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Deciphering the geochronology of a large granitoid pluton (Karkonosze Granite, SW Poland): an assessment of U-Pb zircon SIMS and Rb-Sr whole-rock dates relative to U-Pb zircon CA-ID-TIMS

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Abstract

Granitoid plutons are often difficult to radiometrically date precisely, due to the possible effects of protracted and complex magmatic evolution, crustal inheritance and/or partial re-setting of radiogenic clocks. However, apart from natural/geological issues, also methodological and analytical problems may contribute to blurring geochronological data. This may be exemplified by the Variscan Karkonosze Pluton (SW Poland). High-precision chemical abrasion (CA) ID-TIMS zircon data indicate that the two main rock types, porphyritic and equigranular, of this igneous body were both emplaced at ca. 312 Ma, while field evidence points to a younger age for the latter. This is in contrast to the earlier reported SIMS (SHRIMP) zircon dates that scattered mainly between ca. 322 and 302 Ma. In an attempt to overcome this dispersion, at least in part caused by radiogenic lead loss, the chemical abrasion technique was used before SHRIMP analysis. The $^{206}\text{Pb}/^{238}\text{U}$ age obtained in this way from a sample of porphyritic granite is 322 ± 3 Ma, ~16 Ma older than the untreated zircons; another porphyritic sample yielded a mean age of 319 ± 3 Ma, and the mean age was 318 ± 4 Ma for an equigranular granite sample,— all three somewhat older than

the age obtained by ID-TIMS. Older SIMS dates of ca. 318-322 Ma might indicate either faint inheritance or that zircon domains crystallized during earlier stages of Karkonosze igneous evolution.

The ID-TIMS results have been used to re-assess the whole-rock Rb-Sr data. Excluding a porphyritic granite with excess radiogenic ^{87}Sr , it appears that isotopic homogeneity was achieved for most samples during the 312 Ma event, as shown by a pooled 21-point isochron with an age of 311 ± 3 Ma and an initial $^{86}\text{Sr}/^{87}\text{Sr}$ of 0.7067 ± 4 . Local crustal contamination by stopping of metapelitic material might account for the more radiogenic Sr isotope signature observed in biotite-rich schlieren.

A critical re-evaluation of all available SHRIMP data using the ID-TIMS age of 312 Ma as a benchmark suggests that the observed scatter may be partly attributed to analytical and methodological problems, in particular failing to distinguish subtly discordant spots from truly concordant ones, which is a serious limitation of the microbeam analytical approach. Other likely pitfalls contributing to geochronological scatter are identified in the published Re-Os ages on molybdenite, and the $^{40}\text{Ar}/^{39}\text{Ar}$ data on micas. A scenario postulating 15-20 Ma evolution of the Karkonosze Pluton cannot be established on the basis of available geochronological data, which rather supports a brief igneous event, although a more protracted pre-emplacement evolution is possible. A short timescale for crystallization of large igneous bodies, as suggested by the ID-TIMS data from the Karkonosze Granite, is in line with models of transport of granitic magmas through dikes to form large plutons.

Keywords: U-Pb zircon dating; SHRIMP; chemical abrasion; ID-TIMS; Rb-Sr isotopes; Re-Os dating; granitoids; short-lived vs protracted magmatic evolution, Variscan Karkonosze Granite

1. Introduction

Precise and accurate dating of many composite granitoid plutons is still a challenging task, even when applying high-precision modern analytical techniques (*e.g.*, Schmitz and Kuiper 2013; Schoene *et al.* 2013). Indeed, radiogenic isotope systems may be difficult to interpret due to the combined effects of inheritance (that is, heterogeneous mineral assemblages including xenocrystic grains), and post-igneous disturbances leading to partial opening(s) of

the isotopic clocks. In such complex situations, microbeam techniques (*e.g.* SIMS) can be used to analyze small, pristine zircon domains at a spatial resolution of ca. 20-30 μm (Nemchin *et al.* 2013, and references therein), but even this does not eliminate the possibility to sampling an isotopically disturbed or inherited domain. Ion probe analyses, however, suffer from significant limitations inherent to the small sample volume analyzed, specifically the intrinsically imprecise $^{207}\text{Pb}/^{235}\text{U}$ ages when dealing with Phanerozoic zircons which preclude a precise assessment of concordance of the two isotopic clocks ^{238}U - ^{206}Pb and ^{235}U - ^{207}Pb to be made (*e.g.*, Pin and Rodriguez 2009). For this reason, the measured dates are basically $^{206}\text{Pb}/^{238}\text{U}$ *apparent* ages which can be biased towards too young values by unresolved minor lead loss, or towards too old values by minor, unresolved inherited radiogenic lead or sample/standard matrix misfit. Applying the chemical abrasion (CA) technique developed by Mattinson (2005) as a pre-treatment for TIMS analysis and adapted for SIMS by Kryza *et al.* (2012) removes the altered metamict portions of zircon grains prior to isotope measurements, aiming to obtain more accurate ages. However, such data, shifted to older dates, may also show scatter difficult to interpret in detail, *e.g.* in the light of age determinations obtained by other methods.

In this paper, we discuss numerous attempts to date the Variscan Karkonosze Pluton in the West Sudetes, which is one of the largest granitoid bodies in the NE part of the Bohemian Massif (Fig. 1). The Karkonosze Pluton has been well known since the classical granite-tectonic studies by Cloos (1925). Later on, the petrology of the granite has been studied in detail, *e.g.* by Borkowska (1966), Žak and Klominský (2007), Słaby *et al.* (2007), and Słaby and Martin (2008). Despite the increasing amount of geochronological data obtained by various methods during the past three decades, including the most recent SIMS (SHRIMP) and ID-TIMS studies (Duthou *et al.* 1991; Pin *et al.* 1987; Kröner *et al.* 1994; Marheine *et al.* 2002; Awdankiewicz *et al.* 2007, 2010; Machowiak and Armstrong 2007; Kusiak *et al.* 2009, 2013; Kryza *et al.* 2012; Žak *et al.* 2013; Kryza *et al.* 2014), the precise timing of the magmatic emplacement of various granite facies and of post-magmatic changes remains controversial.

This study presents new SHRIMP U-Pb age determinations obtained on chemically abraded zircons from samples representing the two main petrological types of the Karkonosze Pluton: porphyritic and equigranular granites, respectively, and referring also to the dates published by Kryza *et al.* (2012) obtained on both untreated and chemically-abraded zircons. These new SIMS data, as well as the earlier published results of conventional SHRIMP dating, are discussed in the light of the recently published high-precision ID-TIMS U-Pb age

determinations ([Kryza et al. 2014](#)). We also discuss in detail previous Rb-Sr results, which provide an example among potential pitfalls of the whole-rock isochron method, and critically assess published Re-Os (molybdenite) and Ar-Ar (micas) data giving ages significantly older than the CA-ID-TIMS U-Pb zircon age.

2. Geological context

2.1. Variscan granitoids in Central Europe

The Karkonosze Pluton studied is located in the Sudetes, in the NE part of the Bohemian Massif, near the eastern end of the Variscan Belt of Europe (Fig. 1). The Bohemian Massif exposes crystalline basement units of the Variscan internides, comprising variously metamorphosed rocks ranging in age from Precambrian to Early Carboniferous. The rocks exposed in the NE part of the Bohemian Massif were deformed and metamorphosed diachronously, during the Variscan orogeny, from the Mid/Late Devonian (in the Central Sudetes), through the Early Carboniferous (in the West Sudetes), to around the Early/Late Carboniferous boundary (in Brunovistulicum of the East Sudetes) (Mazur *et al.* 2006, and references therein). The basement units are sealed by numerous Variscan granitoid plutons and overlain by Carboniferous – Permian molasse and a Mesozoic-Cenozoic sedimentary cover.

The Sudetes area is located between the WNW–ESE trending Upper Elbe Fault Zone to the SW and the Middle Odra Fault Zone in the NE, and cut down in the middle by the Intra-Sudetic Fault. All these main faults represent major Variscan strike-slip zones, parallel to the SW margin of the East-European Platform, the “Teisseyre-Tornquist line” (Mazur *et al.* 2006, and references therein).

The Sudetes have a mosaic structure and, here, the regular structural zonation of the Variscan Belt (Kossmat 1927) becomes obscure. The tectonic mosaic of the Sudetes comprises several structural basement units, interpreted by some authors as terranes ([Matte et al. 1990](#)) of the Armorican Terrane Assemblage (Franke 2000). The West Sudetes have been interpreted as part of the Saxothuringian Zone, and the Central Sudetes as part of the Teplá-Barrandian and Moldanubian zones (Mazur *et al.* 2006; Franke 2012). The East Sudetes are correlated with Brunovistulicum, east of the Bohemian Massif ([Oberc-Dziedzic et al. 2013](#)),

interpreted as an individual microcontinent of Avalonian affinity ([Schulmann and Gayer 2000](#); [Finger et al. 2000](#)).

The intense granitoid magmatism in the Sudetes during the Variscan orogeny spanned a wide time interval between ca. 350 and 280 Ma ([Mazur et al. 2006, 2007](#); [Finger et al. 2009](#); [Oberc-Dziedzic and Kryza 2012](#); [Oberc-Dziedzic et al. 2010a, 2013](#); and references therein). The early granitoids (350–335 Ma) were contemporaneous with the development of major strike-slip faults and shear zones. The granitoid plutonism culminated between 325–290 Ma, producing several large plutons, such as the Karkonosze Pluton studied and the Strzegom-Sobótka Massif. The youngest zircon ages of 280–290 Ma from granites were reported from the Strzelin intrusion ([Oberc-Dziedzic et al. 2013](#), and unpublished data).

