Carboniferous–Permian magmatism and Mo–Cu (W) mineralization in the contact zone between the Małopolska and Upper Silesia Blocks (south Poland): an echo of the Baltica–Gondwana collision

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Abstract

The Kraków–Lubliniec tectonic zone (KLFZ) in southern Poland, which divides the Małopolska Block (MB) from the Upper Silesia Block (USB), is a portion of the SW margin of the Trans-European Suture Zone. Zircon U–Pb dating of a variety of igneous rocks (granodiorites, dacites, lamprophyre and diabase) from the subsurface Kraków–Lubliniec igneous belt along the KLFZ shows that magmatism spanned within a narrow time period (ca. 10 Ma) between 303.8 ± 2.2 and 292.7 ± 4.9 Ma. The earlier magmatism (303.8 ± 2.2 – 294.7 ± 2.3 Ma) was felsic calc-alkaline, and the contemporaneous or/and slightly later alkaline volcanism (294.4 ± 4.9 – 292.7 ± 4.9 Ma) was of mafic–intermediate composition. The felsic rocks (granitoids and dacitoids) are weakly peraluminous, medium to high K, moderate Mg# (0.39–0.46), weakly evolved and I-type rocks. Due to the intensive development of hydrothermal alteration, these rocks are commonly strongly altered and locally mineralized by porphyry and other types of Mo–Cu (W) ores that are closely related to the felsic magmatism in space and time. The zircon U–Pb dating yielded ages which are similar to the previously measured Re–Os ages of molybdenites from the KLFZ. Felsic magmatism at the Myszków Mo–Cu–W deposit yielded ages in the range 301.0 ± 2.1 – 295.9 ± 2.9 Ma. The youngest rocks dated are from the Mysłów area in the USB—volcanic alkaline rocks (lamprophyre and diabase) of shoshonitic character, with low Mg# (0.49 and 0.69, respectively) and Ni contents (< 62 ppm), indicative of a relatively juvenile magma composition. Inherited zircon cores, remnant detrital zircon from a sediment component in the source rocks, were dated to be ranging from ca. 2775 to 575 Ma. Inheritance of ca. 600 Ma (Cadomian basement) and ca. 1.40 Ga (Mesoproterozoic) is common in the rocks from both blocks, but those from the MB contain additional inheritance with dates of 2.78–2.67 and 2.05–1.92 Ga, both ages characteristic of zircon from the Svecofennian of northern Europe (Baltica). The inherited zircon from the youngest alkaline rocks provided evidence for Mesoproterozoic (ca. 1.55–1.44 and 1.09 Ga) and Palaeoproterozoic (1.96 Ga) thermal events in the USB, and its possible affinity to Avalonian cratonic crust as a source for its igneous protolith. U–Pb isotopic studies of zircons from KL igneous belt indicate its inherited signatures from the crustal sources and magma emplacements during the KLFZ wrenching which allowed channels and room for magma emplacement along the MB and USB in upper Carboniferous–lower Permian on SW margin of the East-European Craton. Mo–Cu (W) ore mineralization, associated with the ~300 Ma felsic magmatism, represents rather the product of decompression melting induced in the areas of decreased pressure, undergone in the regional wrench fault zones than the classic Mo–Cu porphyry-style mineralization.

Keywords Variscan magmatism · SHRIMP zircon geochronology · Zircon inheritance · Mo–Cu (W) ores · Małopolska Block · Upper Silesia Block

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Introduction

During the late Carboniferous to Permian, there was intensive granitoid plutonism associated with bimodal volcanic activity within a wide belt along the Kraków–Lubliniec Fault Zone (part of the major Hamburg–Kraków–Dobrogea transcontinental strike-slip tectonic zone, Żaba 1999) that separates the Małopolska Block (MB; a thinned marginal part of Baltica)

from the Upper Silesia Block (USB; part of the Brunovistulia composite Terrane) (Żelaźniewicz et al. 2016, and references therein). The KLFZ is a part of the Trans-European Suture Zone (TESZ; Żelaźniewicz et al. 2016), one of the most important composite suture zones in Europe (Matte 1986; Ziegler 1986; Pharaoh 1999; McCann et al. 2006; Franke 2006; Breitreuz et al. 2007; Mazur et al. 2010). Igneous rocks that occur along the KLFZ are the products of bimodal magmatism, associated either with crustal thickening (Słaby et al. 2010) or with the dextral wrench regime and fault activity on TESZ (Żelaźniewicz et al. 2016). It has been proposed that they originate from two different sources: enriched metasomatized mantle and primitive crust (Słaby et al. 2010). There are few isotopic ages for the bimodal magmatic processes within the KLFZ, and some isotopic systems have yielded poor or questionable results. Previous work on some of the igneous rocks selected for the present study, for example, yielded a wide range of ages from 340 ± 8 to 281 ± 17 Ma (K–Ar, Truszel et al. 2006). Only two igneous rocks from the selected areas of the KLFZ (Będowska Valley and Mysłów) have previously been dated by modern zircon U–Pb (Nawrocki et al. 2007; Żelaźniewicz et al. 2008).

In this paper, we report the results of zircon U–Pb isotopic investigations of 15 igneous rocks as they appear subsurface in ca. 60 km long and 5–15 km wide magmatic belt on either side of the fault zone, i.e., on both the Upper Silesia and Małopolska sides. The isotopic data obtained are assessed within the context of the geochemistry and petrology of igneous rocks from the whole zone that extends from Mysłów in the NW to the Będowska Valley in the SE (Fig. 1). Our data are placed within the context of other isotopic ages of igneous rocks from the Variscan orogenic belt in central Europe (Benek et al. 1996; Breitreuz and Kenedy 1999; Oberc-Dziedzic et al. 2003; McCann et al. 2006; Breitreuz et al. 2007; Nawrocki et al. 2007, 2008, 2010; Żelaźniewicz et al. 2008, 2016; Mazur et al. 2010; Zech et al. 2010). We compare our U–Pb data with Re–Os ages measured previously on molybdenite (Stein et al. 2005; Mikulski and Stein 2012) from the Myszków Mo–Cu–W deposit and from numerous ore manifestations along the KLFZ. Another aim of this study was the investigation of inherited zircon in the magmas with regard to their possible affinity to Gondwana and/or Baltica. There has been very little zircon U–Pb dating of the igneous rocks from the KLFZ—this paper attempts to fill that gap.

Geological setting of the contact zone between the Małopolska and Upper Silesia Blocks

The study area is located in southern Poland along the regional Kraków–Lubliniec Fault Zone (KLFZ) which, in the subsurface, separates the Upper Silesia (USB) and

Małopolska Blocks (MB), both concealed under Mesozoic–Cenozoic platform cover and Carpathian nappes (Fig. 1; Żaba 1999). The KLFZ is ca. 150 km long and up to 0.5 km wide and part of the transcontinental Hamburg–Kraków tectonic zone that constitutes the larger Trans-European Composite Tectonic Suture Zone (TESZ) that separates the East-European Craton (Laurussia–Baltica) from mosaic terranes in Western and Central Europe (Gondwana blocks, e.g., Arthaud and Matte 1977; Buła et al. 1997; Narkiewicz et al. 2015; Żelaźniewicz et al. 2016). Several granitoid bodies are present in the Variscan foreland in central Europe. Their origin has been linked alternatively with the Variscan orogeny and associated crustal thickening or calc-alkaline volcanism that accompanied the opening of a Permo-Mesozoic platform basin (Benek et al. 1996; Zech et al. 2010), which was dominated by silica-rich volcanism (e.g., in the North German–Polish Basin at 303–290 Ma; Breitreuz et al. 2007). The KLFZ is an important, long-lived strike-slip feature dominated by sinistral kinematics in the late Silurian and dextral kinematics in the late Carboniferous to early Permian (Żaba 1999). The USB is the NE part of the Brunovistulicum composite terrane, whereas the MB is a thinned marginal part of the Baltica/Laurussian craton (Żelaźniewicz et al. 2009). The KLFZ marks the contact between Baltica and the Palaeozoic European platform. Its multistage tectonic development had an impact on the deposition of Precambrian and Palaeozoic sediments on both blocks, as well as controlling their structural and magmatic evolution (e.g., Buła et al. 1997; Żaba 1999; Buła and Habryn 2011). The Precambrian basement of the USB consists of three complexes of different ages and origin: Archaean–Palaeoproterozoic metamorphic rocks, Neoproterozoic metamorphic and igneous rocks, and Ediacaran anchimetamorphic flysch (Buła et al. 1997). The main differences in the development of these blocks were in the early Palaeozoic (Żaba 1999). The Palaeozoic sedimentary cover, near the edge of the USB, consists of early and middle Cambrian clastic rocks, and Ordovician, Devonian and early Carboniferous clastic–carbonaceous deposits (culm facies; Buła et al. 1997). At the southwestern edge of the MB, the Precambrian basement consists of Ediacaran anchimetamorphic clastic rocks that are strongly deformed tectonically, and locally phyllitized (Żaba 1999). The lithological and sedimentary features of the Ediacaran rocks are characteristic of flysch, with a predominance of muddy clay. The Ediacaran sediments form a large horst-like structure that is divided by tectonic grabens and semi-grabens filled with Ordovician and Silurian sediments (e.g., in the vicinity of Żarki and Zawiercie; Buła et al. 1997). The Palaeozoic sedimentary cover consists of Ordovician carbonates and Silurian clastic and carbonaceous rocks with a maximum thickness up to 1 km. These sediments lie discordantly

