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SHRIMP zircon study of a micromonzodiorite dyke in the Karkonosze Granite, Sudetes (SW Poland): age constraints for late Variscan magmatism in Central Europe

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Abstract – The large Variscan Karkonosze Granite in the West Sudetes, representative of the vast Variscan granite plutonism in Central Europe and located adjacent to regional tectonic suture and strike-slip-zones, has been difficult to date precisely; a range of published data varies between *c.* 304 and 328 Ma. However, the granite is cut by locally numerous lamprophyre and other dykes. Dating of the dyke rocks, emplaced shortly after the granite intrusion and cooled more rapidly, provides a promising tool for the verification of published SHRIMP results on the granite itself. SHRIMP zircon geochronology of a studied micromonzodiorite dyke indicates substantial admixture of inherited zircons of *c.* 2.0, 1.4 Ga (^{207}Pb–^{206}Pb minimum ages), and *c.* 570 (and 500?) Ma. The average concordia age of the main magmatic population of the zircons in the dyke is 313 ± 3 Ma (2σ); however, the true magmatic age might be older, around 318 Ma. This would constrain the age of the hypabyssal magmatism in the Karkonosze Massif and the minimum age of the host Karkonosze Granite. Thus, the Karkonosze Granite is confirmed as representative of an early phase of Variscan granite plutonic activity in the central-European Variscides.

Keywords: zircon, SHRIMP geochronology, Variscan magmatism, dykes, Karkonosze Granite, Sudetes.

1. Introduction

The Bohemian Massif in the Central European Variscides is characterized by intense late- to post-orogenic magmatism, with the most active period spanning broadly the time between *c.* 330 and 290 Ma. The magmatic activity has left large granitic plutons which seal the basement units of the Variscan orogen. One of the largest plutons is the Karkonosze Granite in the West Sudetes, straddling the Czech/Polish border. The pluton occupies the centre of the medium-grade metamorphic Neoproterozoic–Palaeozoic envelope of the Izera-Karkonosze Massif (Fig. 1).

Despite extensive geological research, including the classical granite-tectonics studies by Cloos (1925), detailed geological and petrographic investigations by Borkowska (1966), Klomínský (1969), Mierzejewski & Oberc-Dziedzic (1990), as well as more recent petrological studies (Žák & Klomínský, 2007; Słaby & Martin, 2008), the exact timing of the emplacement of the Karkonosze Pluton remains unresolved. The ages obtained by various isotopic methods are scattered between *c.* 304 and 328 Ma (Machowiak & Armstrong, 2007; Kusiak *et al.* 2008*a*,*b* and references therein, and R. Kryza, T. Oberc-Dziedzic & C. Pin, unpub. data 2008). Some authors report difficulties in obtaining precise magmatic ages in these rocks due to, for instance, high U contents, common Pb contamination, and secondary alteration of magmatic zircons.

Why is the timing of the Karkonosze Pluton so important within the Variscan context? Recent petrological and geochemical studies (Słaby & Martin, 2008) have shown that the origin of that pluton involved considerable input of mafic, mantle-derived magmas, thus marking a period of significant tectonothermal activity at deep lithospheric levels, in particular, extensive mantle upwelling and melting during the final stages of the Variscan orogeny. Furthermore, the late Variscan granite plutonism was a major crust-building process, and the Phanerozoic evolution of the lithosphere of central Europe cannot be well constrained without reliable geochronological data. The Sudetes area, where the Karkonosze Granite is the largest Variscan pluton, is one of the key areas where extensive international structural, petrological and geophysical projects were recently undertaken (e.g. Franke *et al.* 2000; Winchester *et al.* 2002; Grad *et al.* 2006 and references therein). Dating of the Karkonosze Granite bears important implications for the reconstruction of the structural evolution of the complex Sudetic segment of the Variscides. The emplacement of the Karkonosze Granite followed extensional collapse along a regional suture zone located within the eastern metamorphic cover of the pluton (possibly a