2.2. The Karkonosze Pluton

The Karkonosze Pluton in the West Sudetes, straddling the border between Poland and the Czech Republic, is a large (~ 70 x 20 km), late-orogenic Variscan granitoid intrusion within the core of the dome-shaped Karkonosze-Izera Massif in the NE part of the Bohemian Massif (Fig. 1). The envelope of the granite comprises, from bottom to top, ca. 500 Ma orthogneisses ([Kröner et al. 2001](#); [Oberc-Dziedzic et al. 2009](#); [Żelaźniewicz et al. 2009](#)) and mica schists, overlain by a set of tectonic units composed of Palaeozoic metavolcanic-sedimentary successions (for condensed description see [Mazur et al. 2006](#)). The pronounced contact aureole of the pluton, up to several hundred metres wide, on its NE side is truncated by a major strike-slip fault, the Main Intra-Sudetic Fault Zone ([Aleksandrowski et al. 1997](#)).

Mierzejewski (in [Mierzejewski and Oberc-Dziedzic 1990](#)), based on detailed structural studies including the internal fabric of the granite, argued that the magma was supplied from a deeper “centre” located in the eastern part of the pluton. In that part of the pluton, also a large lamprophyre dyke swarm is located ([Awdankiewicz 2007](#)).

The Karkonosze Pluton is formed of several types of granitoids (Fig. 2). The most widespread is the *coarse-grained porphyritic Bt granite (type I)*. In the eastern (Polish) part of the pluton, it was named the “central granite” ([Borkowska 1966](#)). In the western (Czech) part, the coarse-grained porphyritic biotite granite was subdivided into two types: the Liberec granite (in the lower part) and the Jizera granite (in the upper part of the pluton ([Žák and Klomínský 2007](#)). The Liberec and Jizera types were reported to differ in (1) modal and chemical composition, (2) average size of K-feldspar phenocrysts (2–3 cm in the Liberec granite, 5–7 cm in the Jizera granite), and (3) magnetic properties. In the porphyritic granites

on the Polish part of the pluton, the features (1) and (2) change from place to place (Borkowska 1966), thus, we show only one variety of the porphyritic Bt granite in Figure 2. The porphyritic facies hosts lamprophyre dyke swarms located in the eastern and western parts of the pluton (Fig. 2).

The second type of granite, *medium-grained equigranular Bt granite (type II)*, forms two larger outcrops: in the middle part of the pluton (the “Harrachov granite” of [Žák and Klomínský 2007](#)) and several smaller bodies hosted by the coarse-grained porphyritic Bt granite in the eastern part of the pluton (Fig. 2).

Another granite facies (type III) is represented by *the fine-grained equigranular Bt granite* (“ridge granite”, Borkowska 1966; “crestal granite”, Žák and Klomínský 2007). Both, type II and III, further in the text, are named, in short, medium-grained Bt granite and fine-grained Bt granite, respectively, and, collectively, as the equigranular granites.

A subordinate variety of the Karkonosze Granite (type IV) is *the granophyric Bt granite* that forms small bodies near Jelenia Góra and is considered to be related with the porphyritic Bt granite (Borkowska 1966).

At the contact between the coarse-grained porphyritic Bt Jizera and Liberec granites, there occur small bodies of *the amphibole–biotite granodiorite* (type V, the “Fojtka granodiorite”). At the SW edge of the pluton, we find a distinct two-mica granitoid, *the medium-grained Bt-Ms granite* (type VI, the “Tanvald granite”; Fig. 2).

Žák and Klomínský (2007) proposed a granite emplacement model for the Karkonosze Pluton that involved a sequence of complex processes including “chamber-wide mixing and hybridization”, followed by “laminar magma flow in highly localized weaker channel-like domains within the higher-strength crystal framework”, and later complex processes of schlieren and dyke formation. [Słaby and Martin \(2008\)](#), referring to the earlier petrographic studies and based on detailed geochemical and mineralogical investigations, elaborated a geochemical model of the pluton evolution that is, in general, in agreement with the emplacement sequence suggested by Žák and Klomínský (2007). According to this model, several granitoid facies resulted from a combination of fractional crystallization and mixing-mingling processes. The pluton originated from fractionating crustal-derived acidic magma (equigranular granites), progressively injected by basic magma from an enriched mantle source ([Słaby and Martin 2008](#)). The dominant porphyritic granites were interpreted ([Słaby and Martin 2008](#)) as products of mixing of crustal magma (equigranular type), with mantle-derived basic melts (lamprophyre-type magmas). In our opinion, the equigranular Bt granites represent most evolved melts and, in general, postdate the porphyritic-type granites. However,

timing of the processes operating during the formation of this large pluton remains problematic. Based on field evidence, such as the observation of an enclave of the schlieren-bearing, porphyritic granite in the equigranular granite, and the occurrence of veins of light-coloured granite cutting through the porphyritic facies (Mierzejewski *et al.* 1994), an igneous emplacement sequence can be deduced in which the porphyritic facies was emplaced earlier, and behaved as a partly (at least) consolidated crystal framework at the time of intrusion and crystallisation of the equigranular facies. This is in line with the broadly central position of the main body of equigranular facies in the pluton, as well as with its more fractionated petrographic and geochemical character. Another argument is the zircon-saturation temperature of magma crystallization, by ca. 40 °C lower in the equigranular granite than in the porphyritic type (see below).

Recently, Žak *et al.* (2013) published a paper presenting their structural and petrological observations combined with LA ICP-MS U-Pb zircon ages from the Czech part of the Karkonosze Pluton. They conclude that the shallow-level “Krkonosé-Jizera plutonic complex” resulted from multistage magma emplacement, between ca. 320 and 315 Ma, and progressive strain accumulation.

3. Outline of petrology and published geochronological data

3.1. General petrography and geochemistry

In this study, we provide new SHRIMP zircon data from three samples representing two main facies of the Karkonosze Granite: the porphyritic granite and the equigranular granite. These are the most widespread types that have repeatedly been shown to have distinct petrological and geochemical characteristics. We should keep in mind, however, that there might be more than one porphyritic, and more than one equigranular varieties, not necessarily all of the same age.

The predominant **porphyritic granite** contains characteristic pink K-feldspar phenocrysts, up to several cm large, with whitish plagioclase rims (rapakivi-type), and of much rare and smaller plagioclase phenocrysts (Fig. 3a-d). The **equigranular granite** (the “ridge granite”), is pale in colour, with fine- to medium-grained texture and specific rounded larger (up to several mm in diameter) quartz grains, as well as rather scarce biotite (Fig. 3e, f). Fine-grained varieties of the equigranular variety have an aplitic appearance. Field evidence

indicates, in several places, that the equigranular granite intrudes the relatively older porphyritic granite ([Mierzejewski and Oberc-Dziedzic 1990](#); [Mierzejewski et al. 1994](#)).

The modal composition of representative samples of the Karkonosze granites are shown in Figure 4. The compositional loops of the main granite facies – porphyritic and equigranular, largely overlap (as far as the main mineral components Q, A, P, are concerned), however, the average of the equigranular granite is slightly richer in quartz and poorer in plagioclase.

In general, the Karkonosze granites are calc-alkalic to subalkalic in composition ([Mikulski 2007](#)). The chemical composition of selected samples of the Karkonosze granites is shown in Table 1 and Figure 5. The granite samples studied are peraluminous rocks, with the A/NK ratios of 1.0–1.4, and A/CNK of 1.0–1.2. The porphyritic granite (samples SZH, MICH and A1) contains CIPW-normative *Q* 30.4–34.4 %, *C* 0.1–0.7 %, *Or* 21.2–28.7 %, *Ab* 27.0–30.4 %, and *An* 6.5–9.4 %. The equigranular granite (samples SAM 2 and M4) is significantly richer in SiO₂ compared with the porphyritic granite: 76.5–77.7 vs 72.4–73.1 wt. %, respectively. It contains: *Q* 38.3–41.5 %, *C* 0.5–0.6 %, *Or* 26.0–27.1 %, *Ab* 26.4–27.1 %, and *An* 3.0–3.2 %. The porphyritic granites are much richer in Mg and Fe than the equigranular granites, and the least evolved rock is sample MICH.

The multi-element diagram of trace-element concentrations, normalized to chondrite (normalization values of Sun and McDonough, 1989; Figure 5a), show a general similarity of all the samples analyzed, and a steeply decreasing trend from more- to less incompatible elements. The samples of the equigranular granite. SAM 2 and M4, display relatively lower concentrations of less incompatible elements, in particular between Sr and Ti. Negative anomalies are distinct, especially for Nb, Sr, P and Ti.

The total REE contents in the Karkonosze granites analyzed are within a range of 49–288 ppm (Table 1). The lowest concentrations are typical of the equigranular granite that is poor in mafic minerals (SAM 2: 91 ppm, M4: 65–97 ppm). On the REE diagram normalized to chondrite (Figure 5b), the concentrations increase from Sm to La and, in contrast, a flat pattern for the HREE, between Gd and Lu, for all the samples. The equigranular granites show the most pronounced negative anomalies in Eu.

The data normalized to the average composition of the total Earth crust ([Rudnick and Gao 2005](#)) shows that the trace-element patterns (Figure 5(c)) display, in general, only a slight enrichment in most incompatible elements (except for the Ba negative anomaly). On the REE diagram (Figure 5(d)), the porphyritic granites (SZH, MICH and A1) display broadly horizontal patterns, slightly above 1.0 level, whereas the equigranular samples, SAM 2 and M4, show distinct depletion in LREE.

The observed strong Eu and Sr anomalies probably indicate plagioclase fractionation during magma crystallization. The flattening of the HREE branch, combined with the strong negative P anomaly in the equigranular granite (SAM 2 and M4), likely reflect a REE-bearing phase (allanite, apatite ?) fractionation. The negative anomalies in Nb, Ti and Sr are typical of the crustal materials ([Taylor and McLennan 1985](#); [McLennan *et al.* 2006](#)). The Nb anomaly is fairly similar in all the granite varieties which suggests that it is simply inherited from calc-alkaline source materials (cf. [Pin *et al.* 2007](#)). The strong negative Ti anomalies may indicate that the magmas were separated from a residuum containing a Ti-rich phase, *e.g.* rutile. The common negative anomalies in Sr, P and Ti are characteristic of „mature” magmas developed after the fractionation and removal of plagioclase, apatite and ilmenite.