Fig. 1 Geological sketch of the studied area without Mesozoic and Cenozoic sediments along the contact zone of the Małopolska Block with the Upper Silesia Block in the southern Poland (after Buła et al. 2002) with the location of the boreholes being subject of sampling for the purpose of U–Pb studies. BT Brunovistulian Terrane, CF Caledo-

nian Front, H–Cz Hamburg–Częstochowa Tectonic Zone, H–K Hamburg–Kraków Tectonic Zone, KLFZ Kraków–Lubliniec Fault Zone, MT Małopolska Terrane, TESZ Trans-European Suture Zone (Teisseyre–Tornquist Zone), VF Variscan Front

on Ediacaran clastic rocks of unknown thickness (probably up to a few kilometres; Buła et al. 2002). The upper Palaeozoic rocks at the edge of both blocks are similar—carbonate and clastic rocks of Devonian and Carboniferous age (Narkiewicz and Racki 1984). These sediments occur in large tectonic grabens (Buła et al. 2002). The Palaeozoic and Precambrian rocks form a monocline that runs NE from the Kraków–Lubliniec tectonic zone, but is

dislocated by normal transverse faults of regional extent and large amplitudes of displacement. During the Carboniferous to Permian, there was extensive plutonic and volcanic activity in the Małopolska and Brunovistulian terranes along the Kraków–Lubliniec regional fault zone. This Kraków–Lubliniec igneous belt comprises deep-seated, calc-alkaline, granodiorite–diorite to quartz monzonite–monzogranite intrusions (e.g., Wolska 2012 and

references therein) and a bimodal suite of sub-volcanic and volcanic rocks represented by mafic–intermediate (trachybasalts–trachyandesites with minor lamprophyres) and felsic (dacites–trachydacites–rhyolites) rocks (Ryka 1974; Wolska 1984; Heflik et al. 1992; Słaby 1987; Muszyński 1991, 1995; Muszyński and Pieczka 1996; Muszyński and Czerny 1999; Truszel et al. 2006; Żelaźniewicz et al. 2008; Słaby et al. 2010; Wolska 2012). It is likely that the bimodal igneous suite formed from magmas is derived from different types of sources, some of which might have been evolved by fractional crystallization (e.g., Czerny and Muszyński 1997). Słaby et al. (2010) suggested that the magmas forming the Krzeszowice volcanic rocks were derived from two different sources: the basalts–trachybasalts–trachyandesites from enriched (metasomatized) lithospheric mantle, and the dacite–trachydacites–rhyolites from the continental crust. Initially, it was unclear whether the felsic magmatism in the KLFZ was of early (Znosko 1983; Harańczyk 1989) or late (Karwowski 1988) Paleozoic age. This uncertainty arose from a lack of accurate isotopic age determinations. Dating by the K–Ar method yielded a wide range of ages (ca. 380–310 Ma), most of relatively low precision (Jarmołowicz-Szulc 1985). More recent geochronological studies (palaeomagnetism, Ar–Ar, U–Pb) indicate a Variscan age for the magmatism, peaking at the Permo–Carboniferous boundary (Podemski et al. 2001; Nawrocki et al. 2007, 2010; Żelaźniewicz et al. 2008, 2016). Granitoids with extrusive rocks have been intersected in about 260 boreholes. Granitoids from the boreholes are metaluminous to slightly peraluminous ($ASI < 1.1$), I-type rocks of calc-alkaline, medium- to high-K character (Wolska 2012, and references therein) with high Na_2O content (> 3.2 wt%) and normative diopside and corundum (mainly $< 1\%$). Most are multiphase intrusions into a variety of rocks ranging in age from Precambrian to late Carboniferous. The most common are granitoid intrusions, found so far only near the western edge of the MB. These small hypabyssal granitoid bodies (mainly granodiorite) occur in several parts of the Będowska Valley, Pilica, Zawiercie and Myszków–Mrzygłód–Nowa Wieś Żarecka areas (Fig. 1). Around these intrusions, porphyry dykes and diabase and lamprophyre veins developed (Ryka 1974; Piekarski 1995). The largest polyphase (complex) intrusion occurs in the MB in the area of Myszków–Mrzygłód–Nowa Wieś Żarecka. This linear intrusion was recognized between borehole 60Z in the north and borehole PZ10 in the southeast. It extends to a distance of ca. 7–8 km and has a width of up to ca. 1 km. This type of intrusion probably is also present in the vicinity of Żarki–Kotowice and Mysłów in the USB (Markowiak 2015). They probably relate to a batholith at depth, the existence of which is indicated by a negative gravimetric

anomaly that extends over a distance of about 30 km from Pilica to Żarki (Podemski et al. 2001).

Analytical methods

For the purpose of the isotopic studies, between 0.5 and 10 kg of rock was crushed and the heavy mineral fraction (40–250 μm) was separated using standard heavy liquid and magnetic procedures. Zircon grains were hand-picked, 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 sensitive high-resolution ion microprobe (SHRIMP) analysis at the Research School of Earth Sciences, Australian National University (ANU), using procedures described by Williams and Claesson (1987). The data were processed by methods described by Williams (1998, and references therein), and Williams and Hergt (2001) using PRAWN and LEAD software written by T.R. Ireland. Concordia diagrams were prepared using the ISOPLOT software written by Ludwig (2008). Individual analyses are plotted in the concordia diagrams with 1σ error ellipses, and uncertainties in the mean ages, which include the uncertainty in the standardization, are quoted at the 95% confidence level ($t\sigma$, where ‘ t ’ is Student’s t).

Major element contents of the 15 samples were measured at the Polish Geological Institute by wavelength dispersive X-ray fluorescence technique on glass beads, and minor and trace elements by WDS-XRF on powder pellets using a Philips PW-2400 and by digestion ICP-AES techniques. The conditions of the measurements for major oxides and trace elements were as follows: 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.

Sample sites and characteristics of igneous rocks and ore mineralization

U–Pb isotopic and geochemical work was carried out on eleven felsic igneous rock samples (six granitoids and five dacitoids) collected from the eight archive boreholes located on the MB near Mysłów, Myszków, Zawiercie, Pilica and Będowska Valley (Fig. 1). The other four samples (two dacitoids, a lamprophyre and diabase) were taken from two boreholes located on the USB near Koziegłowy. For detailed characterization/localization of studied samples, consult Table 1 and Figs. 1, 2.

Table 1 Description of samples for SHRIMP zircon U–Pb studies

Type of rock/sample symbol	Description	Mineral composition	Accessory minerals	Alterations	Borehole/depth (m)/Geo. cords
Granodiorite/ 60Z/29 KH2/14 PZ10/36 RK2/18 DB5/4	Dark grey or beige-grey, coarse to fine-grained, holocrystalline or non equigranular, porphyritic texture. Phenocrysts: 0.3–11.0 mm; matrix 0.05–0.6 mm; q-sulphide v.	Plagioclase, quartz, subordinate K-feldspar, biotite, hornblende, minor chlorite, hydro-micas	Apatite, zircon, sphene, ilmenite and/or magnetite, pyrrhotite, pyrite and/or goethite, chalcocopyrite, galena sphalerite, molybdenite	Weak plagioclase and feldspars sericitization, biotite chloritization, silicification, carbonatization, sulphidization, oxidation of ilmenite or/and pyrrhotite	60Z/253.0/50°35'13.31"/19°17'09.86" KH2/805.6/50°27'01.59"/19°37'14.42" PZ10/1163.0/50°32'51.37"/19°21'14.66" RK2/712.0/50°29'19.87"; 19°24'46.55" DB5/1239.0/50°11'24.95"/19°46'13.01"
Granodiorite strongly altered/ RK3/37 KH2/13	Grey or rose-grey holocrystalline, medium to fine-grained, locally equigranular, locally with porphyritic texture. Phenocrysts: 0.5–6.0 mm; quartz-carbonate-sulphide and chlorite-epidote v.	Quartz, plagioclase, alkali-feldspar, biotite, hornblende	Zircon, epidote, sphene, rutile, pyrite, ilmenite, pyrrhotite, chalcocopyrite, molybdenite, galena, sphalerite, covellite, goethite	Intensive sericitization, epidotization, chloritization, carbonatization, sulphidization, silicification, oxidation of ilmenite and pyrrhotite	RK3/847.0/50°29'21.38"/19°25'02.23" KH2/756.0/50°27'01.59"/19°37'14.42"
Dacite/ PZ11/21 DB5/7	Dark rose, hypocrystalline, medium to fine-grained; porphyritic texture with brownish matrix and light rose plagioclase (0.4–4.0 mm), quartz (0.8–3.0 mm) and dark biotite phenocrysts; matrix—0.02 mm; quartz ± chlorite ± sulphide ± carbonate v.	Phenocrysts: plagioclase, quartz, K-feldspar (up to 15 mm), biotite, hornblende, chlorite; matrix: plagioclase, quartz, biotite, hydro-micas	Zircon, calcite, apatite, epidote, sphene, rutile, magnetite, chalcocopyrite, molybdenite, pyrite, galena, sphalerite, goethite, arseno-pyrite, Bi- and Te-minerals	Chloritization, sericitization, carbonization, epidotization, silicification, sulphidization, oxidation of ilmenite and sulphides	PZ11/425.0/50°33'38.99"/19°18'56.63" DB5/1410.0/50°11'24.95"/19°46'13.01"
Dacite strongly altered/ PZ11/24 25WB/26 DB10/10	beige-grey, medium to fine-grained, porphyritic texture; locally with micropoilitic texture (DB-10) Phenocrysts: 0.3–12.0 mm; matrix 0.05–0.1 mm; quartz-sulphide ± carbonate ± goethite v.	Phenocrysts or relicts of plagioclase, biotite, quartz, and hornblende, and/or K-feldspar, chlorite; fine-crystalline matrix with quartz, plagioclases	Zircon, calcite, epidote, sphene, pyrite, molybdenite, galena, chalcocopyrite, Te- and Bi-mineral, sphalerite	Intensive sericitization and carbonization of plagioclases; biotite chloritization, epidotization, sulphidization, silicification	PZ11/1046.0 25WB/610/50°35'03.15"/19°13'01.09" DB4/763.0/50°10'53.55"/19°45'06.11"
Trachyte/ KO4/16	Porphyritic texture with dark brownish matrix and light brown plagioclase phenocrysts; 0.4–5.0 mm; matrix 0.05–0.2 mm	Phenocryst of plagioclase (samidine) and quartz; fine-crystalline matrix with quartz, plagioclases, K-feldspar, biotite and pyroxene	Sphene, epidote, apatite, zircon, ilmenite (up to 0.1 mm pillar-like crystals); pyrite	Sericitization of plagioclases and feldspars; biotite chloritization; fine-grained carbonatization; ilmenite oxidation	KO4/636.1/50°35'16.70"/19°08'44.27"

Table 1 (continued)

