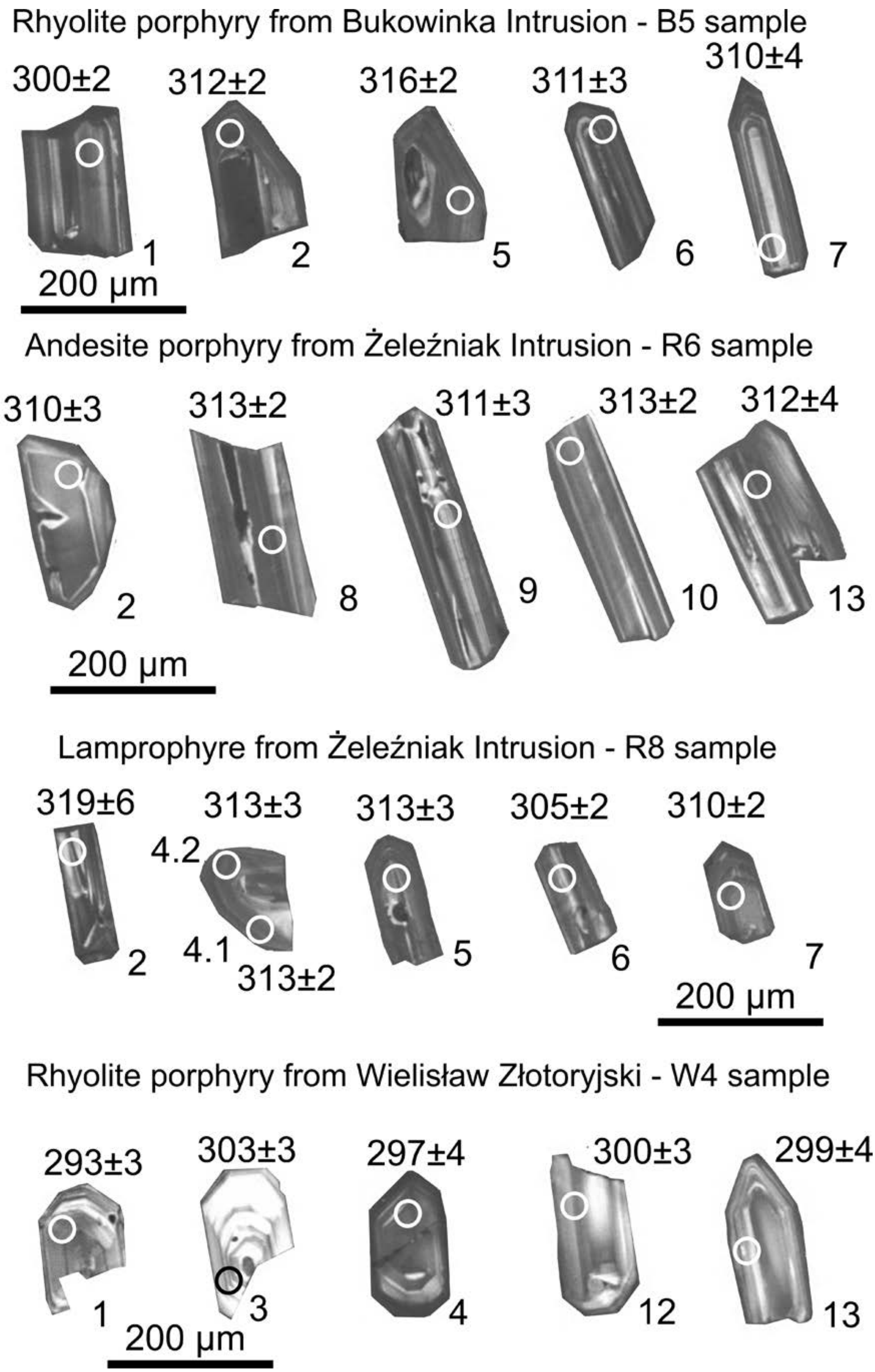

Fig. 8. Cathodoluminescence images of selected zircon grains from the sampled igneous rocks of the Żeleźniak and Bukowinka intrusions, from the Radzimowice Au-Cu-As deposit and from the rhyolite porphyry from the "Organy" exposure at Wielisław Złotoryjski. Circles are the locations of SHRIMP U-Pb analyses, ages in Ma.

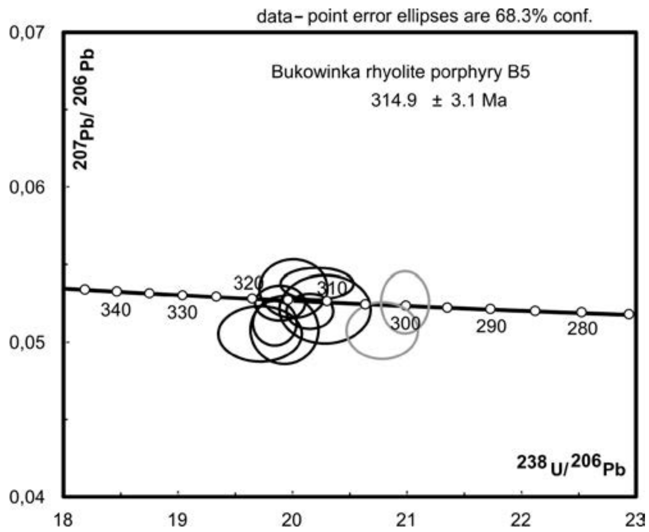

Fig. 9. Concordia diagram showing SHRIMP zircon U-Pb analyses from a rhyolite sample B5 from the Bukowinka intrusion at the Radzimowice Au-Cu-As deposit. Analytical uncertainties 1σ.