3.2. Published geochronological data

A number of earlier geochronological studies, using various isotopic techniques, provided dates scattered mostly between ca. 328 and 302 Ma.

[Pin *et al.* \(1987\)](#) and [Duthou *et al.* \(1991\)](#), using the Rb–Sr whole rock isochron method, dated the porphyritic granite at 328 ± 12 Ma, and the equigranular granite at 312 ± 6 Ma. [Kröner *et al.* \(1994\)](#), applying the ^{207}Pb – ^{206}Pb lead evaporation single zircon method, obtained a date of 304 ± 14 Ma for porphyritic monzogranite, apparently (taking the uncertainties into account) younger than the Rb–Sr age of the porphyritic granite cited above.

Later on, several U–Pb SIMS zircon studies ([Machowiak and Armstrong 2007](#); [Awdankiewicz *et al.* 2007, 2010](#); [Kusiak *et al.* 2009](#); [Kryza *et al.* 2012](#)) also provided somewhat scattered dates, spanning a 20 Ma range, from 322 to 302 Ma. [Machowiak and Armstrong \(2007\)](#) reported zircon SHRIMP dates of 314 ± 3.3 Ma and 318.5 ± 3.7 Ma for samples of porphyritic granites of the NE part of the pluton, with an average of 316 ± 2 Ma.

SHRIMP dating of zircons from a micromonzodiorite dyke (from the lamprophyre dyke swarm in the eastern part of the pluton) yielded an age of 313 ± 3 Ma or, alternatively (preferring an older age within the main population, instead of the mean), 318 ± 3 Ma ([Awdankiewicz *et al.* 2007, 2010](#)).

SHRIMP zircon data reported by [Kusiak *et al.* \(2009\)](#) from a microgranular enclave in the equigranular granite yielded a “poorly constrained” age of 314 ± 8 Ma. Their CL investigations of zircons from this enclave revealed unusual morphologies and re-equilibration textures in these U and Th-rich zircons, interpreted as products of diffusion-controlled reactions and re-growth caused by late-magmatic fluids. The $^{206}\text{Pb}/^{238}\text{U}$ apparent

age of 304 ± 2 Ma reported for the re-equilibrated zircons was interpreted to reflect fluid activity postdating the main part of the pluton by several millions of years.

Difficulties with the geochronology of the Karkonosze Granite were reported by Kryza *et al.* (2012) who performed a test SHRIMP study of porphyritic granite from Szklarska Poręba Huta (sample SZH). The complexity was, apparently, due to the high U contents and resultant metamictization and radiogenic Pb loss in the zircons studied. The sample analyzed yielded a large scatter of $^{206}\text{Pb}/^{238}\text{U}$ dates, mostly between ca. 300 and 316 Ma, with a mean of 306 ± 4 Ma (2σ ; 9 analyses, MSWD 0.86). The same sample, re-analyzed after chemical abrasion (Mattinson, 2005), yielded a considerably older mean $^{206}\text{Pb}/^{238}\text{U}$ date of 322 ± 3 Ma (2σ ; 11 analyses, MSWD 1.15). The SHRIMP results from this sample of the porphyritic granite (SZH, chemically abraded), together with new, unpublished data on two other samples, MICH and SAM, are discussed below.

The recent SIMS U-Th-Pb data, obtained on zircon and monazite from ten samples of various rocks of the Karkonosze Pluton by Kusiak *et al.* (2013), have shown that the porphyritic and hybrid granitoids, as well as composite dykes were emplaced within a short time interval, between 314 ± 4 and 311 ± 3 Ma. These authors argue that there are indications that whole Karkonosze thermal episode possibly lasted as long as 15 My.

Žak *et al.* (2013), based on their most recent LA ICP-MS U-Pb zircon data from the Czech part of the Karkonosze Pluton, proposed a model of multistage magma emplacement, starting with “the separately evolved S-type Tanvald granite (317.3 ± 2.1 Ma), followed by at least two voluminous batches of the I-type porphyritic Liberec (319.5 ± 2.3 Ma) and Jizera (320.1 ± 3.0 Ma and 319.3 ± 3.7 Ma) granites. The intrusive sequence was completed by uppermost, minor intrusions of the equigranular Harrachov granite (315.0 ± 2.7 Ma).”

Mikulski and Stein (2007), applying the Re-Os method on molybdenite, got very precise ages, by virtue of the extremely high Re/Os ratios typical of that mineral. However, these data also show significant scatter, far in excess of the reported analytical uncertainties: 315 ± 1 Ma for molybdenite from fissures in the porphyritic granite from Michałowice, 326 ± 1 Ma for quartz veins in the porphyritic granite from Łomnica, and 312 ± 1 Ma for skarns from Kowary (eastern contact aureole of the pluton). Later on, Mikulski and Stein (2011) dated, by the same method, disseminated and vein-type molybdenites from aplite from the Szklarska Poręba Huta quarry, at 323 ± 1 and 310 ± 1 Ma, respectively. More recently, Mayer *et al.* (2012) found molybdenite mineralization in bright, fine-crystalline aplite in Szklarska Poręba Huta which yielded Re-Os ages of 307 ± 2 and 309 ± 2 Ma.

[Marheine et al. \(2002\)](#), using the ^{40}Ar – ^{39}Ar method on biotite from the Liberec porphyritic granite, obtained a plateau age of 320 ± 2 Ma, with the two last high temperature steps at 315 and 314 Ma. More recently, [Danišík et al. \(2010\)](#), based on a combination of zircon (U–Th)/He, apatite fission track (AFT) and apatite (U–Th–[Sm])/He thermochronology, suggested that, during cooling, the isotherm 190°C was reached in the Karkonosze Pluton between 285 ± 19 and 308 ± 21 Ma.

4. New SHRIMP zircon data

4.1. Sample description

For our SHRIMP zircon dating, we have selected two samples of the porphyritic granite (SZH and MICH) and one sample of the equigranular granite (SAM; see Fig. 2 for sample location). The same samples were analyzed by the ID-TIMS method ([Kryza et al. 2014](#)). However, short petrographic descriptions of the same samples studied here, for convenience, are given below.

Porphyritic granite from Szklarska Poręba – Huta (sample SZH)

This porphyritic granite (Fig. 3a, b) has a coarse-grained matrix composed of pink K-feldspar, whitish plagioclase, grey quartz and minor biotite. The matrix encloses large euhedral phenocrysts of K-feldspar, usually showing Carlsbad twinning and common whitish plagioclase rims. Scarce plagioclase phenocrysts display one or two internal biotite-rich rings. Under the microscope, the K-feldspar phenocrysts appear to contain numerous subhedral inclusions of plagioclase, with distinct albite rims. Thin, thread-like perthites do not change their orientation near these inclusions; the abundance of perthites does not correlate either with these inclusions, both suggesting no genetic interrelationships. Apart from plagioclase, also quartz is found as concave inclusions in K-feldspars.

In the matrix, K-feldspars have similar features as those in the phenocrysts, but they are smaller and xenomorphic. The matrix plagioclases form two generations. The older generation, Pl-1, is represented by small grains displaying zonation reflected by strongly sericitized interiors and clear external parts. Typically, they are enclosed in K-feldspars and tend to form glomeroporphyritic aggregates overgrown by the second generation of plagioclase, Pl-2 (Fig. 3b). The younger plagioclase also forms individual grains of

rectangular shape. They also show zonation and thin albite twining, but no inclusions. Quartz, similarly to Pl-2, is often found as agglomerates of several variously oriented grains sealed with a thin "film" of K-feldspar. Brownish biotite is slightly chloritized.

Porphyritic granite from Michalowice quarry (sample MICH)

This porphyritic granite contains rather small amount of phenocrysts (Fig. 3c, d). K-feldspar phenocrysts, filled with numerous thin vein-like perthites, contain inclusions of plagioclase, imbricated in places, as well as small inclusions of quartz and biotite. The phenocrysts show evidence of deformation in semi-brittle- to brittle conditions: bending of perthites, cracks filled with quartz and plagioclase; such crystals are surrounded by myrmekite (Fig. 3d). The plagioclase is zoned and displays albite and Carlsbad twinings. The internal parts of the grains are cloudy and filled with sericite. Oval quartz grains are less than 5 mm large. Dark brownish biotite occurs as individual plates ca. 1.5 mm in size or, together with olive-green hornblende and plagioclase, a few mm large aggregates. The biotite contains zircon and apatite as inclusions. Locally, biotite and hornblende are partly replaced by chlorite.

Equigranular granite from Mały Staw (sample SAM 2)

The equigranular granite studied is a pale-grey rock, with a fine-grained matrix (Fig. 3e, f) composed of quartz, K-feldspar and plagioclase and enclosing rare larger, grey oval or subhedral quartz grains, 3-5 mm in diameter, and subhedral or anhedral, twinned K-feldspar crystals, up to 4 mm in size. Small (0.5 mm) biotite plates, partly chloritized, are evenly dispersed within the matrix. Sporadically, small aggregates of tiny muscovite flakes (0.2 mm) are found.

4.2. Methods

The samples studied, each ca. 3 kg in weight, were crushed, sieved, and the 0.06–0.25 mm heavy fraction separated using the conventional heavy liquid (sodium polytungstate) and magnetic procedure. Part of zircon separate from sample SZH, and the entire zircon separates from samples MICH and SAM 2 were chemically abraded, following the procedure of Mattison (2005; see also Kryza *et al.* 2012).

Hand-picked zircons representing slightly different morphological types from the chemically abraded (CA) fractions were mounted in one epoxy puck, polished and used for optical microscopy, cathodoluminescence (CL) imaging (Fig. 6) and, finally, SIMS analysis.

U–Pb SIMS zircon analyses were made on a SHRIMP-II at the Centre of Isotopic Research (CIR) at VSEGEI, St. Petersburg, Russia. The details of the analytical procedure are given in the Appendix.