Type of rock/sample symbol	Description	Mineral composition	Accessory minerals	Alterations	Borehole/depth (m)/Geo. cords
Lamprophyre/ KO4/15	Dark-grey, holocrystalline porphyritic texture. Phenocrysts: 0.4–2.0 mm; matrix 0.08–0.2 mm; quartz-carbonate-chlorite veinlets	Alkali feldspar, biotite, chlorite, hornblende, minor quartz (individual > 1 mm)	Sphene, calcite, zircon, chalcocopyrite, pyrite, magnetite, ilmenite, goethite	Opacite rims around augite strong sulphidization, sericitization, carbonatization, chloritization	KO4/498.0/50°35'16.70"/19°08'44.27"
Diabase strongly altered/ 25WB/27	Dark-grey, holocrystalline and ophitic texture; quartz-carbonate-sulphide veinlets	Plagioclase set in a finer matrix of altered clinopyroxene (augite), olivine, hornblende, biotite, magnetite and ilmenite	Apatite, TiOx, pyrite (< 50 µm), pyrrhotite, chalcocopyrite (10–30 µm), calcite, chlorite, serpentine, marcasite	Sericitization, silicification, sulphidization, Ti-oxidation, pyroxene replaced by amphiboles or chlorite; and olivine to serpentine and magnetite	25WB/628.0/50°35'03.15"/19°13'01.09"

Granodiorites

They are calc-alkaline coarse-, medium- and fine-grained rocks with equigranular or/and porphyritic textures and appear undeformed. Those strongly altered are usually greyish red, rose-grey or brownish (Appendix 1a–g). Most granodiorites consist of plagioclase, quartz, K-feldspar, biotite and hornblende. Accessory minerals include apatite, zircon, epidote, Ti-oxides, magnetite and/or ilmenite, pyrite and Fe-oxides. Apatite and zircon form inclusions in biotite (zircon < 40 µm) and hornblende (zircon mostly > 100 µm). Secondary phases including albite, epidote, calcite, chlorite, titanite and sericitized feldspar are also abundant. Biotite and hornblende are subject to replacement by chlorite and, in the presence of ore minerals, plagioclase commonly is replaced by sericite (Fig. 3a–c). Most of the granodiorites are hydrothermally altered to variable degrees (Table 1), mainly by sericitization, carbonatization, chloritization, silicification, feldspathization, epidotization, oxidation, argillitization and sulphidization (Fig. 3d). In the log profiles, numerous intervals that are dozen metres long are cut by veinlets composed of quartz, feldspar, and chlorite–carbonates with sulphides.

Dacitoids

The group of sub- and volcanic calc-alkaline felsic rocks with porphyritic to aphyric textures is represented mainly by dacites and trachyte (Table 1; Appendix 1h–m). These rocks are pinkish, violet-red or red-beige in colour and medium to coarse grained. They are composed of K-feldspar, quartz and sodic plagioclase phenocrysts (1–12 mm diameter) within an allotriomorphic matrix of quartz and potassic feldspar. The phenocrysts in places comprise up to 30 vol% of the rock. The quartz phenocrysts have characteristic magmatic corrosion (Fig. 3e, f). Other minerals present are hornblende, biotite and small amounts of titanite, zircon, magnetite, ilmenite, pyrite, pyrrhotite, apatite, calcite and epidote. Dark minerals in places are chloritized and calcified and plagioclase may be replaced by sericite, albite or kaolinite due to hydrothermal activity (Fig. 3g, h). The dacite sample PZ11/24 is cut by quartz veinlets with molybdenite mineralization (Fig. 3i). Sericite, albite, kaolinite, calcite, Ti-oxides and sulphides form pseudomorphs after biotite and feldspar phenocrysts.

Lamprophyre and diabase

They are fine- and coarse-grained alkaline mafic–intermediate rocks with porphyritic textures (Appendix 1n, o). The lamprophyre (minette) and diabase samples were taken from boreholes KO4 near Kozięłowy, and 25WB north of

Fig. 2 Location of the sampling sites (arrows) for SHRIMP zircon U–Pb studies shown on the selected fragments of the geological log profiles of the eight different boreholes drilled on the Małopolska Block and two other drilled on the Upper Silesia Block

Mysłów, both on the USB (Fig. 1). One sample of diabase (25WB/27) is black-dark green in colour and cut by narrow quartz and pyrite veinlets (Appendix 1n). The diabase is strongly altered. Plagioclase is sericitized and pyroxenes are replaced by amphiboles and chlorites and olivine by serpentinite and magnetite. Lamprophyre KO4/15 is dark grey, with a porphyritic texture (Appendix 1o). 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, quartz, biotite and carbonates (Fig. 3j). Besides disseminated pyrite, ilmenite and magnetite, the lamprophyre contains narrow veinlets with chalcopryrite and pyrite.

Ore mineralization

The Mysłów Cu–Mo–W porphyry-type deposit, and several very prospective areas for other porphyry-, skarn-contact metasomatic and vein-type deposits, have been recognized along the KLFZ under the Mesozoic–Cenozoic platform cover (Harańczyk 1980; Piekarski 1995; Chaffee

et al. 1997; Koszowska and Wolska 2000; Podemski et al. 2001; Truszel and Karwowski 2003; Truszel et al. 2006; Oszczepalski et al. 2010 and references therein; Mikulski et al. 2012; Markowiak 2015). All are genetically related to Variscan felsic magmatism. Economic resources down to a depth of 1000 m in the Mysłów Mo–Cu–W deposit are estimated at >550 Mt, with 0.295 Mt of Mo, 0.238 Mt of W and 0.8 Mt of Cu (Malon et al. 2018). The Mysłów deposit has not yet been exploited. Its ore mineralization is mostly present as stockwork, forming a system of quartz veins with ore minerals (molybdenite, chalcopryrite, pyrite and scheelite). Molybdenite blades are curved and form separate aggregates up to 20 mm in diameter in thicker quartz veins (3–5 cm of thickness). Rosette-like aggregates that are 5–10 mm in diameter also occur disseminated in quartz veinlets and country rocks. Larger molybdenite crystals are curved and intergrown with K-feldspar or/and plagioclase. Fine-grained euhedral pyrite and single anhedral grains of chalcopryrite and native bismuth and/or bismuthinite may occur between parallel flakes of molybdenite. Scheelite occurs as fine crystals or aggregates, commonly <150 µm

Fig. 3 Microscopic photographs (in transmitted light: **a–c, e–h** and **j** and in reflected light: **d, i**) of igneous rocks from the Kraków–Lubliniec tectonic zone. **a** Slightly altered plagioclase (Pl, sericitized, carbonatized) and biotite (Bt, chloritized) with quartz (Q) crystals in the RK3/18 granodiorite sample. **b** Weak sericitization of plagioclases (Pl) and biotite (Bt) chloritization (Clc) in the KH2/14 granodiorite sample; *Q* quartz. **c** Intensive pyritization (Py), carbonatization and chloritization of the KH2/13 granodiorite sample. **d** Pyrrhotite (Po) with chalcopyrite (Cp) and sphalerite (Sf) intergrowths in the RK2/37 granodiorite sample. **e** Phenocrysts of quartz (Q) and sericitized plagioclase (Pl) within the plagioclase, quartz, biotite matrix in the PZ11/21 dacite sample. **f** Phenocrysts of plagioclase (Pl) being subject to sericitization and biotite (Bt) to chloritization in the DB5/7 dacite sample. *Q* quartz. **g** Carbonatization and sericitization of matrix in the DB4/10 dacite sample with xenomorphic crystals of sulphides (Suf). **h** Strong carbonatization of matrix with visible phenocrysts of plagioclase being subject to sericitization in the KO4/16 trachyte sample. **i** Molybdenite (Mo) flakes forming aggregates with chalcopyrite (Cp) in quartz veinlets cut altered dacite in the PZ11/24 sample. **j** Sericitized alkali feldspar phenocrysts in dendritic texture of groundmass composed of fibres of potassium feldspar in the KO4/15 lamprophyre sample

diameter in association with ilmenite and rutile (as inclusions) or more rarely with sulphides. Chalcopyrite, pyrite and sphalerite occur separately or as intergrowths and aggregates up to 10–30 mm diameter. They also occur included in other sulphides. Chalcopyrite may be replaced by bornite and covellite. The rocks hosting ore are commonly strongly altered to varying degrees, mainly by sericitization, carbonatization, chloritization, silicification, feldspathization, epidotization, oxidation, argillitization and sulphidization.

Gold-bearing veinlet-impregnation mineralization is found in the DB4 borehole in paragenetic association with pyrite, sphalerite, galena, chalcopyrite and minor arsenopyrite. Gold and electrum occur in the form of inclusions in sulphides and as fine grains (<0.1 mm) in quartz (Mikulski et al. 2008). Tellurium and bismuth minerals and variable composition of Bi, Ag, Pb, Cu and Ni sulfosalts have been found in different prospects along the KLFZ (Harańczyk 1980; Mikulski et al. 2015a and references therein). For example, in the Myszków (PZ40 and 82Z boreholes) and Mysłów (25WB borehole) areas, Bi minerals of the tetradymite group (tetradymite, kawazulite and sulfotsumoite), Bi tellurides from the hedleyite–tellurobismuthite group (pilsenite, tsumoite and rucklidgeite) and bismuth sulphides (bismuthinite, nevskite and paraganajuatite) have been recognized. In the PZ40 borehole, there are Ag tellurides (hessite and empressite) and Ag, Bi sulfosalts (matildite), as well as a variable composition of sulfosalts of Bi, Ag, Au, Pb, Se, Cu (e.g., padëraite, heyrovskýite, gustavite, aleksite, pavonite and others). Tellurium and bismuth mineralization occur together with various sulfosalts in close association with base metal sulphides (galena, chalcopyrite, pyrite and sphalerite). They formed veinlet-impregnation type mineralization in the marginal zones around Variscan granitoid intrusions and their porphyritic dykes.

Traces of REE mineralization are present in the KO4 borehole (depth, ca. 500 m). In a microprobe study, in addition to monazite and unidentified minerals from the anhydrous phosphate group enriched in REE (mainly Ce, La, and Nd), calcioancylite (Ce), synchysite (Ce), bastnäsite and zircon were also found. The form and composition of REE mineralization indicate that it is the product of a late metasomatic process (Mikulski et al. 2015b).