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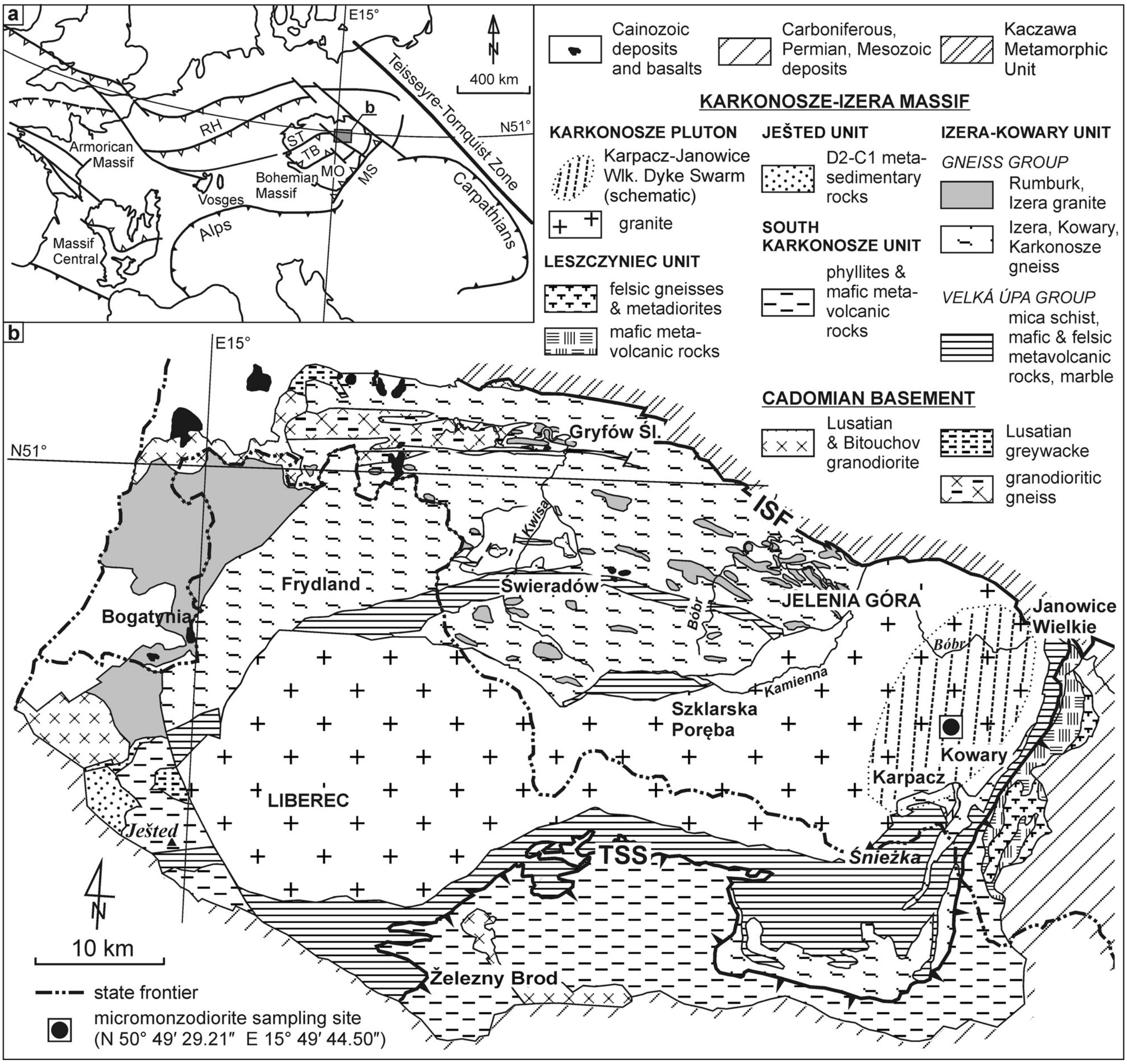

Figure 1. (a) Location of the study area within the Variscan Belt of Europe (based on Mazur *et al.* 2006). The grey rectangle shows the area of the main map (b). MO – Moldanubian, MS – Moravo-Silesian, RH – Rhenohercynian, ST – Saxothuringian, TB – Teplá-Barrandian. (b) Geological sketch of the Karkonosze-Izera Massif and the general location of the sampling site for SHRIMP study reported in this paper (based on Oberc-Dziedzic *et al.* 2008). ISF – Intra-Sudetic Fault, TSS – Teplá-Saxothuringian Suture (inferred eastern continuation).

fragment of the Teplá/Saxothuringian suture: Mazur & Aleksandrowski, 2001; Mazur *et al.* 2006; Oberc-Dziedzic *et al.* 2008). The NE side of the Karkonosze Granite is, in turn, cut by the Intra-Sudetic Fault (Fig. 1), a regional-scale strike-slip fault zone parallel to the Teisseyre–Tornquist Line that defines the SW edge of the East-European Platform. Relatively late sinistral movement along this fault has cut off part of the contact aureole of the granite against the Kaczawa Complex to the NE (Fig. 1), thus giving evidence that the movement post-dated the emplacement of the pluton (interpretation of R. Kryza and S. Mazur *in* Aleksandrowski *et al.* 1997). Therefore, dating of the Karkonosze Granite puts constraints on the timing of tectonic movements along major suture and strike-slip zones defining likely terrane boundaries, and on the transitions between various tectonic regimes (thrusting–extension–strike-slip) within the eastern segment of the Central European Variscides.

The large 25 Ma scatter in the published geochronological data on the Karkonosze Granite shows that the emplacement of the granite cannot be easily dated even with sophisticated *in situ* methods. Instead of multiplying SHRIMP results on the granite itself (nine SHRIMP determinations so far), often not easy for geological interpretation, we have tried to date a dyke which cross-cuts the granite. The arguments for this are: (1) simple geological relationships prove the dyke to be younger than the host granite; (2) fast cooling of the magma in the dyke provides fewer opportunities

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for modifications of isotopic signatures of zircons in the dyke compared to those in the host granite pluton, therefore a simpler interpretation can be expected; (3) petrological data indicate that the emplacement of the dyke shortly followed the emplacement of the Karkonosze granite (Awdankiewicz, 2007; Słaby & Martin, 2008). These arguments suggest that an upper age limit for the granite can be easily obtained, and that the existing data set on the age of the granite can be verified by dating even a single dyke sample.