Uncertainties for individual analyses (ratios and ages) are given at the 1σ level, uncertainties in calculated mean $^{206}\text{Pb}/^{238}\text{U}$ ages are reported at 2σ level. The Stacey and Kramers (1975) common-Pb corrected results of zircon analyses are shown in Table 2 and in Figure 7.

4.3. SHRIMP zircon results

4.3.1. Porphyritic granite – sample SZH (untreated and chemically abraded)

Sample SZH was originally studied using the conventional SHRIMP method and yielded a large scatter of $^{206}\text{Pb}/^{238}\text{U}$ zircon dates, mostly between ca. 300 and 316 Ma, with several much younger dates between 224–287 Ma ([Kryza et al. 2012](#)). Nine selected analyses, excluding the outliers, yielded a mean $^{206}\text{Pb}/^{238}\text{U}$ age of 306 ± 4 Ma (MSWD = 0.86, probability 0.55).

The most likely reason of that wide scatter (and of the relatively young mean $^{206}\text{Pb}/^{238}\text{U}$ age) is radiogenic lead loss from the metamict zircon damaged by the observed unusually high U and Th contents in the zircons, up to 20,000 ppm U and 1,600 ppm Th ([Kryza et al. 2012](#)).

All these difficulties inspired the authors to attempt application of an annealing-partial dissolution technique (known as “chemical abrasion”, CA; [Mattinson 2005](#)) prior to the SHRIMP analysis ([Kryza et al. 2012](#)).

The chemical abrasion of zircons from sample SZH (Fig. 6a) revealed many cracks and exposed massive fresh domains suitable for microbeam SHRIMP analysis. Comparing selected chemical features of the analytical results of the abraded zircons (Table 2, data from [Kryza et al. 2012](#), shown here for comparison with the newly presented here results from abraded samples MICH and SAM 2) with those of the non-treated ones ([Kryza et al. 2012](#)), it is obvious that the latter are, on average, much richer in U and Th, and often have elevated $^{206}\text{Pb}_c$. Overall, the $^{206}\text{Pb}/^{238}\text{U}$ dates of the chemically abraded grains lie between ca. 346 and ca. 297 Ma (Table 2, Fig. 7a). The main cluster of 11 spots gives a mean $^{206}\text{Pb}/^{238}\text{U}$ age of 322 ± 3 Ma (MSWD = 1.15, probability 0.32; Fig. 7a). Two spots have slightly older $^{206}\text{Pb}/^{238}\text{U}$ ages (ca. 338 Ma); it is equivocal from CL images whether or not these contain inherited cores. One grain gives an older $^{206}\text{Pb}/^{238}\text{U}$ age of 346 ± 6 Ma and the CL image for

this grain indicates that it is likely to have an inherited core. Two other zircons give apparent $^{206}\text{Pb}/^{238}\text{U}$ ages slightly younger than the main population cluster, presumably due to some residual Pb loss.

4.3.2. Porphyritic granite – sample MICH (chemically abraded)

The zircon population in this sample is similar to that in sample SZH. Typically, euhedral, prismatic crystals display oscillatory, magmatic-style zoning, and a few grains have fairly well defined internal parts, distinct in CL images, possibly representing earlier-crystallized portions or inherited cores; the latter, however, have not been confirmed as distinctly much older domains. CA has revealed many thin cracks, thus making easier selection of fresh and likely undisturbed portions of grains for analysis (Fig. 6b).

The U and Th contents range from 270 to 1,705 and 58 to 499 ppm, respectively, and $^{232}\text{Th}/^{238}\text{U}$ ratios between 0.22 and 0.98. The non radiogenic lead $^{206}\text{Pb}_c$ is low, between 0 and 0.4 %.

The $^{206}\text{Pb}/^{238}\text{U}$ dates of the CA zircons fell between 300 ± 5 and 325 ± 7 Ma, with two apparent outliers of ca. 335 ± 5 and 285 ± 5 Ma (Table 2). Discordance ($D = [(\text{age}_{207/206})/(\text{age}_{206/238}) - 1] \times 100$) is variable, but in a few points, ca. 318–325 Ma old, near zero. When compared with chemically abraded sample SZH, which comprised 7 spots older than 325 Ma, sample MICH has only one point above this age. However, the mean $^{206}\text{Pb}/^{238}\text{U}$ age for 11 selected points (excluding 5 distinctly older and younger outliers, not overlapping within the errors with the main cluster) is 319 ± 3 Ma (MSWD = 0.65, probability 0.75; Fig. 7b).

4.3.3. Equigranular granite – sample SAM 2 (chemically abraded)

The zircons in the equigranular granite are broadly alike those from the porphyritic granite samples described above. However, they look more strongly corroded and disintegrated after CA (Fig. 6c). The oscillatory zoning is similar and some grains contain internal parts that may represent older zircon fractions or even inherited cores; however, results older than 332 Ma have not been ascertained.

The U and Th concentrations are broadly similar to those in the porphyritic granite samples, and range from 369 to 2182 and 56 to 1,110 ppm, respectively. The $^{232}\text{Th}/^{238}\text{U}$ ratios vary between 0.17 and 1.19, the $^{206}\text{Pb}_c$ contribution is low, between 0 and 0.45 % (Table 2).

The $^{206}\text{Pb}/^{238}\text{U}$ ages of the CA zircons are scattered between 298 and 320 Ma, with a few outliers around 286 and 332 Ma (Table 2). Characteristically, the two oldest obtained results

represent internal parts of grains (cores?). The numerical value of discordance D is variable, but in several grains it is close to zero. The mean $^{206}\text{Pb}/^{238}\text{U}$ age for 6 points (excluding significantly older and younger outliers) is 318 ± 4 Ma (MSWD = 0.84, probability 0.52; Fig. 7c).

5. Re-assessment of Rb-Sr data

Previous whole-rock Rb-Sr work on both rock-types gave results consistent with the chronology based on field evidence of the earlier emplacement of the porphyritic granite, relative to the equigranular facies. Specifically, a 328 ± 12 Ma (MSWD=1.51) age was obtained for the porphyritic granite, as measured at the meter scale on five rock slabs cut in a schlieren-bearing block collected in the Szklarska Poręba Huta quarry (Pin *et al.* 1987). A similar result (328 ± 9 Ma, MSWD=1.72) was later obtained for the porphyritic granite on eight samples collected at the scale of the Michałowice quarry (Duthou *et al.* 1991). Analyses from the equigranular granitoids, reported by Mierzejewski *et al.* (1994) allowed to calculate a younger age (312 ± 6 Ma), in line with geological field observations.

Due to the relative large uncertainty inherent to the Rb-Sr whole-rock isochron method (typically, in the ± 5 to 10 Ma range), these early attempts failed to establish whether or not a significant time span elapsed between the two igneous pulses. The high precision, CA-ID-TIMS data now available for the two rock-types show that the time interval separating their emplacement cannot be resolved, even at the few- 10^5 year scale, and therefore establish that the magmas parental to the equigranular granite were emplaced quite shortly after, most likely during, the final consolidation stage of the porphyritic granite (Kryza *et al.* 2014).

Because these earlier Rb-Sr results were published only in a cursory form, as abstracts or in short papers written in Polish, we present here the corresponding analytical data, completed by new results (Table 3), along with a discussion based on the new CA-ID-TIMS results. Indeed, the CA-ID-TIMS ages can be used as a benchmark in order to shed light into the possible causes of the biased whole-rock isochron ages of the porphyritic facies.

While the equigranular granite gave a Rb-Sr age of 312 ± 6 Ma, in excellent agreement with the much more precise U-Pb age of 312.2 ± 0.3 Ma obtained by CA-ID-TIMS (Kryza *et al.* 2014), the porphyritic granite (sampled at the same sites) yielded two whole-rock isochrons with ages of 328 ± 12 and 328 ± 9 Ma, some 16 Ma older than the 312.8 ± 0.3 , and 312.4 ± 0.3 Ma ages of zircons from two different samples by the CA-ID-TIMS method. Albeit not very

much greater than analytical uncertainty, the positive age bias of 16 ± 12 Ma and 16 ± 9 Ma of the two whole-rock isochrons acquired for the porphyritic granite is believed to be significant, and to reflect a systematic bias deserving a geochemical explanation.

In order to get an insight into the “zero-age” relationships of the different samples analyzed, all the measured $^{87}\text{Sr}/^{86}\text{Sr}$ ratios have been corrected for *in situ* radioactive decay of ^{87}Rb since 312 Ma. The results are listed in Table 3 as $^{87}\text{Sr}/^{86}\text{Sr}_{312\text{ Ma}}$, along with their 95 % confidence interval. An examination of these age-corrected ratios show that, in each of the three loci studied (Szkłarska Poręba Huta and Michałowice quarries, and Jakuszyce borehole; Fig. 2), one or several samples (A4 from Huta, Mi-2b and Mi-6 from Michałowice, and sample 400 m from Jakuszyce borehole) depart significantly from the rest of samples. Importantly, all these samples are also characterized by $^{87}\text{Rb}/^{86}\text{Sr}$ ratios (7.0 for one sample, and from 9.5 to 10.9 for the three others), distinctly above those of the other samples (ranging from 3.5 to 7.4; Table 3). By virtue of these relatively high ratios, the samples with “ ^{87}Sr -excess” (or, hereafter “radiogenic outliers”) exert a significant effect on the slope of the regression lines, and thereby bias the calculated isochron age to spuriously old values. Indeed, the whole-rock isochron approach strictly requires that all the samples used were coeval and shared the same initial isotope composition. This condition is not easy to fulfil with a great degree of confidence *a priori*, making this method prone to significant bias.