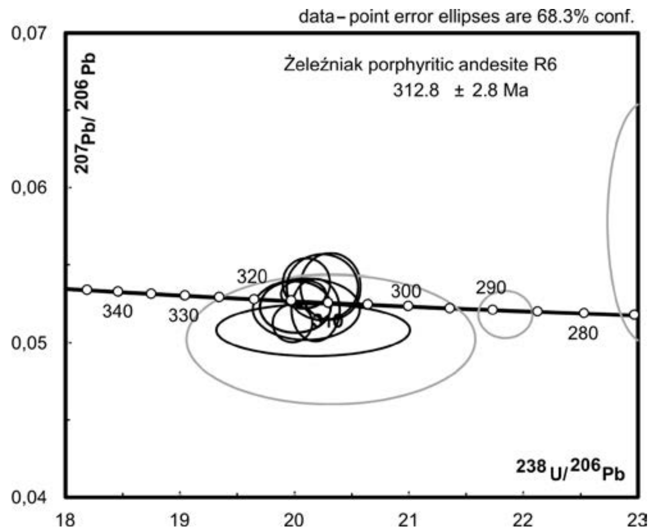

Fig. 10. Concordia diagram showing SHRIMP zircon U-Pb analyses from andesite porphyry sample R6 from the southern part of the Radzimowice Au-Cu-As deposit. Analytical uncertainties 1σ.

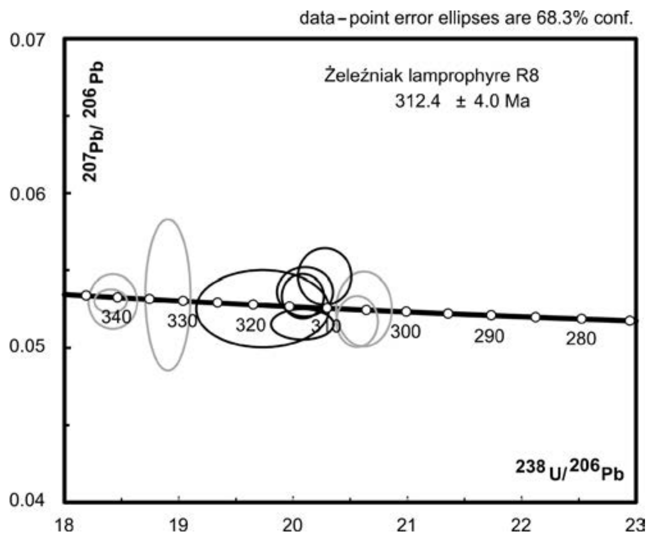

Fig. 11. Concordia diagram showing SHRIMP zircon U-Pb analyses from lamprophyre sample R8 from the southern part of the Radzimowice Au-Cu-As deposit. Analytical uncertainties 1σ.

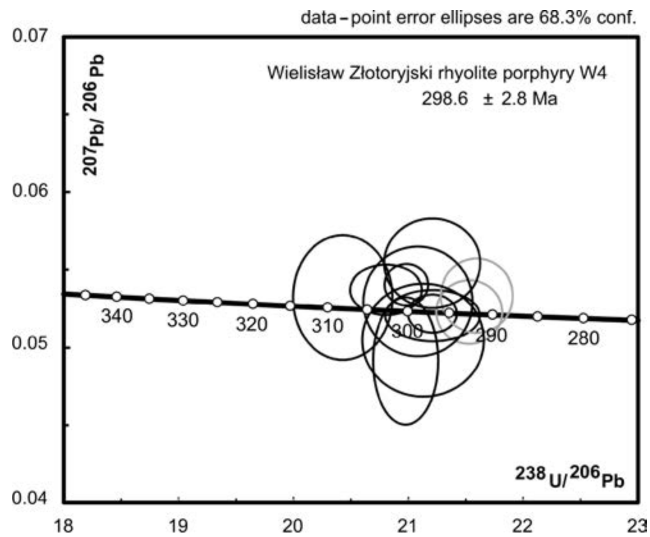

Fig. 12. Concordia diagram showing SHRIMP zircon U-Pb analyses from rhyolite porphyry sample W4 from the "Organy" exposure at Wielisław Złotoryjski. Analytical uncertainties 1σ.

isotopic analyses are tightly clustered and concordant within analytical uncertainty (Fig. 12). Omitting one $^{206}Pb/^{238}U$ measurement (from a low-U banded grain, 5.1) that is slightly, but significantly higher than the rest, leaves 10 analyses equal within analytical uncertainty (MSWD = 1.64), giving a weighted mean age of 297.5 ± 2.8 Ma (95% c.l.).