After detailed petrological investigations (Awdankiewicz, 2007), a sample from micromonzodiorite dyke in the eastern part of the Karkonosze Pluton was selected for a SHRIMP zircon study. Such dykes are widespread, belonging to the Karpacz-Janowice Wielkie Dyke Swarm of calc-alkaline lamprophyres (Awdankiewicz, Awdankiewicz & Kryza, 2005; Awdankiewicz *et al.* 2007; Awdankiewicz, 2007). Dating of zircons separated from the micromonzodiorites (1) gives information on the age of the hypabyssal magmatism in the Karkonosze Massif and, through the dating of inherited zircons, on the deep crustal sources involved in the magmatic processes, and (2) constrains the age of the Karkonosze Granite, one of the largest plutons in the Central European Variscides, adjacent to major regional suture and strike-slip zones (Mazur *et al.* 2006).

2. Geological context

2.a. The Karkonosze Pluton and the Karpacz-Janowice Wielkie Dyke Swarm

The Karkonosze Pluton, about 60 km long and up to 20 km wide, comprises several granite types, with two dominating varieties: (a) porphyritic and (b) equigranular (aphyric) granites; other varieties (e.g. 'granophyric' type) are subordinate (Borkowska, 1966; Mierzejewski & Oberc-Dziedzic, 1990). The Karkonosze Granite is considered as a late- or post-orogenic pluton (Duthou *et al.* 1991; Diot, Mazur & Couturie, 1994; Wilamowski, 1998) of KCG type (K-rich calc-alkaline granitoids of Barbarin, 1999) and of mixed origin (Słaby *et al.* 2007). Słaby & Martin (2008), based on geochemical modelling, showed that mixing of coeval mantle-derived lamprophyre magmas and crust-derived granitoid magmas strongly influenced the evolution of the predominant porphyritic granites, whereas the equigranular granite facies originated by fractional crystallization.

The granite has been dated by the Rb–Sr whole rock isochron method at 328 ± 12 Ma ('central' porphyritic granite) and 309 ± 3 Ma ('ridge' equigranular granite: Duthou *et al.* 1991; Pin, Mierzejewski & Duthou, 1987); conventional Pb–Pb and U–Pb multigrain-zircon datings yielded an age of 304 ± 14 Ma for porphyritic monzogranite (Kröner *et al.* 1994). Broadly similar ages were obtained using SHRIMP zircon geochronology: 314 ± 3.3 Ma and 318.5 ± 3.7 Ma for porphyritic granites of the NE part of the pluton (Machowiak & Armstrong, 2007), and between 302.2 ± 6.4 and 314 ± 4.8 Ma for various types of the granite (Kusiak *et al.* 2008*a*,*b*). ^{40}Ar–^{39}Ar dating of a single biotite from porphyritic granite (Liberec-type granite) gave an age plateau at 320 ± 2 Ma, with the two last high temperature steps at 315 and 314 Ma (Marheine *et al.* 2002). Rather surprisingly, these ^{40}Ar–^{39}Ar ages are older than most of the SHRIMP ages (see above). An application of chemical abrasion prior to SHRIMP dating (R. Kryza, T. Oberc-Dziedzic & C. Pin, unpub. data 2008) yielded more refined data and indicated a likely magmatic age of the main porphyritic granite facies within the range 320–330 Ma, that is, close to the earlier Rb–Sr results (Duthou *et al.* 1991; Pin, Mierzejewski & Duthou, 1987).

The eastern part of the Karkonosze Pluton is cut by the Karpacz-Janowice Wielkie dyke swarm, which consists of several tens of mafic to felsic dykes cropping out in a NE-aligned area approximately 20 × 10 km in size (Awdankiewicz, Awdankiewicz & Kryza, 2005; Awdankiewicz *et al.* 2007; Awdankiewicz, 2007). The Karpacz-Janowice Wielkie swarm comprises minettes, vogesites, spessartites, monzonites, micromonzodiorites and porphyrytic microgranites. The more mafic, geochemically primitive rock types are subordinate to the more felsic, evolved rocks. Based on geochemical, isotopic and mineralogical data, Awdankiewicz (2007) considered that the petrological diversity of the dykes resulted mainly from the interaction of mantle-derived minette magmas with the lower continental crust; mixing of mantle and crustal magmas was responsible for the formation of various lamprophyric melts, which further evolved into monzonitic–monzodioritic compositions due to assimilation–fractional crystallization processes. Some of the dykes intruded while the host granite was incompletely solidified, but the majority are generally younger than the granites.