Then, the question arises how to interpret the higher $^{87}\text{Sr}/^{86}\text{Sr}_{312\text{ Ma}}$ ratios observed in some of the samples of the porphyritic facies. Taken at face value, these ratios reflect an excess of crustal component in their parent magmas. As noticed above, the samples with an excess of ^{87}Sr are also characterized by higher Rb/Sr ratios than the other porphyritic granite samples. If the Rb/Sr ratio is interpreted as a differentiation index, this association would be reminiscent of combined assimilation and fractional crystallization (AFC). However, the fact that the coeval, even more fractionated equigranular granites (with $^{87}\text{Rb}/^{86}\text{Sr}$ as high as 15, 25, or even 34) do not show any ^{87}Sr excess does not support this hypothesis. Rather than providing evidence for a more differentiated magma, the higher Rb/Sr ratios observed in those porphyritic samples with anomalously radiogenic Sr might reflect a higher modal abundance of biotite, as can be observed in samples corresponding to dark portions of schlieren (Szkłarska Poręba Huta). Interestingly, the leucocratic equigranular granite, including its microgranular mafic enclaves, does not show any sample with ^{87}Sr -excess, in keeping with its whole-rock isochron age (312 ± 6 Ma), in perfect agreement with the CA-ID-TIMS U-Pb zircon age.

The ^{87}Sr -rich “outliers” are represented by Bt-rich schlieren in the porphyritic granite, thus the nature of these schlieren becomes the key point to interpret the isotopic anomalies and, consequently, the Rb-Sr dates. Most of the schlieren are accumulations of biotite, with sharp base and normal modal grading. In some cases, they are both modally-graded and size-sorted, *i.e.*, biotite schlieren passes upwards into Pl-phenocryst rich and then Kfs-rich layers. Locally, the schlieren are folded (Mierzejewski 2003; [Žák and Klomínský 2007](#)). Such schlieren can be interpreted as products of magmatic flow and “sedimentation” rather than relics of country rocks. However, biotite in the schlieren may be in part xenocrystic in origin. Locally, in the central part of the pluton, the mafic schlieren in the porphyritic granite contain hornblende and relict pyroxene (Borkowska 1966) which indicates that the porphyritic granite facies may enclose domains with not perfectly homogenized mantle or lower-crustal material. Upper-crustal xenoliths are, apparently, less common in the Karkonosze Pluton. However, at least some of the dark schlieren, especially those close to the pluton margins, might correspond to imperfectly assimilated, “ghost xenoliths” of metapelitic origin, as suggested by their radiogenic Sr isotope composition.

It can be noticed that samples from the Szklarska Poręba Huta quarry, located close to the northern margin (or roof) of the intrusive body, record (albeit at the scale of a meter-sized block containing a schlieren) an average Sr signature more radiogenic (0.7079) than samples taken from more internal parts of the pluton (0.7067 at Michałowice, 0.7065 at Jakuszyce). This suggests that in this part of the pluton, local interactions with country-rocks were not merely limited to a subordinate role but, instead, could have contributed to a general shift towards more crustal isotope compositions.

Accordingly, it is proposed that the samples with more radiogenic initial Sr isotope signatures represent sub-volumes of the crystallizing magma which assimilated crustal xenoliths, probably incorporated to the magma chamber by stopping ([Paterson *et al.* 2008](#); [Clarke and Erdmann 2008](#)). No conspicuous trace of partly assimilated material in the samples studied has been observed, indicating that the digestion process went almost to completion, through partial melting and dissolution of most mineral phases (but probably biotite and zircon). Sr isotopes failed to reach full equilibration with the bulk of surrounding magma, possibly because of a large initial isotopic contrast, more difficult to erase, or because temperature decreased quickly below the blocking temperature of the Rb-Sr system, or any combination of both. The high-level emplacement of the pluton would have favoured a relatively fast cooling rate, especially in its marginal domains.

As a corollary of this tentative model, those samples free of such (isotopically) unequilibrated crustal components, left after separation of xenocrystic phases, or simply not affected by local assimilation phenomena, should represent isotopically broadly homogeneous magmas, which might subsequently have differentiated through closed-system fractionation, thereby producing a range of Rb/Sr ratios while keeping a constant Sr isotope composition. Only these samples would be appropriate to construct whole-rock isochrons able to provide reliable igneous emplacement ages. Indeed, all of the twelve leucocratic, fine-grained granitoids (ten samples of the equigranular type, including their microgranular enclaves, plus two leucocratic dykes of the Szklarska Poręba Huta quarry and the Jakuszyce borehole, with $^{87}\text{Rb}/^{86}\text{Sr}$ comprised between 3.8 and 34) allow to calculate an isochron giving an age of 311 ± 4 Ma, identical within error to the much better defined U-Pb zircon CA-ID-TIMS age of 312.2 ± 0.3 Ma. Based on the elevated value of MSWD (4.19), which indicates that the degree of “geochemical” scatter of the data points is distinctly in excess to that allowed by the analytical uncertainties alone, the Rb-Sr WR isochron age was calculated by using Model 3 of Ludwig’s (1994) algorithm which assumed in that specific case a scatter of $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratios (*i.e.*, isotope heterogeneity of the magma body) equal to ± 0.0006 . It is worth noticing that the initial ratio deduced from this isochron, 0.7066 ± 7 , is identical within error to the average values measured in the porphyritic granite at Michałowice (0.7067 , $\sigma = 0.000$, $n = 6$) and Jakuszyce (0.7065 , $\sigma = 0.0002$, $n = 4$), after rejection of the “radiogenic outliers”. Indeed, a pooled whole-rock isochron calculation encompassing the twelve samples of equigranular granite plus those nine samples of porphyritic granite from Michałowice and Jakuszyce not considered as radiogenic outliers (see Table 3) gives an age of 314 ± 2 Ma. Again, the MSWD value of 4.72 reveals an excess of geochemical scatter. Accordingly, a Ludwig’s model 3 solution is favoured, with the following results: 311 ± 3 Ma, with an initial $^{87}\text{Sr}/^{86}\text{Sr} = 0.7067 \pm 4$. This shows that not only the comparatively late-stage leucocratic granitoids, but also the bulk of the melt which fed the magma chamber and generated the porphyritic rock-types, were broadly homogeneous, as far as Sr isotopes are concerned, at least in the Polish part of the pluton. This suggests that beyond a given evolutionary stage, the parental magma differentiated mostly through closed-system fractionation, without significant degree of concomitant assimilation. In other words, AFC was probably not an important mechanism in the petrogenetic evolution of the Karkonosze Pluton at its emplacement level, although it may have been at work at deeper levels. Crustal contamination processes responsible for the Sr isotopic scatter found in the porphyritic granite appear to have been local, and rather subordinate (as, for example, in Szklarska Poręba Huta, where $^{87}\text{Sr}/^{86}\text{Sr}_{312} =$

0.7079), probably by stopping of wall-rocks, and shortly before its final emplacement. Obvious mingling phenomena are documented in the south-western part of the pluton, *e.g.*, at Rudolfov and Fojtka, near Liberec (Czech Republic), where syn-plutonic dioritic dykes yield $^{87}\text{Sr}/^{86}\text{Sr}_{312}$ ranging from 0.7055 to 0.7064 (C. Pin, unpubl. results), suggesting that the magma chamber was locally replenished by isotopically more primitive melts.

In an alternative model, the Rb-Sr data could be interpreted to reflect a late-stage isotope homogenization having occurred through a process of “post-emplacement annealing “ such as that proposed by Glazner *et al.* (2004) to account for the textural homogeneity of large plutons that probably formed incrementally, by amalgamation of many successive small magmatic additions. However, in the present case, the preservation of contrasted rock textures, including granophyric ones, does not support this model, but instead favours relatively fast transport and crystallization of a melt emplaced into much colder country-rocks. Indeed, it has been shown that large granitic plutons might be built during a very short time span provided that magma supply occurred along dikes (*e.g.*, [Clemens and Mawer 1992](#); [Petford *et al.* 2000](#)).

The re-interpretation of the Rb-Sr data presented above implies that the Rb-Sr system has not been significantly disturbed at the whole-rock scale during the late- and post-magmatic processes (at least in the granites samples analyzed). This would also imply, that the observed scatter of the SHRIMP ages towards the dates younger than ca. 312 Ma has resulted, predominantly, from the disturbance of the U-Pb system due to metamictization of extremely U-rich zircons, rather than to intense post-magmatic fluid activities affecting the bulk of the samples.

6. Discussion

6.1. Constraints from the high-precision CA-ID-TIMS results

Zircons from two samples of the porphyritic granite and one of the equigranular facies (the same samples as those used here for the SHRIMP dating) were analyzed by [Kryza *et al.* \(2014\)](#) using the high-precision CA-ID-TIMS method. In all three samples, the zircon $^{206}\text{Pb}/^{238}\text{U}$ dates were spread beyond pure analytical scatter (*op. cit.*), thus the authors adopted the strategy to use the youngest date of a given sample to approximate the age of final

crystallization and solidification (see Schaltegger *et al.* 2009; Schoene *et al.* 2010). The final conclusion was that the crystallization of the three analyzed samples, representing the two main granite facies, happened between 312.5 ± 0.4 and at 312.2 ± 0.3 Ma, thus unresolvable at the 0.08 to 0.1% analytical precision level of a single $^{206}\text{Pb}/^{238}\text{U}$ age. This conclusion differs significantly from many earlier attempts of age determination of the Karkonosze Granite and prompts us to discuss the possible reasons of the large scatter of the results obtained by the geochronological methods applied previously.

6.2. How to explain the scattered geochronological data: SHRIMP zircon, Re-Os molybdenite, and Ar-Ar biotite ages?

6.2.1. SHRIMP U-Pb on zircon

A compilation of available geochronological data, mostly U-Pb SIMS (SHRIMP) results, for the Karkonosze granites is shown in Figure 8. The earlier published SHRIMP dates are scattered between ca. 322 and 302 Ma. However, the new SHRIMP ages presented above are significantly (in so far as the quoted uncertainties are realistic estimates) older, by 6 (SAM 2) to 10 Ma (SZH), than the ID-TIMS ages obtained on the same samples. However, new SIMS U-Pb results on zircon and monazite from various granitoid types by Kusiak *et al.* (2013) are in line with the CA-ID-TIMS results (Kryza *et al.*, 2014). These authors suggest that the main types of the Karkonosze Granite were emplaced within the time interval between 314 ± 4 and 311 ± 3 Ma. However, the relatively poor precision of the SIMS method still leaves a ca. 10 Ma time interval of uncertainty as to either possibly short of or protracted magmatic evolution of the pluton.