DISCUSSION

Two main stages of auriferous ore mineralization have been recognized in the quartz vein-type polymetallic sulphide deposit at Radzimowice, both associated with hydrothermal processes related to successive magmatic pulses in the Żeleźniak intrusion (Mikulski, 2005a). The first stage of mineralization is characterized by the presence of cobaltiferous arsenopyrite and pyrite with refractory (submicroscopic) Au in quartz veins. The auriferous ores of the first stage are strongly cataclased and overprinted by a younger generation of base metal sulphides and microscopic Au, associated with quartz and carbonates. The auriferous sulphides (Co-arsenopyrite, pyrite and chalcopyrite) from the first stage of ore mineralization were the subject of a Re-Os isotopic study (Mikulski *et al.*, 2005a), giving a six-point Re-Os isochron age of 317 ± 17 (Fig. 13), the large uncertainty being due to the low Os contents of the sulphides. This age is within the range of uncertainty of the more precise model age of 316.6 ± 0.4 Ma for Co-arsenopyrite sample G-4 from the Klecza orogenic Au deposit, located about 10 km west of the Radzimowice deposit in the Kaczawa Mountains (Mikulski, 2003). Previous SHRIMP zircon dating of magmatic rocks from the Żeleźniak intrusion yielded

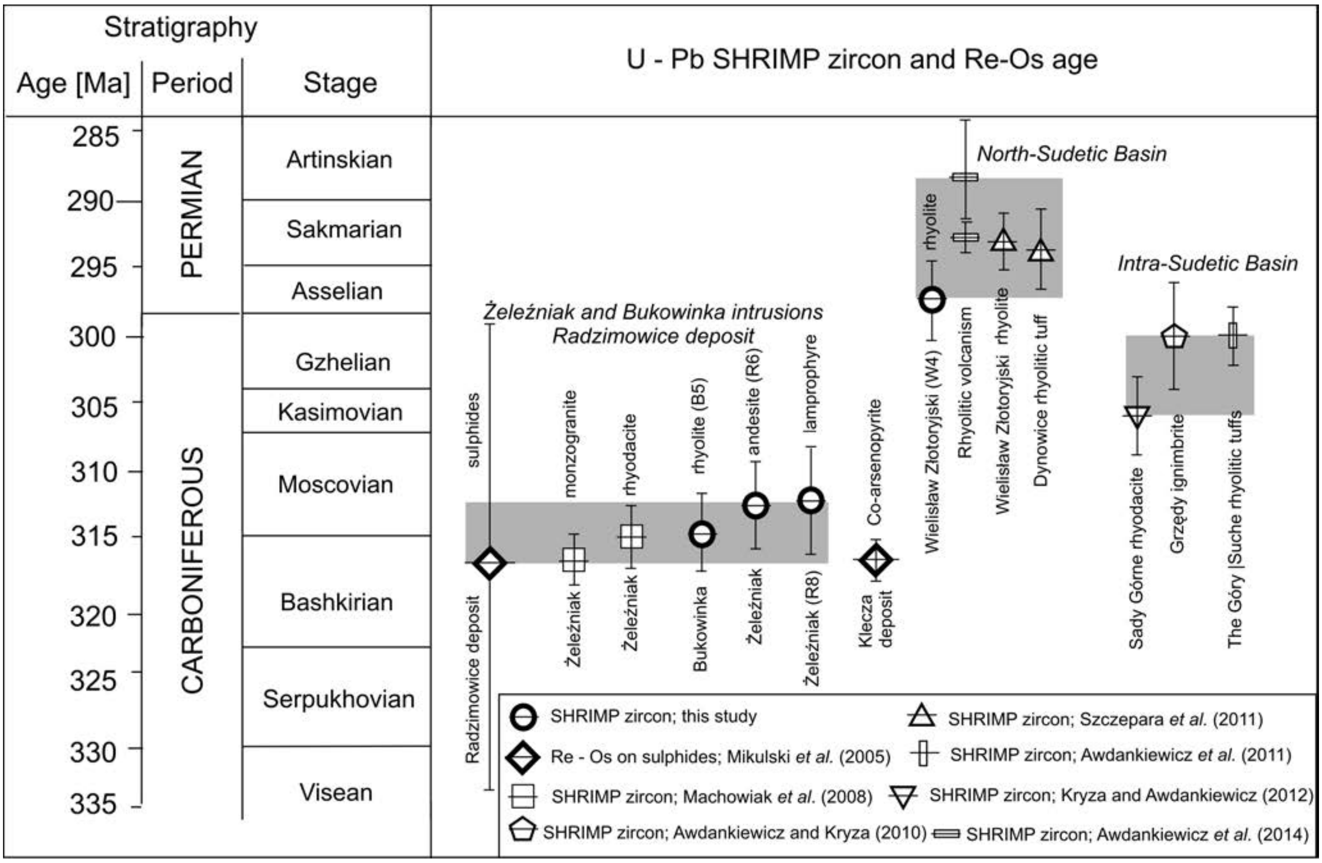

Fig. 13. Compilation of SHRIMP zircon data (this paper: samples B5, R6, R8, W4) and other data from the Radzimowice deposit and Wielisław Złotoryjski quarry on a stratigraphic chart (after International Commission on Stratigraphy, 2014).

similar ages of 316.7 ± 1.6 Ma for a monzogranite and 315.0 ± 2.1 Ma for a rhyodacite (Machowiak *et al.*, 2008). These Re-Os and U-Pb results indicate that the main magmatic episode in the Żeleźniak intrusion and post-magmatic hydrothermal activity took place at about 315 Ma (Mikulski, 2007). However, there are numerous igneous dykes in the ZI, for which ages were not previously determined. Moreover, the Bukowinka sub-volcanic rhyolite intrusion, which is in direct contact with the Żeleźniak intrusion, had not been dated previously.