The dykes cutting the Karkonosze intrusion have not been dated prior to this study. However, the mafic rocks of the dykes are not easy subjects for isotope geochronology; ^{40}Ar–^{39}Ar dating often fails because of alteration of suitable minerals. Zircon, in turn, is not common; separation of zircon for SHRIMP analysis from other mafic rocks in the swarm was attempted but failed. Only one sample of a micromonzodiorite provided a sufficient amount of zircons for dating.

2.b. The micromonzodiorites

The micromonzodiorites are widespread in the Karpacz-Janowice Wielkie dyke swarm and represent relatively evolved members of this hypabyssal suite. Individual micromonzodiorite dykes are up to 10–20 m thick, several hundred metres long, and they cut the porphyritic granites. Sharp contacts with the host granite, local cataclasis of the granite along the contacts, and chilled margins of the dykes (mainly observed in blocks) show that the emplacement of the micromonzodiorite dykes post-dated the consolidation of the host granites.

Micromonzodiorite samples were collected in several old quarries near Bukowiec, about 12 km SE of Jelenia Góra (Fig. 1b). The petrographic observations are based on 25 thin-sections and EMP results from two samples, discussed in detail in Awdankiewicz (2007). The micromonzodiorites are mesocratic, moderately to sparsely porphyritic rocks with a microcrystalline groundmass. The magmatic minerals are strongly replaced by various post-magmatic phases. The phenocrysts, up to 2 mm long, comprise altered plagioclase, augite and chlorite pseudomorphs (after olivine?). Plagioclase and augite are also the dominant components of the groundmass, where they form euhedral to subhedral, prismatic, 0.5–0.1 mm long crystals. Plagioclase is strongly replaced by very fine-grained aggregates of sericite with less common prehnite. Relics of magmatic labradorite and oligoclase/albite are found in places. Augite phenocrysts show sieve textures, variable zoning and intergrowths of Mg-hornblende, actinolite and ferro-actinolite, but smaller groundmass crystals are more homogeneous. Other groundmass components are sanidine, albite, quartz, ilmenite, titanite, chlorite, calcite, clinozoisite, brown hornblende and, in some specimens, small crystals of post-magmatic Ca–Fe garnet (grossularite–andradite).

Micromonzodiorite specimens usually contain various inclusions, crystal aggregates and enclaves, of millimetre to centimetre size. Apart from quartz and feldspar xenocrysts derived from the host Karkonosze granite, there are also alkali feldspar-rich ocellae, as well as glomerocrystals and fine-grained comagmatic enclaves composed of augite, altered plagioclase and chlorite pseudomorphs (after olivine?). Other, less common enclaves represent migmatitic and restitic rocks. The phenocrysts, glomerocrystals and enclaves, together with geochemical and isotopic data, indicate that the micromonzodiorite magmas formed due to assimilation–fractional crystallization processes that affected the parental, lamprophyric melts at lower crustal levels (Awdankiewicz, 2007).

3. SHRIMP zircon study

3.a. Methods

The sample selected for zircon geochronology comes from the longest micromonzodiorite dyke near the village of Bukowiec, and was collected in an old quarry about 0.6 km ESE of the village centre (locality 7 in Awdankiewicz, 2007). The sample, about 3 kg in weight, was crushed, sieved, and the 0.06–0.25 mm heavy fraction separated using the conventional heavy liquid (sodium polytungstate) procedure. Hand-picked zircons representing various morphological types were mounted in epoxy resin, and a polished section was used for optical microscopy, CL imaging and SHRIMP analysis.

The Sensitive High Resolution Ion Microprobe (SHRIMP II) at the All Russian Geological Research Institute (VSEGEI) in St Petersburg was used to determine zircon ages in the sample selected. SHRIMP analytical details are given in Appendix 1. Uncertainties for individual analyses (ratios and ages) are at the 1σ level (see text, Table 1, Fig. 2); however, the uncertainties in calculated concordia ages are reported at the 2σ level. The results of the zircon analyses are shown in Table 1 and in Figures 2 and 3.

3.b. Zircon characteristics and SHRIMP ages

The zircons are diversified in morphology and many crystals are broken. Some of the crystals are euhedral but many tend to be subrounded. Many grains are also strongly structured, with CL bright and dark oscillatory zoning (Fig. 2). Distinct cores are visible in a number of crystals and a few grains have somewhat irregular forms.

Common Pb is rather low, between 0 and 0.68 %, whereas the Th/U ratio is mostly moderate to fairly high (~0.2–0.6), typical of magmatic zircons (Table 1).

Sixteen points in fourteen zircon crystals have been analysed. Most of the analytical points were selected within oscillatory zoned external parts of grains in order to determine the main magmatic event(s). A few points, however, were placed in cores or central parts of crystals, to test the possible presence of inheritance. Four analytical points have appeared to be significantly negatively discordant (two of them having ^{207}Pb–^{206}Pb minimum ages of *c.* 500 Ma) and these have been excluded from our interpretation.