Geochemical characteristics of the igneous rocks

The major element oxide and trace element contents of 15 igneous rock samples from the contact zone between the MB and USB along the KLFZ are listed in Table 2. Several of the analysed samples were highly altered and mineralized (PZ11/24, KH2/13, RK2/37, DB4/10, 25WB/26, 25WB/27 and KO4/15), excluding them from being plotted

on the geochemical diagrams presented here. In the following diagrams, the compositions of the least altered samples are compared with those of igneous rocks collected by other researchers from boreholes (Ryka 1974; Muszyński 1991; Wolska 2012) and outcrops in the southern part of the KLFZ (Słaby et al. 2010) (Appendix 2). According to Słaby et al. (2010), the data for the felsic and intermediate suites from the KLFZ indicate two different unrelated trends which show a negative correlation with SiO₂ (Appendix 3). Our less altered felsic rocks are peraluminous (A/CNK = 1.01–1.13, Fig. 4a) and those of other authors also fall in the transition from metaluminous to peraluminous fields (0.90–1.23*, where * number given in parentheses refers to data taken from cited papers; Appendix 3). These felsic rocks have a small range in Mg# (atomic Mg/(Mg + Fe) 0.32–0.46 (0.21–0.55*)) and SiO₂ content 59.4–68.2 wt% (*61.5–73.0 wt%). They represent a magnesian series and are calc-alkaline with medium to high K (Fig. 4b) and a Na₂O/K₂O ratio of 0.4–3.1 (0.1–2.0*). The increase in K content is the result of magma differentiation and hydrothermal alteration (Słaby 1994). Altered samples show decreased A/CNK (Table 2).

In the R1 vs. R2 multicationic diagram (De la Roche et al. 1980), the main felsic rock types in the contact zone between the MB and USB (omitting the strongly altered samples) plot mostly in the granodiorite field (Fig. 4c), with some in the tonalite and monzogranite fields. All the unaltered granite samples studied have A/CNK < 1.1 and Na₂O contents above 3.2 wt%, classifying them as I-type granites according to the scheme of White and Chappell (1977). The granitoids belong to the magnetite and/or magnetite–ilmenite series of Ishihara (1981). In the dacitoids, magnetite is more abundant than ilmenite. In the altered granodiorites, magnetite is replaced by goethite and ilmenite by magnetite and/or secondary Ti-oxides.

In the volcanic rock (Na₂O + K₂O) vs. SiO₂ diagram (Fig. 4d), the felsic rocks plot in the fields of dacite, transitional to rhyolite and trachydacite, and the rocks with intermediate and mafic characteristics plot in the transition fields of alkaline trachybasalt (lamprophyre—KO4/15) and trachyandesite (diabase—25WB/27). Data from other authors plotted in Fig. 4d indicate that tephrite–basanite, phonotephrite and basaltic andesite are also present within the KL igneous belt. The Mg# in this group of rocks ranges from 0.39 to 0.69 and SiO₂ contents from 46.9 to 55.9 (Table 2; Appendix 2). Our lamprophyre and diabase samples have alkaline and shoshonitic characteristics with a range of K₂O, Fe₂O₃ and transition element (Cr, V, Ni and Co) contents (Table 2). Chemical compositions of our least altered granodiorite samples are plotted on Harker diagrams for the major oxides (Appendix 3a–g) for comparison with granitoid compositions reported by Wolska (2012) and Żelaźniewicz et al. (2008). These plots show negative correlations with SiO₂ for

Table 2 Chemical analyses (WDS-XRF) of the igneous rocks from the contact zone between the Małopolska and Upper Silesia Blocks

Borehole ID	60Z	KH2	PZ10	RK2	DB5	RK3	KH2	PZ11	DB5	PZ11	DB4	KO4	KO4	25WB
Depth (m)	253	805.6	1168	712	1239	847	756	425	1410	1046	603	636	497.5	614
Type of rock	Granodiorite	Granodiorite	Granodiorite	Granodiorite	Granodiorite	Granodiorite	Granodiorite	Dacite	Dacite	Dacite	Dacite	Trachyte	Lamprophyre	Diabase
Sample ID	60Z/29	KH2/14	PZ10/36	RK2/37	DB5/4	RK3/18	KH2/13	PZ11/21	DB5/7	PZ11/24	25WB/26	DB10/10	KO4/16	25WB/27
wt. %														
SiO ₂	68.18	67.69	67.49	67.88	67.37	66.59	59.36	67.73	68.22	63.62	66.76	62.32	63.69	48.09
TiO ₂	0.43	0.562	0.468	0.454	0.608	0.472	1.048	0.416	0.486	0.244	0.421	0.8	0.388	0.818
Al ₂ O ₃	16.05	15.71	16.38	16.52	16.03	16.65	16.50	15.33	15.51	9.95	15.66	15.68	15.21	17.19
Fe ₂ O ₃	2.59	3.51	2.83	2.68	3.50	2.92	5.43	2.96	2.89	1.45	2.61	5.95	3.23	9.50
MnO	0.043	0.075	0.025	0.045	0.053	0.081	0.126	0.072	0.038	0.149	0.079	0.164	0.05	0.198
MgO	1.04	1.15	1.13	1.12	1.24	1.23	2.08	1.16	1.26	0.99	1.11	1.44	1.29	10.60
CaO	2.45	2.76	2.43	2.59	3.00	2.15	3.28	1.36	2.06	7.85	1.83	2.87	3.23	2.82
Na ₂ O	4.15	3.74	4.47	4.50	4.20	4.11	4.58	3.93	4.35	1.30	2.20	4.41	3.69	1.59
K ₂ O	3.21	3.73	3.39	2.78	3.00	3.51	3.61	4.27	3.31	3.59	5.27	1.42	2.87	4.74
P ₂ O ₅	0.117	0.152	0.141	0.128	0.137	0.126	0.195	0.122	0.115	0.115	0.164	0.205	0.133	0.094
(SO ₃)	0.08	0.05	<0.01	0.01	0.05	0.24	0.70	0.26	0.09	1.73	0.47	0.76	0.16	0.57
(Cl)	0.021	0.037	0.024	0.024	0.029	0.017	0.025	0.020	0.024	0.040	0.020	0.025	0.020	0.030
(F)	<0.01	0.06	<0.01	0.05	0.06	<0.01	<0.01	<0.01	<0.01	0.09	<0.01	<0.01	<0.01	<0.01
LOI	1.45	0.62	1.00	1.04	0.57	1.65	2.81	2.19	1.49	6.5	3.08	3.79	5.85	3.62
SUM	99.8	99.85	99.8	99.83	99.86	99.74	99.62	99.79	99.82	97.62	99.67	99.76	99.81	99.86
A/CNK	1.08	1.03	1.061	1.09	1.02	0.49	1.15	1.13	1.07	0.94	1.23	1.12	1.01	1.34
Na ₂ O/K ₂ O	1.29	1.00	1.32	1.62	1.40	0.36	1.17	0.92	1.31	1.27	0.42	3.11	1.29	0.34
Mg#	0.44	0.39	0.44	0.45	0.41	0.45	0.43	0.44	0.46	0.58	0.46	0.32	0.44	0.69
ppm														
As	3	<3	<3	<3	<3	<3	17	11	<3	5	22	14	4	7
Ba	678	677	652	695	709	975	1454	678	652	311	1056	351	738	189
Br	3	4	5	3	3	4	4	3	3	4	3	3	3	3
Ce	27	43	34	40	46	25	50	53	32	28	63	40	26	7
Co	8	14	6	8	26	7	16	6	8	<5	12	7	6	33
Cr	<5	<5	8	7	<5	<5	14	<5	7	<5	10	<5	<5	102
Cu	50	16	17	12	8	121	132	86	17	22	182	180	11	190
Ga	18	17	19	18	17	19	17	18	16	13	18	18	18	17
Hf	5	<3	4	4	4	<3	3	5	<3	4	4	5	3	<3
La	17	30	34	36	30	28	37	29	37	29	29	45	13	8
Mo	36	<2	<2	4	<2	<2	19	5	<2	15,835	<2	<2	<2	25

Table 2 (continued)

Borehole ID	60Z	KH2	PZ10	RK2	DB5	RK3	KH2	PZ11	DB5	PZ11	25WB	DB4	KO4	KO4	25WB
Depth (m)	253	805.6	1168	712	1239	847	756	425	1410	1046	603	763	636	497.5	614
Type of rock	Granodiorite	Granodiorite	Granodiorite	Granodiorite	Granodiorite	Granodiorite	Granodiorite	Dacite	Dacite	Dacite	Dacite	Dacite	Trachyte	Lamprophyre	Diabase
Sample ID	60Z/29	KH2/14	PZ10/36	RK2/37	DB5/4	RK3/18	KH2/13	PZ11/21	DB5/7	PZ11/24	25WB/26	DB10/10	KO4/16	KO4/15	25WB/27
Nb	12	15	10	10	12	10	14	11	11	1109	8	12	8	15	7
Ni	3	4	<3	<3	5	3	10	6	4	<3	6	6	5	51	62
Pb	7	21	11	15	8	14	32	18	11	<3	74	96	5	21	10
Rb	95	133	84	74	103	98	129	163	112	118	154	78	68	148	193
Sr	407	281	508	457	345	471	363	258	282	103	275	291	350	585	168
Bi	<3	<3	<3	<3	<3	<3	3	<3	<3	<3	<3	11	<3	<3	<3
Th	8	9	6	9	7	5	5	8	8	3	13	8	5	23	<3
U	2	3	<2	2	2	<2	3	2	3	6	4	3	2	3	<2
V	43	51	41	49	56	44	101	44	50	25	44	82	47	202	176
Y	6	17	10	11	11	10	13	10	14	9	9	<3	5	30	20
Zn	37	53	21	36	34	47	138	35	43	49	585	369	39	51	124
Zr	151	161	178	161	131	163	160	159	137	78	178	160	124	414	78
Cd	3	3	<3	<3	<3	3	<3	3	5	5	11	6	4	5	<3
Sn	<2	3	<2	<2	<2	<2	15	3	<2	<2	<2	<2	<2	<2	<2