The SHRIMP zircon U-Pb dating by the authors shows that the Radzimowice and Bukowinka magmas were intruded at almost the same time. The older magma pulse, represented by the rhyolite porphyry from Bukowinka Hill, was intruded at 314.9 ± 3.1 Ma (Fig. 13). This age overlaps with those previously measured on monzogranite and rhyodacite in the ZI. Granite xenoliths in the rhyolite indicate that it might be connected with a deep-seated granitic pluton (Majerowicz and Skurzewski, 1987; Mikulski, 2007; Machowiak *et al.*, 2008). According to these authors, a former magma chamber for the granite probably underlies the ZI and other intrusions that are up to 15 km away. One of the major processes of post-orogenic extension, namely tectonic displacement and regional subsidence along the Intra-Sudetic Fault, and the emplacement of felsic magmas (granites of post-collisional character at Bukowinka Hill), occurred at about 315 Ma (Late Namurian–Early Westphalian).

The younger pulse is represented by porphyritic andesitic (312.8 ± 2.8 Ma) and lamprophyric (312.4 ± 4 Ma) dykes that cut the ZI. These igneous rocks are characterized by a much lower silica content than other calc-alkaline igneous rocks from the ZI and the BI. The andesitic porphyries are strongly mineralized by polymetallic sulphides, and the lamprophyres in places also are mineralized, with fine-grained sulphides along fracture surfaces. These sulphides are not cataclased, unlike the sulphides of the main stage ores with refractory Au (Co-arsenopyrite and pyrite) later overprinted by base-metal sulphides in association with Bi-, Ag- and Te-minerals.

The geochemistry shows that continental crust played a dominant role in the process of rhyodacite magma generation, with contributions from mafic calc-alkaline magmas (lamprophyre). Probably no earlier than about 312 Ma, deep-seated fractures opened and triggered upwelling of lamprophyric magma; they provided channel ways for the migration of post-magmatic mineralizing fluids, related to alkaline magmas. Several geochemical discriminants suggest that the Żeleźniak and Bukowinka magmas were generated in a post-collisional setting.

The geologic and tectonic locations of the quartz veins at Wielisław Złotoryjski suggest that the auriferous-pyrite and Ag-bearing galena mineralization is related to the Rotliegende magmatic-volcanic events in the eastern part of the North-Sudetic Basin. The zircon U-Pb age of 297.5 ± 2.8 Ma of the authors for the rhyolite porphyry at the "Organy"

SHRIMP U-Pb analyses of zircons from the Żeleźniak and Bukowinka intrusions in the