Two points in irregular zircon grains gave positively discordant ^{207}Pb–^{206}Pb minimum ages of *c.* 1.4 and 2.0 Ga (Table 1). Two other euhedral and zoned crystals (apparently magmatic in origin) yielded Neoproterozoic, fairly concordant ^{206}Pb–^{238}U ages: 565 ± 5 and 578 ± 6 Ma. Evidently, all of these represent inherited materials (Fig. 3).

The main population of zircons displays ^{206}Pb–^{238}U ages dispersed within the range of 298–318 Ma. The average concordia age for seven points is 313 ± 3 Ma (Fig. 3c). However, all the points are slightly to significantly positively discordant, which makes this average age problematic.

Based on the data available, it is difficult to determine precisely the true magmatic age of the micromonzodiorite dyke. One single analysis (11.1) of the youngest age of *c.* 298 Ma and of a strong positive discordance (+69, Table 1) has been excluded from our interpretation. Four other positively discordant points are also relatively young and oscillate around 307 and 311 Ma, but their discordance may indicate Pb loss. More likely, two relatively old ages of *c.* 318 Ma, representing the same main population of the zircons, may approximate the magmatic age of the micromonzodiorite: analytical points 2.1: 318.4 ± 3.2 Ma, and 4.1: 318.0 ± 3.0 Ma. Their relatively high uranium contents and low common-Pb resulted in better accuracy and

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Table 1. SHRIMP data for zircons from the micromonzodiorite dyke from Bukowiec

Spot	$^{206}Pb_c$ (%)	U ppm	Th ppm	$^{232}Th/^{238}U$	$^{206}Pb^*$ ppm	(1) $^{206}Pb–^{238}U$ age	(1) $^{207}Pb–^{206}Pb$ age	% Discordant	Total $^{238}U/^{206}Pb$	±%	Total $^{207}Pb/^{206}Pb$	±%	(1) $^{207}Pb^*/^{206}Pb^*$	±%	(1) $^{207}Pb^*/^{235}U$	±%	(1) $^{206}Pb^*/^{238}U$	±%	Err. corr.
1.1	0.00	514	149	0.30	21.5	306.8±3.1	322±46	5	20.54	1.0	0.05207	1.7	0.0528	2.0	0.3551	2.3	0.04874	1.0	.449
2.1	0.00	474	145	0.31	20.6	318.4±3.2	378±38	19	19.75	1.0	0.05417	1.7	0.05417	1.7	0.3781	2.0	0.05063	1.0	.520
3.1	0.09	245	55	0.23	19.8	578.5±5.9	563±43	−3	10.64	1.1	0.0597	1.7	0.0589	2.0	0.762	2.2	0.0939	1.1	.478
3.2	0.68	158	94	0.61	12.8	578.2±7	413±110	−29	10.58	1.2	0.0606	2.0	0.055	5.1	0.712	5.2	0.0938	1.3	.240
4.1	0.00	648	211	0.34	28.2	318±3	347±34	9	19.78	0.98	0.05318	1.4	0.05342	1.5	0.3724	1.8	0.05056	0.98	.551
4.2	0.00	166	79	0.49	7.05	310.9±3.8	407±80	31	20.28	1.2	0.0534	2.9	0.0549	3.6	0.374	3.8	0.04941	1.2	.329
5.1	0.03	239	92	0.40	10.1	310.6±3.5	363±55	17	20.25	1.1	0.0541	2.4	0.0538	2.4	0.3661	2.7	0.04936	1.1	.424
6.1	0.08	986	306	0.32	77.6	564.7±5	568±22	1	10.91	0.92	0.05968	0.82	0.05902	1.0	0.745	1.4	0.09156	0.92	.673
7.1	0.00	287	117	0.42	12.1	309.7±3.5	481±120	55	20.39	1.1	0.054	2.2	0.0567	5.2	0.385	5.3	0.04921	1.2	.219
8.1	0.52	282	115	0.42	11.4	295.1±3.4	106±140	−64	21.24	1.1	0.0524	2.4	0.0481	5.9	0.311	6.0	0.04684	1.2	.198
9.1	0.00	224	113	0.52	9.62	315.2±8.7	432±97	37	20.02	2.8	0.053	2.4	0.0555	4.3	0.383	5.2	0.0501	2.8	.544
10.1	0.54	329	28	0.09	24.4	530±5.4	460±79	−13	11.60	1.0	0.06062	1.6	0.0562	3.6	0.664	3.7	0.08568	1.1	.283
11.1	0.00	615	206	0.35	25.0	297.8±3.7	503±41	69	21.17	1.3	0.05677	1.6	0.0573	1.9	0.3735	2.2	0.04728	1.3	.562
12.1	0.00	190	40	0.22	24.6	908±24	1383±28	52	6.62	2.8	0.088	1.4	0.088	1.4	1.835	3.1	0.1512	2.8	.889
13.1	0.28	601	175	0.30	40.7	487.2±4.7	411±42	−16	12.70	10	0.05721	1.2	0.055	1.9	0.595	2.1	0.0785	1.0	.468
14.1	0.00	497	134	0.28	110	1472±13	1959±27	33	3.899	0.97	0.1202	1.5	0.1202	1.5	4.25	1.8	0.2564	0.97	.539

Errors are 1σ; Pb_c and Pb^* indicate the common and radiogenic portions, respectively.
Error in Standard calibration was 0.42%.
(1) Common Pb corrected using measured ^{204}Pb.