Fig. 4 The geochemical classification of igneous rocks from the contact zone between the Małopolska and Upper Silesia Blocks, according to various discrimination diagrams. **a** $\text{Al}_2\text{O}_3/(\text{Na}_2\text{O} + \text{K}_2\text{O})$ vs. $\text{Al}_2\text{O}_3/(\text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O})$ molar diagram (Shand 1943)—intermediate rocks are metaluminous, whereas acid rocks plot on the boundary between metaluminous and peraluminous composition; black symbols—own data (square, granitoids; circle, dacitoids); open symbols data (rhomboid, extrusive intermediate rocks, open square, acid intrusive and extrusive rocks) from: Muszyński (1991), Ryka (1974), Słaby et al. (2010), Wolska (1984, 2012). **b** K_2O vs. SiO_2

diagram shows the calc-alkaline and shoshonitic affinity of the igneous rocks from the KLFZ. **c** R_1 vs. R_2 multicationic diagram according to de la Roche et al. (1980). $R_1 = 4\text{Si} - 11(\text{Na} + \text{K}) - 2(\text{Fe} + \text{Ti})$; $R_2 = 6\text{Ca} + 2\text{Mg} + \text{Al}$. **d** $\text{Na}_2\text{O} + \text{K}_2\text{O}$ vs. SiO_2 diagram after Le Maitre (1989). Note black rhomboids own lamprophyre (KO4/15) and diabase (25WB/27) samples. Legend: grey, **e**, **f** Nb vs. Y and Rb vs. Y + Nb after Pearce et al. (1984). *syn-COLG* syn-collisional granites, *WPG* within-plate granites, *VAG* volcanic arc granites, *ORG* ocean ridge granites

Fe_2O_3 , K_2O , MgO , CaO , P_2O_5 and TiO_2 , and positive correlations for Al_2O_3 and Na_2O . According to Wolska (2012), the continuous trends on the Harker diagrams apparently indicate that during fractional crystallization of the granites, the precipitation of Mg–Fe silicates (hornblende and biotite), plagioclase and opaque minerals played an important role. The variable correlation and increasing trend of Na_2O and K_2O vs SiO_2 in some samples is connected with hydrothermal alteration. The compositions of the granitoids overlap with those of the felsic extrusive rocks (Słaby et al. 2010). Our felsic rock samples represented by granitoids and dacitoids have moderate Al_2O_3 (15.2–16.5 wt%) and low MgO (1.1–1.3 wt%) contents. The abundance of CaO and alkalis (Na_2O and K_2O) ranges in less altered samples from 1.4 to 3.3 wt%, from 2.2 to 4.5 wt% and from 2.8 to 5.3 wt%, respectively. As is shown in Table 2, the amount of LOI and SO_3 in the samples is variable, consistent with different degrees of hydrothermal alteration and ore mineralization. The most altered samples have LOI and S contents from 3.8 to 6.5 wt% and from 0.7 to 1.73 wt%, respectively. Moreover, some of them have high contents of Mo (up to 1.58%), Cu (up to 182 ppm), Zn (up to 585 ppm) and Pb (up to 96 ppm). These strongly altered samples are also characterized by high Ba contents (975–1454 ppm), indicating the influence of hydrothermal fluids. The less altered felsic rock samples have a low Rb (68–133 ppm) and high Sr (281–508 ppm) contents. Rb/Sr ratios for the granodiorites are 0.16–0.46. The Zr contents are moderate (124–178 ppm), as are the contents of transition elements: Ni (< 3–6.0 ppm), Co (6–26 ppm), Cr (< 5–8 ppm) and V (41–56 ppm).

On the Y vs. Nb diagram of Pearce et al. (1984), the felsic igneous rocks plot in the island arc (VAG) and syn-collisional (syn-COLG) granite fields (Fig. 4e). On the Y + Nb vs. Rb plot (after Pearce et al. 1984), they fall in the VAG collisional field (Fig. 4f) close to a triple point boundary that is characteristic of post-collisional granites transitional to the within-plate granite field (WPG).

SHRIMP zircon U–Pb results and zircon characteristics

Zircon from granodiorites

The zircon extracted from the granodiorite samples (Fig. 1) represented a bimodal population. In samples PZ10/36, 60Z/29, RK3/18, RK2/37 and KH2/13, about 50% of the zircon occurred as clear, colourless, fine to medium (40–100 μm), stubby (aspect ratio 2–3), subhedral to euhedral grains containing acicular mineral inclusions (probably apatite in KH2/13). Many grains had roughened crystal faces and rounded, simple pyramidal terminations. Others had well-developed {211} crystal faces (60Z/29) (Fig. 5a–e).

The second zircon population (sample KH2/13 about 50%; KH2/14, 60Z/29 and DB5/4 about 20%) occurred as clear, colourless fine to very coarse (50–200 μm diameter) more elongate grains (aspect ratios 2–6) with simple pyramidal terminations. Some lacked terminations, being fragments of larger crystals (Fig. 5f, g). Some grains contained a high abundance of clear acicular mineral inclusions (probably apatite) and rare specks of sulphide (KH2/14, Fig. 5f; DB5/4, Fig. 5g). CL imaging showed a marked contrast between the zoning textures of the two zircon types. The stubby grains consisted almost entirely of zircon with fine, concentric, euhedral zoning and moderate to weak luminescence. Some grains contained a texturally distinct inherited core. The larger, clearer grains all had broad prism–parallel banded zoning with moderate to strong CL and no sign of concentricity, even in the few cases where crystal terminations were preserved. A notable feature of the zircon grains in granodiorite sample KH2/14 was the presence of a roughly linear, fine, rust-coloured, axial cavity, in some cases running the full length of the grain, probably indicative of crystallization in the presence of a fluid phase.

In samples PZ10/36, RK2/37, RK3/18, KH2/14 and DB5/4, the U and Th contents of the igneous zircon were relatively uniform (mostly 25–950 and 50–370 ppm, respectively), with relatively homogeneous, intermediate Th/U ratios (mostly 0.3–0.5 or 0.5–0.7; Appendix 4), consistent with crystallization from a magma of relatively uniform composition. The zoned zircon from granodiorite sample 60Z/29 had a much wider range of U and Th content than similar zircon from most other samples (98–865 and 33–589 ppm, respectively) and also a wide range of Th/U (0.06–0.73). It is unlikely that all this zircon crystallized from the same magma at the same time. Either it represents different stages in the chemical evolution of the magma, or the magma was heterogeneous or a mixture.

As expected from the range in luminescence, in granodiorite sample KH2/13, the zircon grains with concentric zoning had a wide range of U (300–1250 ppm) and Th (135–530 ppm) contents, but mostly a narrow range of Th/U (0.42–0.50). The grains with banded zoning, in contrast, had more uniform U and Th contents (most 100–450 and 100–410 ppm, respectively) and consistently higher Th/U (most 0.9–1.4). The two types of zircon appear to have been precipitated from two different magmas of different compositions under different conditions. Nevertheless, with a single exception, the U–Pb isotopic analyses of both grain types from granodiorite sample KH2/13 in the Pilica area formed a single cluster concordant and equal in radiogenic $^{206}\text{Pb}/^{238}\text{U}$ within analytical uncertainty, with no detectable difference in age between them (Fig. 6a, b). The weighted mean radiogenic $^{206}\text{Pb}/^{238}\text{U}$ of 0.04693 ± 0.00011 was equivalent to an age of 295.6 ± 1.9 Ma (95% c.l.). Similar results were obtained from granodiorite zircon from the areas of

Fig. 5 Cathodoluminescence images of selected zircon grains from granodiorites, dacitoids, diabase and lamprophyre from boreholes located in the Małopolska Block and Upper Silesia Block. **a** Granodiorite 60Z/29, borehole 60Z, depth 253 m. **b** Granodiorite PZ10/36, borehole PZ10, depth 1163 m. **c** Granodiorite RK3/18, borehole RK3, depth 712 m. **d** Granodiorite RK2/37, borehole RK2, depth 847 m. **e** Granodiorite KH2/13, borehole KH2, depth 756 m. **f** Granodiorite KH2/14, borehole KH2, depth 805.6 m. **g** Granodiorite DB5/4, borehole DB5, depth 1239 m. **h** Dacite KO4/16, borehole KO4, depth 631.6 m. **i** Dacite PZ11/24, borehole PZ11, depth 1046 m. **j** Dacite 25WB/26, borehole 25WB, depth 610 m. **k** Dacite PZ11/24, borehole PZ11, depth 1046 m. **l** Dacite DB4/10, borehole DB4, depth 763 m. **m** Dacite DB5/7, borehole DB5, depth 1410 m. **n** Lamprophyre KO4/15, borehole KO4, depth 498.0 m. **o** Diabase 25WB/27, borehole 25WB, depth 628 m

Pilica (KH2/14), Myszków (PZ10/36) and Będowska Valley (DB5/4). In granodiorite samples KH2/14 and PZ10/36, all radiogenic isotopic compositions were concordant within analytical uncertainty. The analyses of the zoned zircon and overgrowths formed a tight cluster with no detectable range in radiogenic $^{206}\text{Pb}/^{238}\text{U}$, the weighted mean $^{206}\text{Pb}/^{238}\text{U}$ values of 0.04678 ± 0.00013 (KH2/14) and 0.04697 ± 0.00015 (PZ10/36) being equivalent to ages of 294.7 ± 2.3 Ma and 295.9 ± 3.0 Ma (95% c.l.), respectively (Fig. 6c–e). Zircon from the granodiorite sample DB5/4 from the Będowska Valley had a small range in radiogenic $^{206}\text{Pb}/^{238}\text{U}$ (Fig. 6f). 10 of the 12 analyses gave a weighted mean radiogenic $^{206}\text{Pb}/^{238}\text{U}$ of 0.04680 ± 0.00015 , equivalent to an age of 294.8 ± 2.6 Ma (95% c.l.).

Slightly older zircon was found in granodiorites from boreholes RK2 and RK3 from the Zawiercie area. The U–Pb isotopic compositions formed a tight cluster of concordant or nearly concordant points with no detectable scatter in radiogenic $^{206}\text{Pb}/^{238}\text{U}$. The weighted mean of $^{206}\text{Pb}/^{238}\text{U}$ for granodiorite sample RK3/18 (Fig. 6g, h), 0.04717 ± 0.00011 , was equivalent to an age of 297.1 ± 2.0 Ma (95% c.l.), and for the strongly altered granodiorite RK2/37 (Fig. 6i), 0.04742 ± 0.00015 , yielded an age of 298.6 ± 2.4 Ma (95% c.l.).