Figure 8 does not show the LA ICP-MS U-Pb zircon ages from the Czech part of the Karkonosze Pluton most recently published by Žák *et al.* 2013. They fall within the range between c. 320 and 315 Ma, namely: the two-mica Tanvald granite – 317.3 ± 2.1 Ma, the porphyritic Liberec granite – 319.5 ± 2.3 Ma, the porphyritic Jizera granite – 320.1 ± 3.0 Ma and 319.3 ± 3.7 Ma, and the equigranular Harrachov granite - 315.0 ± 2.7 Ma. These ages are broadly similar to the “older” cluster of the SHRIMP dates, and they confirm a relatively younger emplacement age of the equigranular facies.

Apart from possible analytical causes (see below) and partly arbitrary approach to data processing, a potential reason of the discrepancy can be the complex petrogenesis of the pluton, involving a prolonged and variable crystallization history of accessory zircon (*cf.* Hoskin *et al.* 2000; Chappell *et al.* 2004), the possible role of older inheritance and

multiphase magma emplacement, as well as late- and post-magmatic processes, in particular fluid activities, disturbing the U-Pb system.

Apparent evidence of the possible U-Pb system disturbance can be the observed inverted ages of zircon rims that are older than cores in the same crystals. This is the case in the following zircon grains ($^{206}\text{Pb}/^{238}\text{U}$ ages; Table 2):

SZH-30.1 core 301 ± 6 Ma (D -7) and SZH 30.2 rim 317 ± 5 Ma (D -35),

SZH-35.2 core 297 ± 7 Ma (D -1) and SZH 35.1 rim 314 ± 5 Ma (D -7),

SAM 2-11.1 core 303 ± 5 Ma (D -16) and SAM-2-11.2 rim 317 ± 5 Ma (D -13).

These inverted dates are difficult to explain, assuming, *e.g.*, metamictization and subsequent radiogenic Pb loss from U-rich domains of zircon crystals, as the cores of these grains have moderate concentrations of uranium, considerably lower compared with the rims of the same crystals. This problem remains unresolved based on the available analytical data. It could, possibly, be resolved accounting for Pb/U increase due to matrix misfit between standard and unknown (Williams and Hergt 2000, White and Ireland 2012) and peculiar balance between Pb-loss and Pb/U artificial rise.

Overview of potential data bias

Inaccuracy in U-Pb SIMS dating can be attributed to several factors, and a shift in $^{206}\text{Pb}/^{238}\text{U}$ ratio and, hence, apparent age, may result from a number of reasons (Schoene *et al.* 2013; see also discussion in Kryza *et al.* 2012), including, *e.g.*: (a) common Pb correction using erroneous lead isotope composition; (b) compositional/crystallographic misfit to standard zircon, so-called “matrix effect” (Black *et al.* 2004); such heterogeneities could be, *e.g.*, lattice disturbance by decay (metamictization); (c) severe reverse discordance of untreated zircon analyzed by SIMS as documented by Wiedenbeck *et al.* (1995); this has been attributed to enhanced ion yields (relative to U yield) of labile radiogenic Pb present in amorphous microdomains within the zircon.

In the case of the Karkonosze Granite zircons, which are U-, Th-, ^{204}Pb -, and impurity-rich, many factors may contribute to the inaccuracy of the SIMS results (Kryza *et al.* 2012). However, the main factor of relatively poor precision and possibly serious inaccuracy in U-Pb microbeam SIMS dating is the tiny amount of analyzable matter, leading to poor counting statistics, particularly on the ^{207}Pb signal and the non-recognition of subtly discordant spots. Specifically, SHRIMP dates are essentially based, at least in Phanerozoic samples, on $^{206}\text{Pb}/^{238}\text{U}$ ages which are, strictly speaking, *apparent* ages, geologically meaningful *only* in so far as the U-Pb radiometric clock behaved as a perfectly closed system, and was not

affected by any mixing process (inheritance). Due to the small count rates of ^{207}Pb (and, in some cases, relatively large correction of the contribution of common lead to the ^{207}Pb), $^{207}\text{Pb}/^{206}\text{Pb}$ and $^{207}\text{Pb}/^{235}\text{U}$ ratios have poor precisions. These are reflected by large, shallow angled error ellipses of individual spots which in many cases encompass the Concordia curve, and can thereby be considered as “analytically concordant”, even though the real result is truly discordant. For this reason, the concept of concordance, of utmost importance in U-Pb systematics (Wetherill 1956), is blurred and the calculated ages can be biased either towards spuriously young dates by (analytically unresolved) radiogenic lead loss, or towards spuriously old dates by faint (unresolved) amounts of inherited radiogenic lead or “matrix effect”. In other words, a considerable error on $^{207}\text{Pb}/^{235}\text{U}$ hampers estimation of result (age) reliability in terms of rejuvenation through Pb-loss or overestimation caused by “matrix effect”. This has a crucial consequence: it is not possible to rigorously establish whether a data point is *really* concordant or, instead, discordant but taken as “analytically concordant” simply due to the large error ellipses of *in situ* methods (see Pin and Rodriguez 2009 for a more detailed discussion). In short, it turns out that the great benefit of spatial resolution, invaluable to study complex grains, is impaired by an inherent loss of chronometric resolution and overall accuracy, due to the impossibility to finely resolve either small degrees of radiogenic lead loss (leading to an underestimation of the true age), or age overestimation caused either by tiny inherited domains or matrix misfit.

This puts significant limitations on the attempts of geological interpretation of the SIMS dates obtained from the Karkonosze Pluton, with two *a priori* possible, alternative scenarios:

- (1) The data points correspond to truly concordant ages, implying that the quoted $^{206}\text{Pb}/^{238}\text{U}$ ages provide unbiased, accurate estimates for the zircon growth ages. In this analytically optimistic scenario, the observed age scatter reflects geologically significant events or processes (*e.g.*, inheritance from the magma source, contamination of the magma by xenocrysts, or several pulses of magma crystallization).
- (2) The $^{206}\text{Pb}/^{238}\text{U}$ ages are merely apparent ages, due to real discordance of the data points, but at a degree beyond the resolving power of SIMS dating. In this more conservative interpretation of the data, several models are permitted, *e.g.*: (a) the $^{206}\text{Pb}/^{238}\text{U}$ dates are minimum estimates of the true igneous emplacement ages, and then the younger results might simply reflect radiogenic lead loss at some later time, or alternatively, (b) rather subtle inheritance might have affected the interpretation of the data, where the youngest dates may provide an upper estimate for the true age of igneous emplacement, while the grains with older apparent ages would reflect inheritance of zircons with

significantly older crystallization age. These interpretations are not mutually exclusive at the scale of a zircon population, and individual spots might have been affected by either of these causes of bias.

Inheritance, protracted magmatic processes and post-magmatic fluid activities

The SHRIMP zircon dates somewhat older than the high-precision CA-ID-TIMS age of 312 Ma ([Kryza *et al.* 2014](#)) may indicate either inheritance (and xenocrysts) or accessory zircon crystallization during prolonged magmatic processes in the Karkonosze Pluton. In fact the models of the Karkonosze Granite emplacement, involving widespread magma mixing of dominant crustal and subordinate mantle-derived melts, and a combination of fractional crystallization and mixing-mingling processes ([Žak and Klominský 2007](#); [Słaby and Martin 2008](#); see also the model recently published by [Žak *et al.* 2013](#)) would support the hypothesis of prolonged and polyphase crystallization of accessory minerals in the granites, a scenario reported from a number of complex batholiths (*e.g.* Galway Batholith in Western Ireland – [Crowley and Feely 1997](#), [Feely *et al.* 2003](#), or Tuolumne Intrusive Suite in California, [Glazner *et al.* 2004](#)). Unfortunately, usually not much is known about the exact time scale of these processes. The Karkonosze Granite may be an example of fairly common granitoids representing “a mix of (cumulate or, possibly, restitic) minerals and melt, not simply a solidified melt” ([Hoskin *et al.* 2000](#)). Zircons in such granites could have crystallized in particular parts of the pluton at various times, depending on local over/undersaturation conditions. In the case of the Karkonosze Pluton, however, it should be noticed that, for solubility reasons, truly inherited grains – that is, inherited from the (deep crustal) source – should be scarce (if any) in the relatively hot and alkali-rich magmas that formed this pluton.

To highlight the problem of possible zircon inheritance in the Karkonosze Granite, we have applied zircon saturation thermometry, which enables estimating the temperature of crystallization of Zr-saturated granitoid magma and assessing the potential to preserve inherited zircons in the rock ([Watson and Harrison 1983](#); [Hanchar and Watson 2003](#), and references therein). The two samples of the porphyritic granite (SZH and MICH) yield the same zircon-crystallization temperatures of 793°C, whereas the equigranular granite (SAM) shows significantly lower temperature of 756°C, in line with its more evolved composition. The calculated temperatures confirm the low potential of preservation of inherited (*i.e.* from the source) zircons in the Karkonosze granites. Because the Karkonosze magmas were emplaced at shallow crustal level, and probably cooled at a relatively fast rate, xenocrystic zircons (arising from late-stage contamination at the margins of the pluton) would be more likely to have survived, but so far no conspicuous ancient zircon cores have been measured.

If we assume the new CA-ID-TIMS age of 312 Ma as corresponding to the main stage of the magma crystallization in the Karkonosze Pluton (at least in the measured granite facies), all relatively younger dates, below ca. 312 Ma, shown in Figure 8, can be interpreted as the effect of disturbance of the U-Pb isotopic system, *e.g.* due to late/post-magmatic fluid activities ([Kusiak *et al.* 2009](#)) and/or long-term zircon metamictization triggered by their very high U and Th contents (up to above 20,000 ppm; [Kryza *et al.* 2012](#)).

