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Devonian deep-crustal metamorphism and exhumation in the Variscan Orogen: evidence from SHRIMP zircon ages from the HT-HP granulites and migmatites of the Góry Sowie (Polish Sudetes)

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Abstract

The high-temperature and high-pressure granulites in the internal zone of the Variscan belt are witnesses of deep crustal processes and subsequent exhumation of deeper lithospheric fragments. The Góry Sowie Block granulites in SW Poland and the surrounding gneisses and migmatites contain different inherited zircon age spectra, testifying different sources of their protoliths: mainly Cadomian (*ca.* 580 Ma) igneous rocks, and early Ordovician (*ca.* 500 Ma) granitoids (or their reworked products), respectively. The metamorphic spheric and oval zircons in the granulites give two statistically distinct ages of *c.* 395 and 380 Ma, in excess of experimental uncertainty. These ages may correspond to the high-temperature (HT) and high-pressure (HP) granulite facies metamorphism and subsequent amphibolite facies retrogression. However, essentially isochemical reconstitution of zircons and inheritance of radiogenic Pb cannot yet be excluded. The retrogression in the granulites coincided with the amphibolite facies metamorphism in the surrounding gneisses evidenced by a range of various isotopic ages between 384 and 370 Ma. The new SHRIMP zircon data provide new evidence of the presence of “old” (*c.* 400–395 Ma) HT-HP granulites in the central European part of the Variscides. The granulites were subsequently exhumed to mid-crustal levels, and tectonically interleaved with gneisses. Continuing uplift and decompression caused migmatization in the surrounding gneisses and partial re-equilibration of the granulites, at around 380 Ma. This high-temperature and medium-pressure (HT-MP) event was followed by rapid uplift and exhumation at *c.* 360 Ma due to Eo-Variscan orogenic movements.

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Keywords: zircon dating; granulites; exhumation of high-P and high-T rocks; Variscides

1. Introduction

A key problem in the reconstruction of orogenic processes is to explain the presence of high-temperature (HT) and high-pressure (HP) metamorphic rocks, such as granulites, within mid- to low pressure, amphibolite facies gneiss and migmatite complexes. Both types of rocks, in many cases, bear records of evidently contrasting P-T conditions of their peak metamorphic equilibration, contradicting the concept of “*in situ*” metamor-

phism, and suggesting separate P-T paths at early stages of their evolution. The granulites and the amphibolite facies rocks in many areas are shown to have, subsequently, been juxtaposed by large scale tectonic displacements and, afterwards, exhumed to the Earth's surface. Timing of particular tectonothermal events in the granulites and enclosing gneisses/migmatites provide important constraints on tectonic evolution models and paths of

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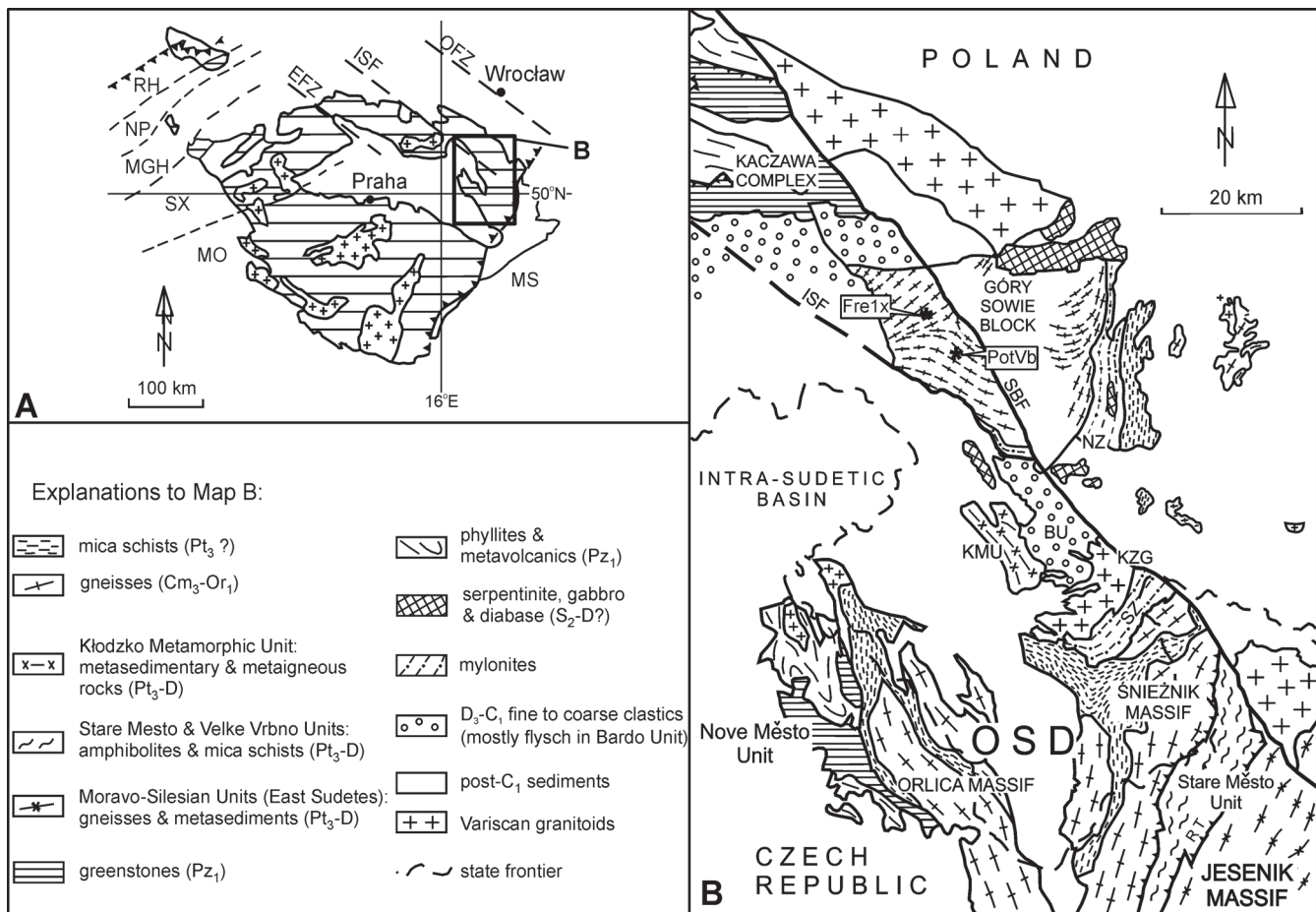