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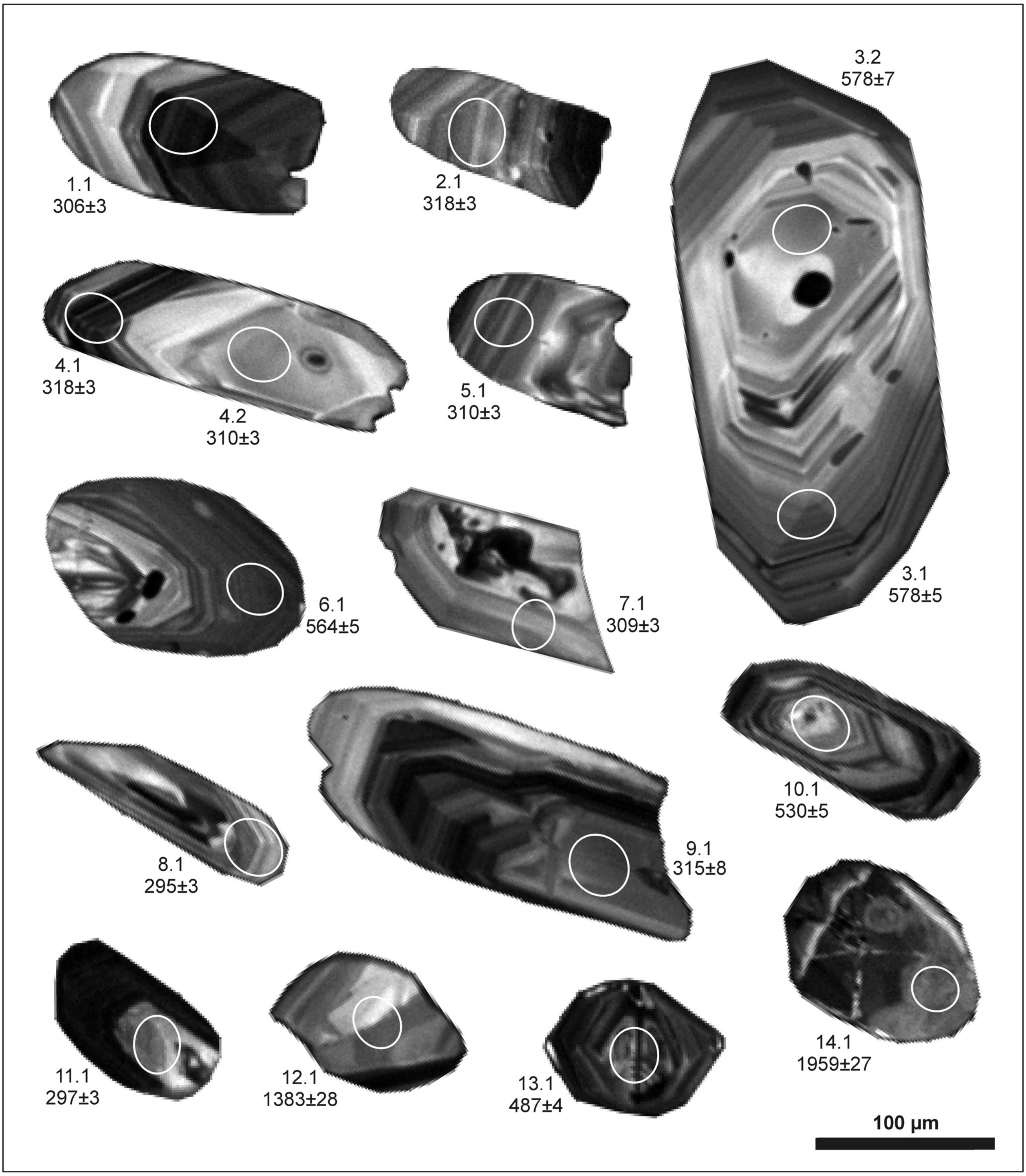

Figure 2. Zircons from the micromonzodiorite from Bukowiec (CL images); Precambrian ages, older than 570 Ma, given as ^{207}Pb–^{206}Pb minimum ages; younger ages are ^{206}Pb–^{238}U ages (uncertainties at 1σ level).

a smaller discordance. Thus, we interpret the age of 318 ± 3 Ma (1σ) as the likely magmatic age of the dyke.