Labels	U ppm	Th ppm	Th/U	±	Pb* ppm	^{204}Pb ppb	^{204}Pb/^{206}Pb	±	f^{206}Pb%	^{208}Pb/^{206}Pb	±	^{208}Pb/^{232}Th	±
B5-1.1	366	132	0.361	0.001	18	2	0.000124	0.000053	0.226	0.1136	0.0040	0.0150	0.0005
B5-2.1	719	230	0.320	0.002	35	2	0.000071	0.000023	0.131	0.0981	0.0016	0.0152	0.0003
B5-3.1	509	477	0.936	0.005	29	1	0.000026	0.000014	0.047	0.2891	0.0030	0.0154	0.0002
B5-4.1	623	171	0.275	0.001	31	2	0.000080	0.000030	0.146	0.0865	0.0018	0.0159	0.0004
B5-5.1	597	160	0.269	0.001	29	1	0.000020	0.000020	0.037	0.0808	0.0026	0.0151	0.0005
B5-6.1	569	399	0.701	0.004	31	0	0.000015	0.000007	0.027	0.2153	0.0025	0.0152	0.0003
B5-7.1	286	157	0.548	0.004	15	1	0.000122	0.000048	0.222	0.1738	0.0048	0.0156	0.0005
B5-8.1	504	230	0.457	0.003	26	6	0.000261	0.000071	0.478	0.1421	0.0039	0.0156	0.0005
B5-9.1	551	230	0.417	0.004	27	7	0.000304	0.000058	0.555	0.1222	0.0029	0.0141	0.0004
B5-10.1	335	233	0.695	0.005	18	1	0.000041	0.000054	0.075	0.2090	0.0036	0.0152	0.0003
R6-1.1	680	444	0.654	0.003	34	8	0.000281	0.000051	0.515	0.2127	0.0029	0.0149	0.0002
R6-2.1	423	156	0.368	0.002	21	1	0.000064	0.000033	0.118	0.1161	0.0023	0.0155	0.0004
R6-3.1	454	96	0.211	0.001	22	1	0.000029	0.000041	0.054	0.0665	0.0021	0.0157	0.0005
R6-4.1	383	401	1.048	0.026	22	10	0.000638	0.000158	1.168	0.3033	0.0084	0.0143	0.0008
R6-5.1	412	92	0.223	0.002	20	1	0.000082	0.000047	0.151	0.0690	0.0027	0.0154	0.0007
R6-6.1	467	400	0.858	0.004	23	48	0.002620	0.000301	4.792	0.2393	0.0126	0.0121	0.0007
R6-7.1	1432	1520	1.061	0.004	49	360	0.007910	0.000386	14.468	0.2062	0.0163	0.0062	0.0005
R6-8.1	1279	703	0.550	0.002	67	17	0.000313	0.000058	0.572	0.1694	0.0033	0.0153	0.0003
R6-9.1	442	134	0.304	0.002	22	1	0.000054	0.000028	0.099	0.0964	0.0022	0.0157	0.0004
R6-10.1	643	513	0.799	0.003	36	0	0.000002	0.000003	0.004	0.2535	0.0026	0.0158	0.0002
R6-11.1	464	106	0.229	0.001	22	1	0.000063	0.000028	0.116	0.0695	0.0018	0.0152	0.0004
R6-12.1	635	319	0.502	0.002	33	3	0.000093	0.000032	0.171	0.1557	0.0021	0.0154	0.0002
R6-13.1	799	403	0.504	0.009	40	6	0.000185	0.000054	0.339	0.1312	0.0026	0.0129	0.0005
R8-1.1	957	425	0.444	0.002	48	6	0.000152	0.000054	0.278	0.1372	0.0031	0.0150	0.0004
R8-2.1	421	411	0.977	0.012	25	6	0.000319	0.000089	0.583	0.3024	0.0055	0.0157	0.0005
R8-3.1	705	313	0.444	0.003	42	336	0.007666	0.000712	13.908	0.0796	0.0349	0.0112	0.0049
R8-4.1	932	295	0.316	0.002	46	3	0.000076	0.000023	0.14	0.0946	0.0017	0.0149	0.0003
R8-4.2	1029	350	0.340	0.001	51	2	0.000044	0.000024	0.081	0.1073	0.0020	0.0157	0.0003
R8-5.1	895	452	0.506	0.002	46	2	0.000045	0.000019	0.083	0.1582	0.0019	0.0156	0.0002
R8-6.1	816	683	0.836	0.004	44	20	0.000577	0.000068	1.055	0.2488	0.0048	0.0144	0.0003
R8-7.1	750	309	0.412	0.002	38	5	0.000166	0.000060	0.304	0.1294	0.0029	0.0155	0.0004
R8-8.1	696	283	0.407	0.001	38	3	0.000082	0.000027	0.149	0.1254	0.0019	0.0167	0.0003
R8-9.1	834	247	0.296	0.001	43	43	0.001118	0.000190	2.045	0.0876	0.0076	0.0157	0.0014
R8-10.1	267	165	0.619	0.004	26	2	0.000079	0.000037	0.141	0.1988	0.0029	0.0294	0.0005
R8-11.1	1490	326	0.219	0.001	78	3	0.000038	0.000013	0.069	0.0685	0.0009	0.0170	0.0002
W4-1.1	372	147	0.396	0.002	17	1	0.000057	0.000032	0.105	0.1221	0.0028	0.0143	0.0004
W4-2.1	783	529	0.676	0.003	34	95	0.003252	0.000338	5.956	0.1914	0.0138	0.0116	0.0009
W4-3.1	215	169	0.785	0.005	12	0	0.000020	0.000010	0.037	0.2558	0.0071	0.0157	0.0005
W4-4.1	362	261	0.720	0.006	19	1	0.000080	0.000045	0.147	0.2207	0.0034	0.0145	0.0003
W4-5.1	90	39	0.432	0.003	4	0	0.000126	0.000107	0.231	0.1300	0.0061	0.0148	0.0007
W4-6.1	714	392	0.548	0.002	35	1	0.000046	0.000025	0.085	0.1729	0.0045	0.0149	0.0004
W4-7.1	257	277	1.077	0.005	14	2	0.000150	0.000066	0.275	0.3385	0.0049	0.0146	0.0003
W4-8.1	116	55	0.468	0.003	6	0	0.000009	0.000007	0.017	0.1552	0.0051	0.0156	0.0006
W4-9.1	293	83	0.284	0.006	14	4	0.000321	0.000121	0.588	0.0892	0.0067	0.0149	0.0012
W4-10.1	796	484	0.608	0.002	41	3	0.000084	0.000029	0.154	0.1907	0.0021	0.0150	0.0002
W4-12.1	253	210	0.833	0.004	13	5	0.000455	0.000101	0.833	0.2503	0.0056	0.0143	0.0004
W4-13.1	210	140	0.667	0.006	11	3	0.000405	0.000108	0.742	0.2049	0.0062	0.0146	0.0005