Fig. 1: Geological position of the Góry Sowie Block in the central Sudetes (**map B**) and Bohemian Massif (**map A**).

Inset map A: EFZ: Elbe Fault Zone, ISF: Intra-Sudetic Fault, MGH: Mid-German Crystalline High, MO: Moldanubian Zone, MS: Moravo-Silesian Zone, NP: Northern Phyllite Zone, OFZ: Odra Fault Zone, RH: Rhenohercynian Zone, SX: Saxothuringian Zone. **Map B:** BU: Bardo Unit, ISF: Intra-Sudetic Fault, KMU: Kłodzko Metamorphic Unit, KZG: Kłodzko-Złoty Stok Granitoid, NZ: Niemcza Shear Zone, OSD: Orlica-Śnieżnik Dome, RT: Ramzova Thrust, SBF: Sudetic Boundary Fault, SZ: Skrzynka Shear Zone.

Abbreviations in the legend: C₁: Lower Carboniferous, Cm₃: Upper Cambrian, D: Devonian, D₃: Upper Devonian, Or₁: Lower Ordovician, Pt₃: Upper Proterozoic, Pz₁: Lower Palaeozoic, S₂: Upper Silurian. (compiled by Stanisław Mazur).

exhumation of deep crustal segments (represented by granulite complexes) in orogenic belts. Typical examples can be found, e.g., in the Variscan Belt of Europe [1-9].

HT-HP granulites are widespread throughout the internal massifs of the Variscan Orogen. They display a range of PT peak metamorphic conditions (exceeding 1000 °C and 20 kbar in several cases), and various isotopic ages, with two distinct, albeit broadly defined groups at c. 400 and 340 Ma [e.g., 4,10-12]. Originally, the older granulites were interpreted as related to the subduction of continental crust, whereas the younger ones were regarded as products of deep crustal processes connected with collision during the Variscan orogeny [1]. However, an alternative scenario is proposed [2-4] in which the younger granulites were exhumed from a deeply subducted orogenic root in subduction-exhumation channels activated after delamination of the lithospheric mantle that caused a major isostatic instability. Before the exhumation, excess crustal thickness prevailed for about 50 Ma.

The older group of the HP-HT rocks in the Variscides are typically represented by eclogites and granulites that attained

their peak metamorphic conditions at high- to very-high pressures but mostly at moderate temperatures, at around 400 Ma, and were subsequently exhumed in mid- to late Devonian times, at 380-365 Ma. Examples are found in the Münchberg Massif and in N Bohemia [4,5,13, and refs. therein]. The younger group comprises mostly granulites equilibrated at extremely high temperatures (often around 1000 °C) and also at high pressures (~15-20 kbar), at c. 340 Ma. Typically, they are associated with mantle-derived garnet-peridotites. We find them for example in the granulite type locality of the Granulitgebirge, in the Erzgebirge, S Bohemia, Moravia and Lower Austria. They are interpreted to have been rapidly exhumed and cut by Variscan granitic plutons c. 315 – 325 Ma old [5].

The age bimodality of the HP-HT rocks in the Variscan Belt is of key importance for orogenic models and for indicating that the very high-grade rocks of deep-crustal derivation of the older group were already at shallow depths (as inferred also from sedimentary records, [13]) at the time when their younger counterparts still resided at deep crustal levels [2-4].