Granodiorite sample 60Z/29 (Fig. 6j, k) was the oldest from the Mysłów area. Six analyses equal within uncertainty had a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ of 0.04767 ± 0.00021 , equivalent to 300.2 ± 3.6 Ma (95% c.l.). The relatively large uncertainty in this age measurement reflects both the small number of analyses averaged and the relatively large uncertainties in some of those measurements.

Zircon from dacitoids

The zircon in the dacitoid samples occurred mostly as subhedral, medium to coarse (50–200 μm), stubby (aspect ratio 2–4, e.g., KO4/16) to moderately elongate (aspect ratio 1–6), colourless, moderately clear prismatic grains, a few with rusty brown mineral inclusions or internal staining and

signs of damage. Most had simple pyramidal terminations with few fractures or inclusions, some (KO4/16, PZ11/24) had {211} faces, commonly somewhat damaged (Fig. 5h, i). In the dacite sample 25WB/26 from the Mysłów area, about 10% of the zircon grains were very large fragments of even larger grains, some formerly anhedral, some sharply euhedral (Fig. 5j). CL imaging showed that the great majority of the grains in KO4/16, PZ11/21, DB4/10 and DB5/7 consisted entirely of zircon with fine, concentric, oscillatory zoning (Fig. 5h–m). CL imaging of zircon from the Mysłów area showed a wide variety of zoning textures ranging from simple euhedral to prism–parallel banding to unzoned (Fig. 5j).

In dacite samples PZ11/21 and PZ11/24 from the Myszków area, the U and Th contents of the zoned zircons were consistently high (500–1440 and 130–5360 ppm, respectively), with uniform but relatively low Th/U (0.23–0.45) (Appendix 4). Zircon from the Będowska Valley had mostly moderate U and Th contents (105–500 and 50–350 ppm, respectively) and relatively homogeneous, intermediate Th/U ratios (most 0.35–0.70). The latter are normal values for an intermediate composition igneous rock. In dacite sample 25WB/26 from Mysłów area, the small grains had a moderate range of U content (150–840 ppm) and larger range of Th (40–750 ppm), leading to a wide range of Th/U (0.27–1.02). In contrast, the large grains were consistently low in both U (69–86 ppm) and Th (32–58 ppm), all but one having almost identical Th/U (0.43–0.47). In dacite sample KO4/16 from the Kozięłowy area, a single spot on each of 15 grains was analysed, 11 on overgrowths, 4 on cores. The overgrowths had a small range of U (320–870 ppm) and Th (100–660 ppm), hence a relatively narrow range of Th/U (most 0.3–0.6).

All isotopic analyses of zircon from the dacitoids, including those of the cores, were concordant within analytical uncertainty, although there was a significant range in radiogenic $^{206}\text{Pb}/^{238}\text{U}$ in some samples. A small number of outliers was omitted from the age calculations. The youngest zircon was found in dacites from the Będowska Valley. The weighted mean radiogenic $^{206}\text{Pb}/^{238}\text{U}$ ratios for dacite samples DB5/7 and DB4/10 were very similar (0.04686 ± 0.00019 and 0.04691 ± 0.00017), equivalent to ages of 295.2 ± 2.9 and 295.5 ± 2.8 Ma (95% c.l.), respectively (Fig. 7a, b). One dacite (PZ11/24) from the Myszków area was slightly older, 297.7 ± 1.9 Ma (Fig. 7c, d). In the second dacite sample from this area (PZ11/21), assuming that radiogenic Pb loss was the most likely reason for the dispersion and omitting the three analyses with lowest $^{206}\text{Pb}/^{238}\text{U}$ left seven measurements just equal within analytical uncertainty, the weighted mean of 0.04780 ± 0.00011 was equivalent to an age of 301.0 ± 2.1 Ma (95% c.l.) (Fig. 7e, f).

Fig. 7 Concordia diagram showing SHRIMP zircon U–Pb analyses of dacitoids, diabase and lamprophyre from the Małopolska Block and the Upper Silesia Block. **a** Dacite DB5/7, borehole DB5, depth 1410 m. **b** Dacite DB4/10, borehole DB4, depth 763 m. **c, d** Dacite PZ11/24, borehole PZ11, depth 1046 m. **e, f** Dacite PZ11/21,

borehole PZ11, depth 425 m. **g** Dacite 25WB/26, borehole 25WB, depth 610 m. **h, i** Dacite KO4/16, borehole KO4, depth 636.1 m. **j–k** Lamprophyre KO4/15, borehole KO4, depth 498.0 m. **l** Diabase 25WB/27, borehole 25WB, depth 628 m

(KO4/16) being equivalent to ages of 302.1 ± 2.7 and of 303.8 ± 2.2 Ma (95% c.l.), respectively.

Zircon from diabase and lamprophyre

The small amount of zircon extracted from lamprophyre KO4/15 and diabase 25WB/27 consisted of fine to medium (50–150 μm) or very fine (≤ 50 μm) grains, respectively. They were clear, colourless, stubby (aspect ratios: KO4/15 2–4; 25WB/27 1–2) with sharply euhedral crystal faces and complex {211} pyramidal terminations with few fractures and with or without inclusions (Fig. 5n, o). Most zircon grains from the lamprophyre and some from the diabase were strongly rounded, consistent with partial dissolution. CL imaging showed a range of growth textures. Several of the larger, better preserved grains consisted entirely of zircon with simple, fine, concentric oscillatory zoning. Only about 60% of the smaller grains were similar. The remainder had either sector zoning, banded zoning, or were unzoned. About 60% of the grains from the diabase were intact crystals, the remainder rounded or angular fragments of formerly larger grains. The simply zoned zircon from KO4/15 had a relatively narrow range of U (most 140–300 ppm) and Th (most 60–165 ppm) contents, and with a single exception, a narrow range of Th/U (0.35–0.53), consistent with precipitation from a single magma (Appendix 4). All but one of the isotopic analyses was concordant within analytical uncertainty, all but three forming a single cluster with a small but significant range in radiogenic $^{206}\text{Pb}/^{238}\text{U}$ (Fig. 7j, k). Rejecting a single low analysis left 11 analyses in which the radiogenic $^{206}\text{Pb}/^{238}\text{U}$ was equal within uncertainty, the weighted mean ratio of 0.04672 ± 0.00016 being equivalent to an age of 294.4 ± 2.5 Ma (95% c.l.).

Many of the grains from diabase 25WB/27, despite their small size, consisted of a small texturally distinct core surrounded by a finely zoned overgrowth. A single spot was analysed on each of the 15 crystals, in most cases placed, because of size limitations, in the centre of the grain. There was a large range in U (56–2300 ppm) and Th (78–7350 ppm) contents, and a commensurate range in Th/U (0.4–3.2). Most of the range was due to two grains, the remainder having $\text{U} < 520$ ppm and $\text{Th} < 400$ ppm. With two minor exceptions, the isotopic compositions were concordant within analytical uncertainty, but the dates ranged widely from ca. 1550 to 290 Ma. Within that range, there were three possible clusters, two grains at ca. 1550 Ma, three at ca. 600 Ma, and four at ca. 290 Ma (Fig. 7l). The four youngest grains had no feature in common to distinguish them from other grains, in fact one (3.1) was a distinctive grain with prism parallel zoning unlike any other. Nevertheless, the radiogenic $^{206}\text{Pb}/^{238}\text{U}$ of the four grains was equal within analytical uncertainty, their weighted

mean of 0.04645 ± 0.00024 being equivalent to an age of 292.7 ± 4.9 Ma (95% c.l.). While unlikely to date the dacite magmatism, on the assumption that all the zircon in the sample is inherited, these grains do place a loose upper limit on the age of the magmatic activity.

Zircon inheritance

A selection of zircon cores from the studied samples was also dated. On average, the U and Th contents of the cores in the granodiorites were lower than in their igneous overgrowths, but Th/U was somewhat higher and more varied (e.g., PZ10/36; 0.5–0.9, 60Z/29; 0.54–1.25), consistent with the cores not having crystallized from the magma (Appendix 4). Inherited cores with pre-magmatic ages were found in 10 of the 15 samples studied, representing each of the major rock types and both the MB and USB. The texturally distinctive cores gave concordant dates of ca. 610, 1980 and 2775 Ma for PZ10/36 (Fig. 6d) and 576 ± 7 Ma (1σ), ca. 1460 and 1835 Ma for 60Z/29 (Fig. 6j). Moreover, the three cores analysed from granodiorite RK3/18 gave concordant results, but with dates ranging from 1950 ± 19 to 2050 ± 20 Ma (1σ) (Fig. 6g). The one core identified in sample KH2/14 yielded 624 ± 14 Ma (1σ). The thick zoned overgrowth around that core, including the CL dark inner layer seen in many other grains, indicated that the core was not a contaminant incorporated by the magma at a late stage, but was present in the magma from the time that the igneous overgrowths on all zircon grains first began to precipitate.

CL imaging of the zircon from the dacite samples showed that cores were present in about 30% (PZ11/21), 50% (PZ11/24) or 20% (KO4/16) of the grains. Most of the cores had very bright luminescence, and all were surrounded by a thick overgrowth of moderate CL zircon with simple oscillatory zoning, the same as the zircon forming the grains with no cores. As expected from their bright CL and hence low trace element contents, the cores of zircons from the PZ11 borehole had low U (50–265 ppm) and low to moderate Th (14–260 ppm). Two of the cores in sample PZ11/21 gave the same date of ca. 1490 Ma, a third gave ca. 1920 Ma (Fig. 7e). They appear to be detrital grains, probably from the source rocks of the magma. The distinct cores in sample PZ11/24 gave concordant dates of ca. 1475, 1485 and 2665 Ma (Fig. 7c). The low U–Th cores in sample KO4/16 yielded a range of concordant dates (ca. 555, 700 and 1435 Ma) (Fig. 7h). The presence of thick igneous overgrowths on these cores again was strong evidence that they were not contaminants or late additions to the magma, but originated from the source rocks from which the magma was derived.