Table 2

Radzimowice deposit and from the "Organy" exposure at Wielisław Złotoryjski

$^{206}Pb/^{238}U$	±	$^{207}Pb/^{235}U$	±	$^{207}Pb/^{206}Pb$	±	Apparent ages (Ma)							
						$^{208}Pb/^{232}Th$	±	$^{206}Pb/^{238}U$	±	$^{207}Pb/^{235}U$	±	$^{207}Pb/^{206}Pb$	±
0.0477	0.0003	0.346	0.009	0.0526	0.0013	301.2	10.8	300.1	1.9	301.5	6.8	312.2	56.4
0.0496	0.0003	0.356	0.006	0.0520	0.0008	305.1	5.5	312.2	2.0	309.0	4.5	284.8	33.4
0.0500	0.0005	0.368	0.010	0.0535	0.0012	309.6	4.7	314.4	3.0	318.4	7.2	348.0	53.4
0.0504	0.0003	0.356	0.007	0.0512	0.0010	318.0	6.9	316.9	2.0	309.1	5.4	250.9	43.2
0.0503	0.0004	0.364	0.006	0.0525	0.0007	303.1	9.9	316.2	2.2	315.2	4.5	308.1	32.3
0.0495	0.0005	0.367	0.006	0.0538	0.0007	304.7	5.1	311.3	3.2	317.2	4.7	361.0	28.6
0.0493	0.0006	0.354	0.011	0.0521	0.0015	313.5	9.7	310.2	3.9	307.9	8.6	290.5	64.9
0.0502	0.0005	0.351	0.011	0.0508	0.0015	312.9	9.2	315.6	3.0	305.8	8.3	231.5	67.1
0.0481	0.0005	0.336	0.009	0.0507	0.0012	283.1	7.7	302.8	2.9	294.2	6.9	226.2	56.0
0.0507	0.0006	0.353	0.010	0.0505	0.0012	305.8	6.8	318.9	3.8	307.2	7.3	219.5	54.8
0.0458	0.0003	0.327	0.007	0.0518	0.0010	299.0	4.7	288.6	2.0	287.4	5.4	277.4	45.0
0.0492	0.0004	0.364	0.010	0.0536	0.0014	311.4	6.9	309.8	2.6	315.1	7.8	354.6	60.5
0.0500	0.0005	0.360	0.009	0.0523	0.0011	315.6	10.5	314.4	3.1	312.6	6.6	299.1	48.8
0.0492	0.0020	0.341	0.025	0.0502	0.0028	286.0	15.7	309.7	12.4	297.7	18.9	204.3	133.0
0.0497	0.0008	0.358	0.011	0.0522	0.0013	308.4	12.9	312.9	4.7	310.5	8.3	292.3	58.4
0.0434	0.0004	0.345	0.031	0.0578	0.0051	243.0	13.0	273.6	2.5	301.2	23.8	520.6	206.7
0.0317	0.0003	0.241	0.029	0.0550	0.0066	124.2	9.9	201.3	1.9	219.0	24.3	413.5	294.0
0.0497	0.0003	0.369	0.008	0.0538	0.0010	307.4	6.4	312.9	2.1	319.0	5.8	363.8	44.1
0.0494	0.0005	0.365	0.011	0.0536	0.0014	314.3	8.1	310.8	3.1	315.8	7.9	352.5	59.9
0.0498	0.0003	0.365	0.005	0.0531	0.0006	316.8	4.0	313.3	2.0	315.8	3.8	334.2	26.2
0.0500	0.0003	0.354	0.006	0.0513	0.0008	304.8	8.1	314.8	1.8	307.5	4.7	252.6	36.9
0.0495	0.0003	0.356	0.010	0.0521	0.0013	308.2	4.9	311.7	2.1	309.2	7.3	290.0	59.5
0.0496	0.0014	0.347	0.013	0.0508	0.0011	259.0	10.0	312.0	8.4	302.8	9.8	232.1	51.1
0.0486	0.0003	0.347	0.008	0.0517	0.0011	301.5	7.1	306.1	1.7	302.3	5.9	272.4	49.2
0.0507	0.0010	0.367	0.014	0.0525	0.0016	314.7	9.1	318.7	6.1	317.4	10.6	308.3	72.8
0.0624	0.0015	0.244	0.113	0.0284	0.0130	224.6	98.2	390.1	9.3	221.9	96.7	0.0	0.0
0.0498	0.0005	0.354	0.006	0.0515	0.0007	299.1	6.0	313.3	2.8	307.6	4.4	264.5	29.3
0.0498	0.0003	0.366	0.007	0.0533	0.0009	315.4	6.2	313.2	1.9	316.8	5.3	343.4	40.4
0.0497	0.0004	0.368	0.008	0.0536	0.0010	312.3	4.6	312.9	2.5	318.0	6.0	355.2	44.4
0.0485	0.0004	0.351	0.011	0.0525	0.0016	289.6	6.1	305.3	2.3	305.5	8.6	307.2	70.7
0.0493	0.0004	0.371	0.009	0.0546	0.0012	310.7	7.4	310.3	2.3	320.7	6.7	396.3	50.1
0.0543	0.0004	0.397	0.010	0.0530	0.0012	335.0	5.8	340.7	2.5	339.1	7.0	328.2	50.5
0.0529	0.0004	0.390	0.024	0.0534	0.0032	314.4	27.2	332.3	2.2	334.0	17.7	346.3	142.3
0.0915	0.0009	0.777	0.015	0.0616	0.0010	585.6	10.6	564.3	5.0	584.0	8.7	661.5	34.4
0.0543	0.0003	0.397	0.005	0.0530	0.0005	341.0	4.9	341.1	1.7	339.7	3.3	330.0	21.7
0.0464	0.0004	0.335	0.010	0.0523	0.0014	287.6	7.0	292.7	2.5	293.3	7.3	298.2	60.2
0.0409	0.0005	0.293	0.033	0.0521	0.0058	232.5	16.9	258.1	3.0	261.1	26.2	287.7	272.9
0.0481	0.0005	0.356	0.008	0.0537	0.0011	314.0	9.4	302.6	2.9	309.1	6.2	358.7	45.1
0.0471	0.0006	0.338	0.009	0.0521	0.0011	290.1	6.2	297.0	3.7	296.0	6.7	288.0	48.5
0.0490	0.0007	0.359	0.019	0.0532	0.0026	295.9	14.5	308.1	4.2	311.6	14.4	337.8	116.3
0.0472	0.0003	0.339	0.006	0.0522	0.0008	298.2	8.1	297.0	1.9	296.6	4.6	293.8	36.0
0.0463	0.0004	0.340	0.011	0.0533	0.0016	292.2	5.2	291.8	2.7	297.5	8.3	342.9	68.1
0.0472	0.0006	0.360	0.014	0.0554	0.0019	313.2	11.3	297.0	3.8	312.4	10.3	429.3	77.8
0.0473	0.0008	0.329	0.017	0.0505	0.0024	298.6	23.8	298.1	4.8	289.1	13.2	217.2	113.7
0.0477	0.0003	0.355	0.006	0.0540	0.0009	300.1	3.8	300.1	1.8	308.5	4.8	372.7	36.8
0.0477	0.0004	0.323	0.018	0.0491	0.0027	287.6	7.0	300.2	2.6	284.2	14.2	154.4	133.8
0.0474	0.0007	0.346	0.017	0.0530	0.0023	292.6	10.1	298.7	4.3	302.0	12.6	327.0	102.5