4. Discussion and conclusions

The SHRIMP data from zircon grains from the micromonzodiorite dyke in the eastern part of the Karkonosze Pluton indicate a significant admixture of inherited materials of *c.* 2.0, 1.4 Ga and *c.* 570 and, tentatively, 500 Ma. This information potentially may help to define the older crustal materials, either in the source of the magma or, more likely, contributing to magma contamination in the assimilation–fractional crystallization processes within the lower crust (Awdankiewicz, 2007). Unfortunately, the small number of these inherited zircons dated limits the possible interpretation, and in particular, leaves obscure the significance of the Palaeo- and Mesoproterozoic minimum ages. The two strongly discordant zircons

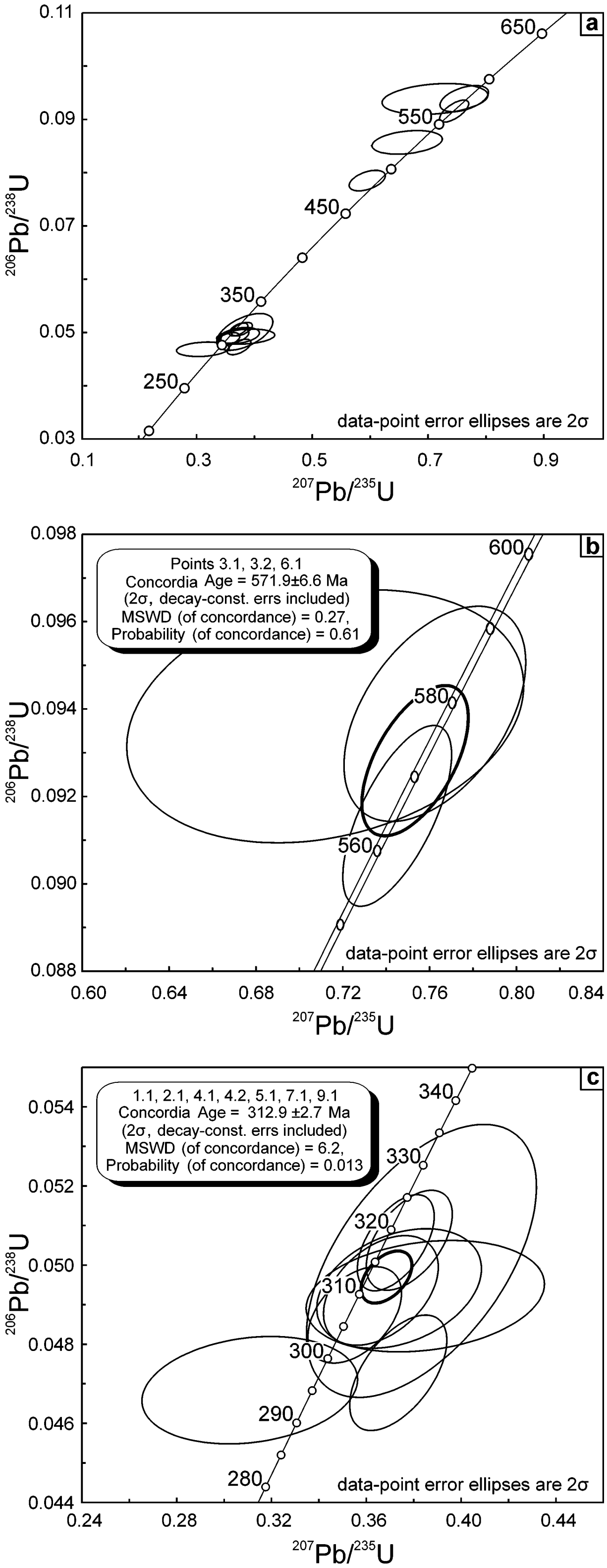

Figure 3. (a) Concordia diagram showing results of SHRIMP zircon analyses from the micromonzodiorite; all data between 270 and 600 Ma. (b) Concordia diagram showing the ages around 570 Ma. (c) Concordia diagram showing the ages around 300–320 Ma.

of 2.0 Ga and 1.4 Ga (^{207}Pb–^{206}Pb ages) have likely minimum ages, resulting, for example, from probable multiple Pb-loss. The latter age of *c.* 1.4 Ga is rather uncommon in the Saxothuringian crustal rocks

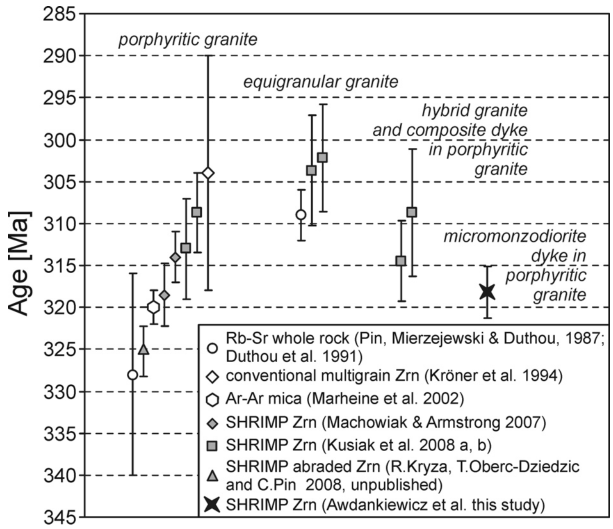

Figure 4. Compilation of geochronological data from the Karkonosze Pluton.