In zircon from lamprophyre KO4/15, the range of U in the centres was similar to the rims, but the Th contents

were higher, giving Th/U ratios mostly of 1.1–1.8. Three grains gave concordant dates of ca. 1085, 1495 and 1965 Ma (Fig. 7j). One of those analyses (11.1) was on a grain with no oscillatory zoned overgrowth, while the other two were on the cores of grains with overgrowths, consistent with those two at least having resided in the magma for much of its crystallization history. Zircon cores in diabase 25WB/27 yielded dates of ca. 1550 and 600 Ma (Fig. 7l).

The number of cores analysed was too small for it to be possible to characterize the sources of the inheritance, but the range of ages measured in every sample indicates that the cores are probably derived from a heterogeneous sedimentary source. The range of core ages from the MB and USB is relatively similar, except for the presence of two Neoproterozoic cores in samples from the MB, and the presence of several cores younger than 500 Ma in one sample from the USB. The principal similarities in the core ages from both the USB and MB are the presence of age clusters at 500–650 Ma, 1.2–1.6 Ga and ~2.0 Ga. These age groupings closely resemble those found in the Palaeozoic sediments of southern Europe (e.g., Kolodner et al. 2006; Marzoli et al. 2017).

Discussion

U–Pb geochronology of igneous rocks along KLFZ

Our U–Pb isotopic study of zircon from igneous rocks representative of several areas on the both sides of the KLFZ has revealed a relatively narrow range of ages from 303.8 ± 2.2 to 292.7 ± 4.9 Ma for bimodal magmatism in the far foreland of the Variscan orogen in central Europe (Fig. 8, grey belt). Both the Małopolska and Upper Silesia blocks were intruded by a synchronous late Variscan magmatic suite. Słaby et al. (2010) advocated for two main magmatic–volcanic episodes during the late Carboniferous to early Permian (ca. 330–290 Ma) in the southern part of the KLFZ. Our results indicate, however, that the felsic and alkaline magmatism and volcanism took place over a much shorter time period, ca. 10 Ma (Appendix 5). In the Mysłów area on the USB, an early episode of felsic magmatism (303.8 ± 2.2 – 302.1 ± 2.7 Ma), represented by dacites, preceded alkaline (mafic–intermediate) potassic magmatism (294.4 ± 2.5 and 292.7 ± 4.9 Ma; Fig. 8, dark grey belt), represented by lamprophyre and diabase dykes. In the MB, the felsic magmatism was active over a similar period, from 301 ± 2.1 to 294.7 ± 2.3 Ma.

Fig. 8 Compilation of geochronological data from the Małopolska and Upper Silesia Blocks. References: 1—Nawrocki et al. (2007); 2—Żelaźniewicz et al. (2008); 3—Jarmołowicz-Szulc (1985); 4—

Harańczyk (1989); 5—Podemski et al. (2001); 6—Nawrocki et al. (2010); 7—Truszel et al. (2006); all other data from this study

The oldest phase of felsic magmatism in the MB is represented by 301 ± 2.1 and 300.2 ± 3.6 Ma dacites and granodiorites near Nowa Wieś Żarecka and Myszków. Slightly younger rocks are found in the region of Mrzygłód (297.7 ± 1.9 dacite), Zawiercie (297.1 ± 2.0 and 298.6 ± 2.4 granodiorite) and Pilica (granodiorite). Previous K–Ar dating of biotite from granitoids in the Myszków–Mrzygłód area also gave late Paleozoic ages, but with large uncertainties (granitoids 312 ± 17 Ma, dacite porphyries 301 ± 29 Ma; Jarmołowicz-Szulc 1985). Rb–Sr dating of igneous rocks from borehole RK2 (Zawiercie) gave 281 ± 17 Ma for granodiorites from the main intrusion and 340 ± 8 Ma for igneous rock apophyses in the lower part of the profile (Truszel et al. 2006). The youngest felsic magmatism along the KLFZ was found in the Będowska Valley, 295.5 ± 2.8 and 294.8 ± 2.6 Ma, respectively, for dacitoids and granodiorites. These results from the youngest magmatism identified so far in the MB are roughly consistent with the zircon U–Pb age of 300 ± 3 Ma measured on granodiorite from the same area (Żelaźniewicz et al. 2008).

Diabase was the youngest rock dated in the present study. Some previous attempts by different methods to date diabase found along the KLFZ have produced a range of higher age estimates, 418–390 Ma (Górecka and Nowakowski 1979; Jarmołowicz-Szulc 1985), leading to a common view that the gabbro–diabase suite in the area is related to Caledonian magmatism. The zircon U–Pb age from the present study (292.7 ± 4.9 Ma) indicates instead that the diabbases are early Permian, a conclusion consistent with previous results such as the biotite $^{40}\text{Ar}/^{39}\text{Ar}$ age of 305 Ma measured on diabase from borehole 16WB by Podemski et al. (2001), the $^{40}\text{Ar}/^{39}\text{Ar}$ dating by Nawrocki et al. (2007, 2008, 2010) and a fission track age of ca. 295 Ma reported by Skowroński (1974).

Zircon characteristics and inheritance

A distinctive feature of the zircon from the two blocks was the common presence of characteristic magmatic oscillatory zoning and minor presence of inherited zircon cores with a wide range of isotopic ages. Most of the igneous zircon from the magmatic rocks in the MB has the concentric zoning and intermediate Th/U (0.35–0.65) consistent with crystallization in a felsic magma of intermediate composition. Similarly, in felsic rocks from the USB, the Th/U in the rims of those zircon grains (0.3–0.6) was typical of intermediate composition magmas, but in the cores was higher (0.5–1.9), suggestive of crystallization in more mafic magmas. Consistent with this, the chemical composition of the alkaline igneous rocks (lamprophyre and diabase) suggests the presence of a mantle-derived component. The presence in the lamprophyre of some

zircon with lower Th/U (0.4–0.5), however, might indicate a component of more felsic magma. This study strongly suggests that the felsic magmas were mainly derived from upper crustal rocks, possibly with some mantle additions.

Reconnaissance U–Pb analyses of the inherited cores gave dates from the MB in the range 2775–575 Ma, with clusters at 625–575 Ma ($n=4$), 1.49–1.46 Ga ($n=5$) and 2.05–1.92 Ga ($n=5$), as well as single measurements at 2.78 and 2.67 Ga. In contrast, the inherited zircon from the USB mostly gave dates of ca. 625–555 Ma ($n=3$) and 1.55–1.44 Ga ($n=4$), and single core dates of 1.96 and 1.09 Ga. Given the thick overgrowths of igneous zircon on the older cores, the inheritance in both areas is likely to be detrital zircon from the source regions of the magmas, not contamination picked up from host rocks as the magmas were emplaced.

All the inherited zircon from the MB is likely to have originated from Baltica (Friedl et al. 2000; Bingen et al. 2008; Żelaźniewicz et al. 2009). Neoproterozoic (ca. 600 Ma) zircon is common in the Cadomian crystalline basement rocks of the Variscan orogenic belt and its foreland (Friedl et al. 2000, and references therein). Mesoproterozoic (ca. 1.49–1.46 Ga) zircon is quite common in the pyroclastic and epiclastic rocks of the East-European Platform in SE Poland (Krzemińska et al. 2014). Palaeoproterozoic (2.05–1.84 Ga) and late Archaean (2.78–2.67 Ga) zircon is common in the Svecofennian rocks that underlie much of central Europe (Friedl et al. 2000; Żelaźniewicz et al. 2009). The inherited zircon from the USB, as well as recording the common presence of Cadomian (625–555 Ma) crystalline basement, provided evidence for Mesoproterozoic (ca. 1.55–1.44 Ga) and Palaeoproterozoic (1.96 Ga) thermal events in this area. Inherited zircon with ages of 2.0–1.5 Ga from other parts of the Saxothuringian and Moravo-Silesian units of the Variscides in the central Europe was identified suggesting the West African, Amazonian and/or Avalonian cratonic crust as a source for igneous rocks protoliths (Friedl et al. 2000; Oberc-Dziedzic et al. 2003; Geisler et al. 2005; Pietranik et al. 2013; Żelaźniewicz et al. 2016). The igneous rocks from the USB contain inherited zircon of very similar ages, which supports the Moravo-Silesian affinity of the igneous rocks (lamprophyre, diabase and dacite) and their possible connection to Avalonia. They were recycled into younger units and underwent partial melting as peri-Gondwana terranes in the realm of the Amazonian cratonic province by the late Precambrian (Friedl et al. 2000). However, according to Żelaźniewicz et al. (2016), inherited zircon from felsic igneous rocks from the foreland of the Variscan orogen in central Poland included Sveconorwegian and older Baltican components.

Geotectonic model for Mo–Cu(W) mineralization along the KLFZ

The Kraków–Lubliniec Fault Zone (KLFZ) is part of the major Hamburg–Kraków–Dobrogea transcontinental strike-slip tectonic zone that separates the amalgamated Laurussian craton and Gondwana blocks on the SW margin of the East-European Craton (Żelaźniewicz et al. 2016). Moreover, several major NW-trending dextral strike-slip faults parallel to the TESZ developed in the hinterland and foreland of the Variscan orogen in central Europe. Those faults were active in Carboniferous–Permian times as part of mega-shear zones that resulted from the clockwise translation of the African plate with respect to the European plate (Arthaud and Matte 1977). The Kraków–Lubliniec igneous belt, along the fault zone, consists of a bimodal (felsic and mafic–intermediate) suite of igneous rocks that intrudes the continental blocks on both sides of the fault, the Małopolska and Upper Silesia Blocks. The compositions of the late Carboniferous magmas reflect a collisional tectonic setting but younger volcanism has signatures consistent with an extensional within-plate setting (Słaby et al. 2010). According to Żelaźniewicz et al. (2016), the geochemistry of the felsic magmas suggests that they were derived mainly from upper crustal rocks, with some mantle input. The felsic magmatism associated with this faulting was important in developing Mo–Cu (W) porphyry-type ore mineralization in different places along the USB and MB boundary beyond the Myszków Mo–Cu–W deposit, and most probably along another regional NW-trending major shear zone developed in the Variscan orogenic belt in central Europe. A close similarity between the zircon U–Pb ages and the Re–Os ages of molybdenite from the same region (Stein et al. 2005; Mikulski and Stein 2012) demonstrates an important link between the magmatism and ore mineralization. Molybdenite in different generations of quartz veinlets in the Myszków Mo–Cu–W deposit crystallized during the time interval 300 ± 2 to 296 ± 2 Ma (Stein et al. 2005). Similarly, molybdenite from quartz veins that cut dacite (at depth 267.7 m) and granitoid (at depth 285 m) in borehole 60Z, Nowa Wieś Żarecka, has yielded