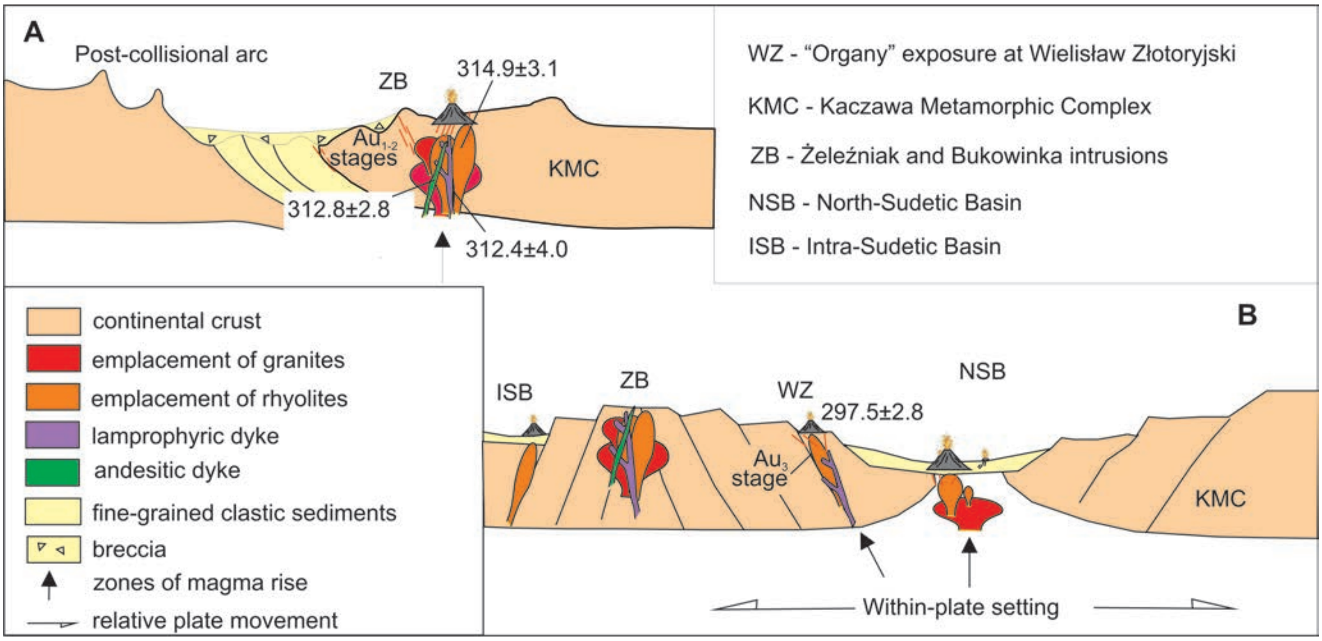

Fig. 14. Updated schematic diagram of formation of gold deposits in the Kaczawa Mountains during the Late Carboniferous to Early Permian (after Mikulski, 2007) with modification of general model after Müller and Groves (2000). **A.** Kaczawa Metamorphic Complex (KMC) formed an accretionary prism as a result of terrane collision with the Bohemian Massif. Post-collisional calc-alkaline granitic magmas (ca. 315 Ma) intruded the KMC in the uplifted orogen. In the upper crust, composite rhyolite laccoliths intruded the Radzimowice deposit. Then post-magmatic hydrothermal fluids formed mesothermal auriferous sulphide-bearing quartz veins (Au1). At about 312 Ma, the regional tectonic movements became extensional, beginning with the development of deep fracturing and the formation of grabens and horsts within the KMC basement, starting to form the Hercynian intramontane basins. The area was uplifted and dykes and veins of lamprophyre (generally of mantle-derived material) and andesite (from the remnant felsic melts) were formed. They were accompanied by hydrothermal processes responsible for the epithermal base metal sulphide mineralization with the paragenetic association of Te-Bi-Ag-Au minerals (Au2 stage). **B.** During the Late Carboniferous to Early Permian (ca. 315–297 Ma), there was a transition from a post-collisional continental setting to a within-plate setting (Autunian). That was accompanied by regional tectonics and volcanic processes, that were responsible for the auriferous mineralization at Wielisław Złotoryjski (Au3, ca. 298 Ma).

exposure in Wielisław Złotoryjski, on the SE margin of the North-Sudetic Basin (Fig. 10), is roughly comparable to zircon ages previously measured (Szczepara *et al.*, 2011; Awdankiewicz *et al.*, 2014) on rhyolite from the "Organy" exposure (ca. 293 ± 2 Ma) and the rhyolite flow exposed at Dynowice (294 ± 3 Ma). During the second cycle of the Rotliegende, deep regional fractures formed and allowed the emplacement of rhyolite magma and andesite lavas in the Wielislaw Złotoryjski area (Milewicz, 1987).