(Linnemann *et al.* 2004), thus this single result should be treated with caution.

A similar assumption can be made as far as the younger inherited zircons are concerned. However, the age of *c.* 570 Ma, corresponding to the Cadomian tectonothermal activity, is typical of the crust in the Saxothuringian Zone (Zeh *et al.* 2001; Linnemann *et al.* 2004), with which the Izera-Karkonosze Massif is correlated (Mazur *et al.* 2006; Oberc-Dziedzic *et al.* 2008) and, more generally, of a West African provenance. Also, the age of *c.* 500 Ma is very typical of the widespread granitic plutonism (orthogneisses) and bimodal volcanic activity in this part of the future Variscan belt (e.g. Kröner *et al.* 2001; Pin *et al.* 2007; Oberc-Dziedzic *et al.* 2008). In any case, the diverse inherited zircon assemblages testify to the polygenetic character of the source/contaminant materials for the monzodioritic magma.

The SHRIMP data obtained suggest that the main zircon population represents the magmatic event of the microgranodiorite, and thus the likely minimum age of the dyke is *c.* 313–318 Ma. This would constrain the age of the hypabyssal magmatism in the Karkonosze Massif, as well as the minimum age of the Karkonosze Granite in that part of the pluton. Such an age is in broad agreement, within error, with the earlier Rb–Sr dating of the porphyritic granite at 328 ± 12 Ma (Duthou *et al.* 1991; Pin, Mierzejewski & Duthou, 1987) and with the more recent SHRIMP zircon ages of 318.5 ± 3.7 Ma for the porphyritic granite of the NE part of the pluton (Machowiak & Armstrong, 2007; Fig. 4). Similarly 'old' ages have recently been confirmed by refined SHRIMP dating using chemically abraded zircons (R. Kryza, T. Oberc-Dziedzic & C. Pin, unpub. data 2008). Providing the age of the main facies of the Karkonosze Granite is *c.* 320–328 Ma, the likely age of the post-granitic dyke would imply that the dyke swarm was formed soon after the consolidation of the granite, probably within the same magmatic event.

The new SHRIMP data on zircons from the microgranodiorite dyke studied clearly constrain the age of the major granite plutonic event in the eastern part of the Variscan orogen to at least *c.* 320 Ma. Thus, the large Karkonosze Pluton represents a relatively early plutonic event in the Variscan orogeny as compared, for example, with younger, *c.* 290–300 Ma, plutons of the Strzegom-Sobótka and Strzelin massifs in the Fore-Sudetic Block (e.g. Turniak, Tichomirova & Bombach, 2005, 2006 and references therein). These age constraints for the plutonic and hypabyssal magmatism are also in accord with the cooling ages broadly ranging between 318 and 280 Ma (Marheine *et al.* 2002; M. Awdankiewicz & M. Timmermann, unpub. data 2008), corresponding to the exhumation path of the Karkonosze-Izera Massif.

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Appendix 1. SHRIMP analytical procedure

In situ U–Pb analyses were performed on a SHRIMP-II at the Centre of Isotopic Research (CIR) at VSEGEI, applying a secondary electron multiplier in peak-jumping mode following the procedure described in Williams (1998) and Larionov, Andreichev & Gee (2004). A primary beam of molecular oxygen was employed to ablate zircon in order to sputter secondary ions. The elliptical analytical spots had a size of about 27 × 20 μm, and the corresponding ion current was about 4 nA. The sputtered secondary ions were extracted at 10 kV. The 80 μm wide slit of the secondary ion source, in combination with a 100 μm multiplier slit, allowed mass-resolution of $M/\Delta M \geq 5000$ (1 % valley) so that all the possible isobaric interferences were resolved. One-minute rastering over a rectangular area of about 60 × 50 μm was employed before each analysis in order to remove the gold coating and possible surface common Pb contamination.

The following ion species were measured in sequence: $^{196}(Zr_2O)$–^{204}Pb–background (∼ 204 AMU) –^{206}Pb–^{207}Pb–^{208}Pb–^{238}U–^{248}ThO–^{254}UO with integration time ranging from 2 to 20 seconds. Four cycles for each spot analysed were acquired. Every fifth measurement was carried out on the zircon Pb/U standard TEMORA (Black *et al.* 2003) with an accepted ^{206}Pb–^{238}U age of 416.75 ± 0.24 Ma. The 91500 zircon with a U concentration of 81.2 ppm and a ^{206}Pb–^{238}U age of 1062.4 ± 0.4 Ma (Wiedenbeck *et al.* 1995) was applied as a 'U-concentration' standard. The collected results were then processed with the SQUID v1.12 (Ludwig, 2005*a*) and ISOPLOT/Ex 3.22 (Ludwig, 2005*b*) software, using the decay constants of Steiger & Jäger (1977). The common lead correction was done using measured ^{204}Pb according to the model of Stacey & Kramers (1975).