Re–Os ages of 300.0 ± 2 and 299.0 ± 2 Ma, respectively (Mikulski and Stein 2012). These are indistinguishable from the zircon U–Pb age of granodiorite at depth 253.0 m from the same borehole, 300.2 ± 3.6 Ma. Zircon ages of 301.0 ± 2.1 – 295.9 ± 2.9 Ma, respectively from the Myszków–Mrzygłód region clarify the interpretation of ages of 300–296 Ma measured previously on igneous biotite and muscovite by the $^{40}\text{Ar}/^{39}\text{Ar}$ method (Chaffee et al. 1997), resolving doubt as to whether they record granitoid intrusion in the Myszków area or an early stage ore mineralization. Within the uncertainties of the current dating, felsic magmatism and ore mineralization were synchronous (Fig. 9). The same is true of Mo–Cu mineralization, in the MB and USB within the area up to 15 km away from the KLFZ (Fig. 9, Appendix 5). Moreover, the ages of magmatism and molybdenite mineralization in the Strzegom–Sobótka massif are similar (ca. 306.0 ± 1 – 296.0 ± 2 Ma) in the Marginal Sudetic Fault zone that separates the Sudetes from the Fore-Sudetic Block in the NE parts of the Bohemian Massif in south-western Poland (Mikulski and Stein 2005, 2011; Mikulski et al. 2007a, b).

A Cu–Mo or Mo–W calc-alkaline classic intrusion-related porphyry model has been proposed for the Myszków Mo–Cu–W deposit (e.g., Karwowski 1988; Podemski et al. 2001; Lason 2003). However, the moderate Re contents (40–75 ppm) of the molybdenites from the Myszków deposit and beyond are inconsistent with subduction-related porphyry-style Mo–Cu mineralization (Stein et al. 2005). Granite-related Cu and Mo deposits are associated with I-type intrusions (Blevin and Chappell 1995; Baker et al. 2005). Granite-related Cu deposits are associated with less fractionated granites (Rb/Sr from ca. 0.01 to 0.1), and Mo and W deposits with more fractionated granites (Rb/Sr ≈ 0.1 to 10, cf. Blevin and Chappell 1995). The unaltered granodiorites from the KL igneous belt in general have Rb/Sr ratios ranging from 0.16 to 0.47, indicative of slightly fractionated granites typical for Mo and W deposits.

According to Żelaźniewicz et al. (2008), granitoids in the MB occur outside the orogenic belt and the parent melt formed from thickened lower crust of the Variscan orogenic

Fig. 9 Comparison of isotopic U–Pb SHRIMP on zircon data from the present study with Re–Os isotopic analyses of molybdenites from the Kraków–Lubliniec Fault Zone in Poland (after Stein et al. 2005; Mikulski and Stein 2012)

belt during extensional decompression melting near the crust/mantle boundary. It was then transported away to the foreland setting along the crustal-scale KLFZ fault zone. If this was the case, the process of magma emplacement had a relatively short duration and took only ca. 10 Ma (from 303.8 ± 2.2 to 292.7 ± 4.9 Ma). The magmatic rocks have collisional, arc-related features and calc-alkaline characteristics that were inherited from an enriched, subduction setting source related to the process of Ediacaran/Cambrian reorganization—collision between Brunovistulia (the break up of Rodinia) and Baltica (Słaby et al. 2010). On the larger scale, the KLFZ is just a fragment of the SW margin of the TESZ along which dextral wrenching occurred due to the interaction between Baltica/Laurussia/Old Red Sandstone Continent and Gondwana in late stages of the Variscan collision (Arthaud and Matte 1977; Żelaźniewicz et al. 2016). The complex TESZ, with Baltica basement in the lower crust, was susceptible to transient effects of mantle upwelling that occurred by the end of the Variscan orogeny and resulted in an episode of the “flare-up” magmatism in the North German–Polish Basin (Breitkreuz and Kenedy 1999; Żelaźniewicz et al. 2016).

Late Carboniferous–Early Permian magmatism may have been triggered by that wrenching when the MB and USB just slipped past each other but did not collide (Żaba 1999; Nawrocki et al. 2010; Żelaźniewicz et al. 2009). I-type granites with oxidized magnetite- and transitional magnetite-ilmenite series from an arc setting are dominant within the KLFZ. However, an arc signature has been inherited from the basement from which the I-type granites were derived most likely by partial melting of an underplate as postulated by Słaby et al. (2010). The dated post Mo–Cu (W) ore rocks from the USB are alkaline (mafic–intermediate) volcanics of shoshonitic character, with low Mg# (0.49 and 0.69) and Ni contents (< 62 ppm), indicating rather evolved magma of relatively juvenile composition.

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 continental extension, uplift and deep fracturing (Römer et al. 2001; McCann et al. 2006; Mazur et al. 2010). This is evidenced by the geochemical characteristics of the Variscan granites from central Europe within the orogenic belt and its foreland (Benek et al. 1996; Zech et al. 2010). This scenario is also consistent with the magmatic–volcanic interpretation of the Sudetes (NE part of the Bohemian Massif) 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, accompanied by Permian alkaline volcanism. The transition from a post-collisional to within-plate setting was favourable for the formation of the transition of porphyry to epithermal Cu–Au mineralization

in uplifted areas of the Sudetes (Mikulski 2005; Mikulski and Williams 2014).

The most recent zircon U–Pb dating by SHRIMP points strongly to the major magmatism along the KLFZ having occurred in the late Carboniferous to early Permian, with older felsic magmatism followed by alkaline potassic volcanism in a narrow period of time (ca. 10 Ma) from 303.8 ± 2.2 to 292.7 ± 4.9 Ma. This U–Pb SHRIMP isotopic ages of felsic magmatism are coeval with Re–Os data of molybdenites (Stein et al. 2005) and together with the current regional models of tectonic (after Żelaźniewicz et al. 2016) and magma evolution (Słaby et al. 2010) allow us to connect the genesis of the Myszków Mo–Cu (W) deposit and other prospects along the KLFZ with regional tectonic movements and magma emplacements as a product of decompression melting induced in the areas of decreased pressure underwent in the wrench fault zones on the SW continental margin of the East-European Craton. There was no suitable environment for development of a classic porphyry-style mineralization along the KL igneous belt.

Conclusions

1. SHRIMP U–Pb dating of zircon from 15 magmatic rocks (felsic and alkaline/mafic–intermediate characteristics) from the igneous belt along the Kraków–Lubliniec tectonic zone (KLFZ), that occurs in the far foreland of the Variscan orogenic belt in Poland, and separates the Małopolska Block (MB) from the Upper Silesia Block (USB), has shown that magmatism in the area was a relatively short-lived event (303.8 ± 2.2 – 292.7 ± 4.9 Ma). Felsic magmatism in the northwest near Koziegłowy and Mysłów in the USB is the oldest (303.8 ± 2.2 – 302.1 ± 2.7 Ma). Felsic magmatism on the MB in general was contemporaneous or/and becoming slightly younger, from Nowa Wieś Żarecka, Myszków and Mrzygłód (301.0 ± 2.1 – 295.9 ± 2.9 Ma) to Zawiercie and Pilica (298.6 ± 2.0 – 294.7 ± 2.3 Ma) and up to the Będowska Valley (295.5 ± 2.8 – 294.8 ± 2.6 Ma).
2. The most voluminous magmatism along the KLFZ is represented by granitoid and dacitoid related rocks which are peraluminous, weakly evolved, and have post-collisional characteristics. This magmatism was followed by alkaline volcanism of mafic–intermediate characteristics. Alkaline magmatism produced lamprophyre (294.4 ± 2 Ma) and diabase (292.7 ± 4.9 Ma) dykes. Felsic magmatism in the USB started at 303.8 ± 2.2 Ma and was followed about 10 Ma later by alkaline volcanism at 292.7 ± 4.9 Ma. Late Carboniferous to early Permian bimodal magmatism was related to the transition from a post-collisional to within-plate setting along the SW margin of East-European Craton.

3. The presence of inherited zircon is a characteristic feature of the igneous rocks from both the USB and MB. The most common inheritance dates from both blocks are ca. 600 Ma (Cadomian basement) and ca. 1.40 Ga (Mesoproterozoic). Zircon from the MB has in addition cores giving dates of 1.92–2.05 and 2.67–2.78 Ga, both of which are characteristic ages for zircon from the Svecofennian of northern Europe. Also, zircon cores from the USB yielded Mesoproterozoic ages (1.09 and 1.44–1.55 Ga) and one Palaeoproterozoic age (1.96 Ga), which may indicate a connection to the Avalonian crust as possible protoliths. The inherited cores of zircon from felsic igneous rocks indicate mainly for crustal origins of primary materials ($U/Pb=0.4\text{--}0.6$), however, in alkaline igneous rocks also for materials input from more mafic rocks ($U/Pb=(0.5\text{--}1.9)$).
4. The zircon U–Pb ages measured on the felsic igneous rocks ($303.8 \pm 2.2\text{--}294.7 \pm 2.3$ Ma) are in accordance with the Re–Os isotopic ages of molybdenite ($300 \pm 2\text{--}296 \pm 2$ Ma, Stein et al. 2005; Mikulski and Stein 2012) from the Myszków Mo–Cu–W porphyry-type deposit and other areas in the KLFZ that are prospective for Cu–Mo ore mineralization. These extend over 60 km from Mysłów down to the Będowska Valley and about 20 km wide zone. Genesis of Mo–Cu (W) ores is correlated with KLFZ tectonic movements and magma emplacements as a product of decompression melting induced in the areas of decreased pressure born in the wrench fault zones that happened concurrently with the uplift in the Variscan hinterland on the SW continental margin of the East-European Craton. Alkaline potassic volcanism post-dated Cu–Mo ore mineralization that was closely related to felsic magmatism. The manifestation of REE mineralization of metasomatic hydrothermal type was connected with the younger alkaline volcanism.

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