During its Carboniferous–Permian transition from a post-collisional to a within-plate setting, the eastern part of the European Variscides was the site of rapid continental extension, uplift and deep fracturing (Mazur *et al.*, 2007). This is evidenced by the geochemical characteristics of the Variscan granites from the region of the Kaczawa Mountains: the compositions of the Karkonosze and Żeleźniak (Bukowinka) granites plot in the late- and post-collisional granite fields, and most of the Strzegom–Sobótka granites in the within-plate granite field (Mikulski and Stein, 2005; Mikulski, 2007). This finding is consistent with the tectonic interpretation of the area presented by Awdankiewicz (1999), namely that the older calc-alkaline volcanic suite of late Carboniferous age from the Intra-Sudetic Basin formed in a post-collisional tectonic setting in transition to a within-plate setting. This early volcanism occurred near the northern margin of the Intra-Sudetic Basin. The age of 310 ± 4 Ma for the Chełmiec intrusion (Awdankiewicz and Kryza, 2010a) corresponds to the middle of the Late Carboniferous (Westphalian/Moscovian). Rhyolitic tuffs from Góry Suche in the Intra-Sudetic Basin have a SHRIMP zircon age of 300 ± 4 Ma (latest Carboniferous – Stephanian), possibly indicating that the climactic stage of volcanism in the Intra-Sudetic Basin occurred about 10 My earlier (Awdankiewicz and Kryza, 2010b).

The transition from a post-collisional to within-plate setting was favorable for the formation of epithermal Au mineralization in uplifted areas of the Kaczawa Mountains. The second stage of epithermal ore precipitation in the Radzimowice deposit, with base-metal sulphides, carbonates and Bi-Te-Ag-Au minerals, postdated emplacement of andesite and lamprophyre dykes at about 312 Ma. The zircon data from the ZI, BI and WZ suggest that the shift in geotectonic setting occurred over a period of 15–20 Ma, between 315 and 298 Ma (Fig. 14).

CONCLUSIONS

Three magmatic pulses within the Palaeozoic Kaczawa Metamorphic Complex in the marginal zones of the Hercynian intramontane basins in the eastern part of the Saxothuringian Zone of the Sudetes have been described more precisely.

The dating of three igneous rock samples from the Radzimowice vein-type Au-bearing polymetallic sulphide deposit in the Kaczawa Mountains shows that they were intruded in two separate pulses. The older pulse is represented by a rhyolite porphyry at Bukowinka Hill, intruded at 314.9 ± 3.1 Ma. It is similar in age to monzogranites and a rhyodacite porphyry from the Żeleźniak intrusion, previously dated by Machowiak *et al.* (2008), at 316.7 ± 1.6 Ma and 315.0 ± 2.1 Ma, respectively. This pulse is associated with the first stage of ore precipitation, represented mainly by mesothermal sulphide mineralization (Co-arsenopyrite and pyrite) with refractory Au.

The first stage of ore mineralization in the Radzimowice deposit was subjected to strong cataclasis and later overprinted by base-metal sulphides and microscopic Au, associated with quartz and carbonates. Lamprophyre and porphyritic andesite dykes (312.8 ± 2.8 Ma and 312.4 ± 4 Ma, respectively) postdate the first stage of auriferous sulphide mineralization and are spatially associated with quartz veins.

A rhyolite porphyry in the "Organy" exposure at Wielisław Złotoryjski on the SE margin of the North-Sudetic Basin yielded a zircon age of 297.5 ± 2.8 Ma, which is roughly comparable with the age of 292.8 ± 2.1, reported by Awdankiewicz *et al.* (2014).

The geochemical characteristics of the calc-alkaline igneous rocks from the Żeleźniak and Bukowinka intrusions studied indicate a post-collisional arc setting and those from the Wielisław Złotoryjski rhyolite, a within-plate setting. These two separate sub-volcanic calc-alkaline intrusions and dykes were emplaced at about 315–312 Ma and about 298 Ma, respectively. The magmatic episodes lasted about 15 Ma and record a geotectonic transition from post-collisional emplacement of sub-volcanic rhyodacite porphyries (the Żeleźniak and Bukowinka intrusions), to a within-plate setting of sub-volcanic porphyries at Wielisław Złotoryjski on the margin of the Hercynian intramontane North-Sudetic Basin, in this segment of the Central European Variscides.

The post-magmatic hydrothermal activity that produced vein-type polymetallic auriferous ore mineralization, in intimate contact with the rhyolite porphyry at Wielisław Złotoryjski, might have begun in the Early Permian, but this has yet to be confirmed.

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