6.2.2. *Re-Os dates on molybdenite*

Further geochronological constraints for the Karkonosze Pluton come from the Re-Os dating of molybdenite mineralization. Individual grains of molybdenite from quartz veins were dated using this method by [Mikulski and Stein \(2007\)](#) at 326 ± 1 Ma (porphyritic granite, Łomnica Górna, S of Jelenia Góra in Fig. 2), 315 ± 1 Ma (porphyritic granite, Michałowice) and 312 ± 1 Ma (contact-metamorphic skarns from Kowary, E edge of the pluton). Mikulski and Stein (2011) reported also two Re-Os ages of disseminated and vein-type molybdenites from the Szklarska Poręba Huta quarry, of 323 ± 1 Ma and 310 ± 1 Ma, respectively. These ages were interpreted to reflect two distinct periods of post-magmatic pneumatolytic and hydrothermal activity during Visean-Westphalian times (Mikulski and Stein 2011). These very precise individual Re-Os ages display a 16 ± 2 Ma scatter. Recently, Mayer *et al.* (2012) obtained two slightly younger dates of 307 ± 2 Ma and 309 ± 2 Ma on molybdenite disseminated in aplogranite from the Szklarska Poręba Huta quarry (analyses on molybdenite separates). Both ages are consistent with the age of the vein-type molybdenite from the same locality reported by [Mikulski and Stein \(2011\)](#). These results were interpreted to indicate penecontemporaneous crystallization of molybdenite (at least part of it) and of the host aplogranite (Mayer *et al.* 2012).

6.2.3. ^{40}Ar – ^{39}Ar mica ages

Finally, an ^{40}Ar – ^{39}Ar analysis of a single biotite grain from the porphyritic granite (Liberec-type granite) that gave a plateau age of 320 ± 4 Ma (for the sake of consistency with the rest of the ages discussed in this paper, the analytical uncertainties of the Ar-Ar ages, given as 1 sigma errors in the original publication, are hereafter quoted at the 95% confidence level), interpreted in terms of cooling below the closure temperature of the K-Ar system in biotite, ca. $300 \pm 50^\circ\text{C}$ ([Marheine *et al.* 2002](#)). These authors also obtained a plateau age of 312 ± 4 Ma on a large ($> 2\text{mm}$) crystal of muscovite from the adjacent Tanvald two-mica granite. Because the Tanvald granite is considered as the oldest intrusion in the Karkonosze-

Izera pluton (Klominsky 1969), [Marheine et al. \(2002\)](#) suggested that their 312 Ma age might reflect resetting of the K-Ar radiometric clock, as the result of the late magmatic pulse represented by the ridge-type granite.

6.3. A critical assessment of “older ages” obtained by different methods

Several dates significantly older than our “reference age” have been obtained by using several independent chronometers, including the U-Pb system on zircons (SHRIMP following chemical abrasion), the Re-Os system on molybdenite, and the K-Ar (Ar-Ar) system. These might be considered as converging pieces of evidence for inferring that the Karkonosze Pluton had a protracted igneous evolution, possibly spanning a 15-20 Ma duration. However, this conclusion would be correct only in so far as these ages do not reflect possible methodological problems. It is therefore necessary to make a critical assessment of all these dates.

- a) **CA-SHRIMP data:** the process of chemical abrasion was used in an attempt to eliminate those zircon domains that suffered radiogenic Pb loss, in order to make the measured data points concordant, thereby allowing us to obtain geologically more reliable $^{206}\text{Pb}/^{238}\text{U}$ ages. However, this could magnify the role of any old inherited component, if present, so careful examination of CL images is needed to evaluate this possibility.
- b) **Re-Os ages on molybdenite:** The Re-Os method in molybdenite is able to provide very valuable age data by virtue of the exceedingly high ratios of Re to common (non radiogenic) Os that are typical for that mineral, enabling extremely precise ages to be calculated. This feature is associated with a very good robustness with regard to geological disturbances (see [Stein et al. 2001](#) for a concise account on the method). However, this chronometer is not entirely free of potential problems, the most serious one being the documented spatial decoupling between radiogenic ^{187}Os from its ^{187}Re parent isotope ([Stein et al. 2001](#)). For this reason, it is crucial to ensure that thoroughly homogenized samples are analyzed if accurate ages are to be obtained. Specifically, it was found necessary to analyse “a critical quantity of molybdenite, unique to each sample, such that recognized spatial decoupling of ^{187}Re parent and ^{187}Os daughter within individual molybdenite crystals is overcome” ([Stein et al. 2001](#)). This may well

be the Achilles Heel of the method, at least when dealing with large crystals. It is noticed that the sample dated at 326 ± 1 Ma was taken from a “single big crystal aggregate up to 20 mm in diameter” (Mikulski and Stein 2007, p. 209), which might have proved uneasy to perfectly homogenize. The rest of published Re-Os ages, all slightly younger than 312 Ma (from 307 Ma to 310 Ma, as compiled by Mayer *et al.* 2012) are in fair agreement with our best estimate for the igneous emplacement age, bearing in mind that molybdenite crystallized at a relatively late stage, during hydrothermal ore mineralization.

- c) **Ar-Ar dates:** the K-Ar system may provide spuriously old ages if K loss occurred at any time since the initial closure of the isotopic system. The Ar-Ar step-heating technique does not relieve this constraint, but offers the great advantage to reveal disturbances that might have affected the system, through an examination of the age spectra measured during step-wise heating and degassing of the sample. In particular, the early, low-temperature steps often display disturbed features, and can be rejected from age calculations. The 320 ± 4 Ma age reported by Marheine *et al.* (2002) for their biotite crystal was not based on a perfect plateau, but on the pooling of 16 heating steps, representing 70% of the ^{39}Ar released. The low temperature steps, amounting 20% of released ^{39}Ar , with ages from 50 Ma to 316 Ma, and the two last, highest temperature steps (of 10 % ^{39}Ar release), yielding ages of 315 and 314 Ma, respectively, were excluded from the plateau age calculation. The total Ar age (corresponding to a conventional K-Ar determination) for that sample was 305 ± 4 Ma. The apparent inconsistency between the two plateau ages measured at 320 ± 4 Ma (biotite) for the porphyritic Liberec granite, and at 312 ± 4 Ma (muscovite) for the geologically older Tanvald granite lent [Marheine *et al.* \(2002\)](#) to interpret the latter date in terms of resetting due to the late thermal pulse caused by the emplacement of the ridge-type granite. This interpretation is not straightforward. Indeed, both samples were taken relatively far from the ridge granite. Also, the closure temperature of the K-Ar system in muscovite is not likely to be lower than that in biotite, but rather some 50°C *higher* (e.g., Hunziker 1979), and there is no obvious reason why (a) large (> 2 mm) muscovite grain would have lost all its radiogenic Ar, while a smaller-sized biotite crystal would still preserve its cooling age undisturbed. Instead, we suggest that the perfectly defined 312 ± 4 Ma age (an “ideal age plateau” according to [Marheine *et al.* 2002](#), p. 148, representing 95% of the Ar released, and thus identical to the total Ar

age of 311 ± 4 Ma), obtained on a large crystal of muscovite, reflects the true cooling age of the Tanvald body. This in turn cast doubts on the accuracy of the biotite age determination, which does not appear to rely on similarly strong analytical evidence, as suggested by its far from “ideal” age spectrum (fig. 2 of [Marheine *et al.* 2002](#)). Specifically, the choice of the steps used for calculating this age may have been somewhat arbitrary, and a younger (and slightly less precise) age would have been obtained if three additional steps at 316, 314, and 315 Ma (located on both sides of the plateau selected by [Marheine *et al.* 2002](#), and not obviously anomalous), had been included in the calculation, thereby totalizing 90% - instead of 70% - of the Ar released.

Summarizing, it appears that the reported radiometric ages older than the chosen “reference” 312 Ma magmatic event might well reflect analytical and/or methodological difficulties of particular techniques, or disturbance of the isotopic systems after magma crystallization. For this reason, a scenario postulating a long-lived, protracted evolution of the Karkonosze Pluton during a 15-20 Ma time span, cannot be corroborated on firm radiometric grounds. Nevertheless, geological causes of the observed scatter cannot be excluded, until more systematic radiometric data obtained with refined high-precision and high accuracy methods, become available.

7. Summary and conclusions

Based on the recently obtained high-precision CA-ID-TIMS data ([Kryza *et al.* 2014](#)), and using new CA-SIMS zircon dating, we have discussed possible reasons for the large scatter of radiometric ages provided by the various analytical techniques (U-Pb SIMS, Rb-Sr, Re-Os, Ar-Ar) previously used in attempts to unravel the history of the large Karkonosze Pluton.

The main conclusions can be summarized as follows:

1. The identical CA-ID-TIMS zircon ages of ca. 312 Ma, recorded in the two main granite facies studied, the porphyritic and equigranular types, show that their igneous emplacement and crystallization occurred within a fairly short (< 1 Ma) time span. Agreement between these two high-precision ages suggests that granite emplacement occurred over a short

duration, although a more comprehensive and representative sampling strategy would be required to investigate if these data are representative of the batholith as a whole.

2. The CA-ID-TIMS age of 312.2 ± 0.3 Ma measured for the equigranular granite corroborates a less precisely defined WR Rb-Sr isochron age of 312 ± 6 Ma obtained earlier for this rock-type. In addition, the analytically indistinguishable CA-ID-TIMS ages of 312.8 ± 0.3 Ma and 312.4 ± 0.3 Ma for two samples of porphyritic granite prompted us to re-interpret the Rb-Sr WR isochron age of 328 ± 9 Ma published for this rock-type, by considering “zero-age” Sr isotope features. The $(^{87}\text{Sr}/^{86}\text{Sr})_{312}$ ratio calculated for each individual sample show that a few biotite-rich samples, taken from schlieren, contained significantly more radiogenic Sr, interpreted to reflect local contamination by country-rocks. Their inclusion in the isochron calculation increased the slope of the best-fit line, and biased the corresponding age by some 5%. The rest of samples of the porphyritic granite had $(^{87}\text{Sr}/^{86}\text{Sr})_{312}$ ratio identical, within error, with the initial ratio given by the isochron constructed by pooling all samples of the chemically more evolved equigranular granite (311 ± 4 Ma, 0.7066 ± 0.0007). This suggests that not only the comparatively late-stage, more differentiated melts which gave rise to the leucocratic equigranular granites, but also the bulk of the magma which generated the porphyritic rock-types, were broadly homogeneous in terms of Sr isotopic characteristics. Local crustal contamination occurred close to the margins of the body (as indicated by the more radiogenic Sr isotope signature found at the Szklarska Poręba Huta quarry), and replenishment by chemically less evolved and less radiogenic $(^{87}\text{Sr}/^{86}\text{Sr})_{312}$ ca. 0.7055) magmas is documented by synplutonic dykes in the south-western part of the pluton. The whole-rock Rb-Sr data further imply that large volumes of magmas, distributed over a wide area, were in broad isotopic equilibrium when the zircons crystallized.

3. Combining the two lines of evidence of precise CA-ID-TIMS dating and Sr isotopic tracing, it is proposed that the 312 Ma age corresponds to the major igneous event of the pluton, that is, the emplacement, crystallization and chemical differentiation of a large, relatively homogeneous batch of magma. Clearly, this was preceded by a possibly much more protracted evolution involving partial melting in the lower crust, likely induced by the ingress of mafic magmas, followed by melt segregation, magma mixing and pooling. However, only the relatively late stages of final emplacement and crystallization in the upper crust are accessible from the available geochemical data, and they appear to have been short-lived (< 1 Ma). Based on the very high estimates for the blocking temperature of the U-Pb system in

zircons ($> 950\text{ }^{\circ}\text{C}$, *e.g.*, Cherniak and Watson 2003), the very narrow age range provided by the other data that we consider as quite reliable (Ar-Ar on muscovite, Re-Os on molybdenite *pro parte*) demonstrates a fast cooling history, in good agreement with the shallow emplacement level deduced from field observations (*e.g.*, local granophyric textures, narrow contact aureoles with cordierite andalusite as typical thermal-metamorphic minerals). The chronology of the precursor stages, which occurred at deeper crustal levels, remains a matter of conjecture.

4. The interpretation of the scattered SIMS zircon ages is equivocal. Radiogenic Pb-loss is clearly a major problem, in particular in zircons extremely rich in U, thus prone to metamictization, and it certainly can explain the age spread towards spuriously young values. This problem can be overcome, at least partly, by application of the chemical abrasion procedure to micro-beam isotopic techniques. Conversely, subtle inheritance, indicated by internal textures of the zircons and the scatter of SHRIMP ages, up to ca. 330 Ma, probably played a role. We should also keep in mind, that the somewhat arbitrary procedure of zircon selection and data interpretation in the CA-ID-TIMS may cause that we lose evidence for any possible earlier igneous stage(s). Nevertheless, re-assessment of the geochronological data indicates that methodological and analytical problems played an important role in the observed scatter of the results. In particular, the failure to distinguish, at least in that age range, subtly discordant spots from truly concordant ones is a serious limitation of the micro-beam analytical approach.

5. From a methodological point of view, the numerous attempts to unravel the evolution of Karkonosze Pluton provide an example of how scattered geochronological data can be produced for a large granitoid body featuring different rock-types, by using a wealth of radiometric methods, each of which have advantages and shortcomings.

The CA-ID-TIMS U-Pb zircon method provides the best precision and accuracy achievable so far, for methodological (both ^{238}U - ^{206}Pb and ^{235}U - ^{207}Pb clocks can be fully used) and for analytical reasons (unrivalled accuracy of the isotope dilution method for measuring element concentrations and their ratios, more precise measurements of $^{207}\text{Pb}/^{206}\text{Pb}$ ratios allowed by better counting statistics). This approach clearly offers the best time resolution and robustness by virtue of the easy internal check for a closed-system behaviour of the radiometric system permitted by using two coupled clock.

The microbeam (*in situ*) approach of U-Pb dating benefits from spatial resolution at the ca. 10 micrometre scale, a decisive advantage in the case of significant inheritance or presence of disturbed domains. From a practical point of view, it also allows for much more straightforward data acquisition and analytical throughput. However, it must not be overlooked that these advantages are obtained at the cost of a significant loss of precision and, possibly, in some cases accuracy, specifically when analytically unresolvable lead loss or inheritance occur.

Although not able to provide highly precise ages, and prone to possible traps, the Rb-Sr WR method can provide useful information as a tracer, concerning the volumes and spatial distribution of rocks which were isotopically homogeneous at a given time.

The Ar-Ar dating is valuable for those high-level bodies which were quickly cooled below the blocking temperature of the K-Ar system in the studied mineral.

Ideally, an approach combining several of these chronometers and tracers should be favoured to best unravel the evolution of granitic intrusions.

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Appendix : SHRIMP analytical procedure

In-situ U–Pb of zircons were performed on a SHRIMP-II at the Centre of Isotopic Research (CIR) at VSEGEI, St. Petersburg, Russia. A secondary electron multiplier in peak-jumping mode was applied, following the procedure described in Williams (1998) and Larionov *et al.* (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 ca. 27 x 20 µm, and the corresponding primary ion current was ca. 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 ca. 120 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: $^{196}\text{(Zr}_2\text{O)}$ – ^{204}Pb –background (ca. 204.5 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 analysis were acquired. Each fifth measurement was carried out on the TEMORA 1 zircon U/Pb standard (Black *et al.* 2003) The 91500 zircon (Wiedenbeck *et al.* 1995) was applied as a “U-concentration” standard. The collected results were then processed with SQUID v1.13a (Ludwig 2005a) and ISOPLOT/Ex 3.22 (Ludwig 2005b) software, using the decay constants of Steiger and Jäger (1977). The common lead correction was accomplished using measured ^{204}Pb according to the model of Stacey and Kramers (1975).

Figure captions:

Figure 1. Geological sketch map of the Karkonosze-Izera Massif (compiled based on Chaloupský *et al.* 1989; Mazur 1995; Mazur and Aleksandrowski 2001; Oberc-Dziedzic 2003; Oberc-Dziedzic *et al.* 2010a). Insets: (a) Position of the Bohemian Massif in the European Variscides; (b) Outline map of Poland. Rectangles show the location of the Karkonosze-Izera Massif. ISF – the Intra-Sudetic Fault.

Figure 2. Sketch map of the Karkonosze Pluton showing the main granitoid types (compiled using the following sources: Geological Map Lausitz-Jizera-Karkonosze, eds. Kozdrój, Krentz and Opletal, 2001; Borkowska, 1966; [Žák and Klomínský, 2007](#)). Location of dated samples referred to in the text and Figure 8 is given. ISF – the Intra-Sudetic Fault.

Figure 3. Petrography of the Karkonosze granites: macro- (left column) and microphotographs with crossed polars (right-hand side column) of samples studied: (a), (b) – porphyritic granite, sample SZH; (c), (d) – porphyritic granite, sample MICH; (e), (f) – equigranular granite, sample SAM 2. Longer edge of macrophotos = 10 cm.

Figure 4. QAP diagram with plots of selected main types of the Karkonosze granites (based on data from Borkowska, 1966).

Figure 5. Chondrite normalized multi-element diagram (a) and REE plot (b) for the Karkonosze granites (normalization values of Sun and McDonough, 1989); (c), (d) Total-crust normalized multi-element diagram and REE plot (normalization values of Rudnick and Gao, 2005).

Figure 6. Cathodoluminescence and reflected light microscopic images of chemically abraded zircons from the Karkonosze Granite samples studied: (a) – porphyritic granite, sample SZH; (b) – porphyritic granite, sample MICH; (c) – equigranular granite, sample SAM 2.

Figure 7. SHRIMP data for chemically abraded zircons from the Karkonosze granites (Concordia plots and mean $^{206}\text{Pb}/^{238}\text{U}$ ages): (a) sample SZH, (b) sample MICH, (c) sample SAM 2.

Figure 8. Diagram compiling the published geochronological data from the Karkonosze granites (modified from [Awdankiewicz *et al.* 2010](#)). The high-precision CA-ID TIMS age of ~312 Ma (red line) after [Kryza *et al.* \(2014\)](#). LA ICP-MS U-Pb zircon ages (within the range of 320-315 Ma, without analytical errors) from the Czech part of the Karkonosze Pluton, recently published by [Žák *et al.* \(2013\)](#), have not been shown in the diagram.

Tables:

Table 1. Chemical composition of selected samples of the Karkonosze granites.

Table 2. SHRIMP results from Karkonosze granites, samples SZH, MICH and SAM 2 (all chemically abraded).

Table 3. Whole-rock Rb-Sr analytical data, with $^{87}\text{Sr}/^{86}\text{Sr}$ ratios corrected for *in situ* decay of ^{87}Rb since 312 Ma, the best estimate for igneous emplacement age as indicated by CA-ID-TIMS U-Pb zircon dating, along with their uncertainty at the 95% confidence level. The results of already published isochron calculations following Ludwig's algorithm ([Ludwig 1994](#)) are also given for each set of samples. Rb and Sr concentrations were measured by wavelength-dispersive XRF spectrometry as outlined by [Pin and Marini \(1993\)](#), while $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were determined by thermal ionization mass spectrometry after separation by conventional cation-exchange techniques, as described in [Pin *et al.* \(1990\)](#). The precision of $^{87}\text{Rb}/^{86}\text{Sr}$ ratios is estimated to be 1.5%, while that for $^{87}\text{Sr}/^{86}\text{Sr}$ is 0.004%, both at the 95% confidence level. The NIST SRM 987 standard measured during the period of sample analyses gave an average value of 0.71022 ± 2 .

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 7.

Fig. 8.