This HP-HT bimodality seemingly occurs in a relatively small area of the Sudetes, at the NE margin of the Bohemian Massif (SW Poland), where the older HP-HT granulites are found in the Góry Sowie Block (GSB), and the apparently younger eclogites and omphacite-granulites are known from the Orlica-Śnieżnik Dome (OSD; Fig. 1). In the GSB, the granulite peak metamorphic event has been documented at c. 400 Ma using vapour digestion and single grain zircon evaporation methods [14] though the relationship between the granulites and the surrounding migmatites remained problematic [15, and refs. therein]. Furthermore, the Sowie Góry granulites, unlike the typical older group of HP-HT rocks, experienced very high metamorphic temperatures (above 900 °C), and are associated with mantle-derived peridotites [14,16,17]. The geochronology of the apparently younger eclogites and omphacite-granulites of the Orlica-Śnieżnik Dome remains unresolved, and the isotopic ages of the peak metamorphic event were reported within the range of 380 and 340 Ma [7,18-20]. In this situation, any detailed models of exhumation of the HP-HT rocks in that area [7,9] should be treated with caution.

This study deals with the HT-HP granulites and the surrounding migmatites in the Góry Sowie Block. It aims at: (1) reviewing available data on the petrology, P-T paths and ages of these rocks, and (2) providing new SHRIMP zircon ages from the granulites and migmatites. The new results complement the previous petrological and geochronological data, and help to refine our knowledge concerning: (a) the provenance and ages of the protoliths of the granulites and surrounding migmatites, (b) the age of the peak HP-HT event in the granulites and (c) the timing of subsequent metamorphic evolution and possible coincidence between the granulite degradation and migmatization in the surrounding gneisses. Overall, the new data, combined with the previous results, refine the timing of deep crustal HP-HT metamorphism and subsequent exhumation processes within the orogen.

2. Geological setting

The Góry Sowie Block is one of the main basement units in the central Sudetes at the NE margin of the Bohemian Massif (Fig. 1; for regional geological context see [21-24]). It comprises high-grade metamorphic rocks, mainly gneisses and migmatites, with minor inliers of granulites and garnet meta-peridotites. The GSB, c. 650 km² in area, is triangular in shape and fault-bounded against the neighboring units: the Niemcza Mylonite Zone and ophiolite bodies in the east (the latter also in the NE, S and SW); the Variscan molasse-fill of the Świebodzice Basin in the NW and the Intra-Sudetic Basin in the SW. The GSB is divided by the Sudetic Boundary Fault (SBF in Fig. 1) into a mountainous Sudetic part and a low-lying Fore-Sudetic segment.

The gneisses and migmatites of the GSB are mainly composed of quartz, plagioclase and biotite (\pm Ms \pm Grt \pm

Šil \pm Crd). Subordinate two-feldspar gneisses, locally with augen textures, may have been derived from magmatic protoliths [25,26]. The predominant gneisses, probably derived from a sedimentary protolith, bear records of an early metamorphic event; this event was related to a relatively high P/T gradient, as evidenced by the widespread occurrence of relict kyanite [25]. Subsequent, partially intense migmatization within changing structural regimes, resulted in many textural varieties of migmatites, with a final phase of melted diatexites (nebulites or in situ granuloids). The late stage of the main metamorphic event in the migmatites was characterized by a low P/T gradient indicated by texturally late cordierite [25].

Żelaźniewicz [27] distinguished five deformation events in the GSB, the latest four of which were interpreted on geochronological evidence to have taken place shortly before the Late Devonian [28,29]. Recent geochronological data indicate that the main high-amphibolite facies metamorphism in the GSB occurred at around 385–370 Ma with rapid subsequent uplift [15, and refs. therein].

The nature and ages of the protoliths of the GSB gneisses have long been controversial. Problematic microfossil findings [30] suggested Early Palaeozoic (Cambrian ?) ages for the sedimentary protoliths, this being roughly in line with the growing evidence for the Cambrian/Ordovician ages of the main population of zircons in the gneisses [31,32]. The dated zircons display magmatic features, thus the source rocks for the gneisses apparently comprised granuloids or their reworked sedimentary products.

Felsic and minor Cpx-bearing granulites form three small (tens to hundreds of metres across) inliers in the gneisses and migmatites in the northern part of the GSB. The most common felsic varieties are composed of perthitic and antiperthitic feldspars, garnet, kyanite, rutile and accessory ilmenite, zircon and monazite. Muscovite is secondary, whereas biotite is at least partly secondary. The age of the peak granulite-facies metamorphism was determined to be about 400 Ma based on ²⁰⁷Pb/²⁰⁶Pb ratios measured by vapour digestion and single grain evaporation techniques for characteristic spherical zircons [14].

The granulites are associated with garnet- and spinel-bearing meta-ultramafites, mostly strongly serpentized [33,34]. The PT conditions of their primary equilibration were estimated at 1030 °C, 27 kbar for cores of grains, and 800 °C, 16 kbar for rims [16], corresponding well to similar high-grade conditions in the granulites. The meta-ultramafites yielded also an age of around 400 Ma [16] identical with that of the granulites.

An important question concerning the relationship between the granulites and associated meta-ultramafites, and the surrounding gneisses and migmatites, remains controversial. Żelaźniewicz [35] interpreted the granulites as tectonic inliers in the gneisses. However, relict mineral parageneses and textures in the country rocks [25,36,37], as well as thermobarometric estimates strongly suggest that the host rocks have also experienced an early metamorphic event at fairly high P and T (see below).

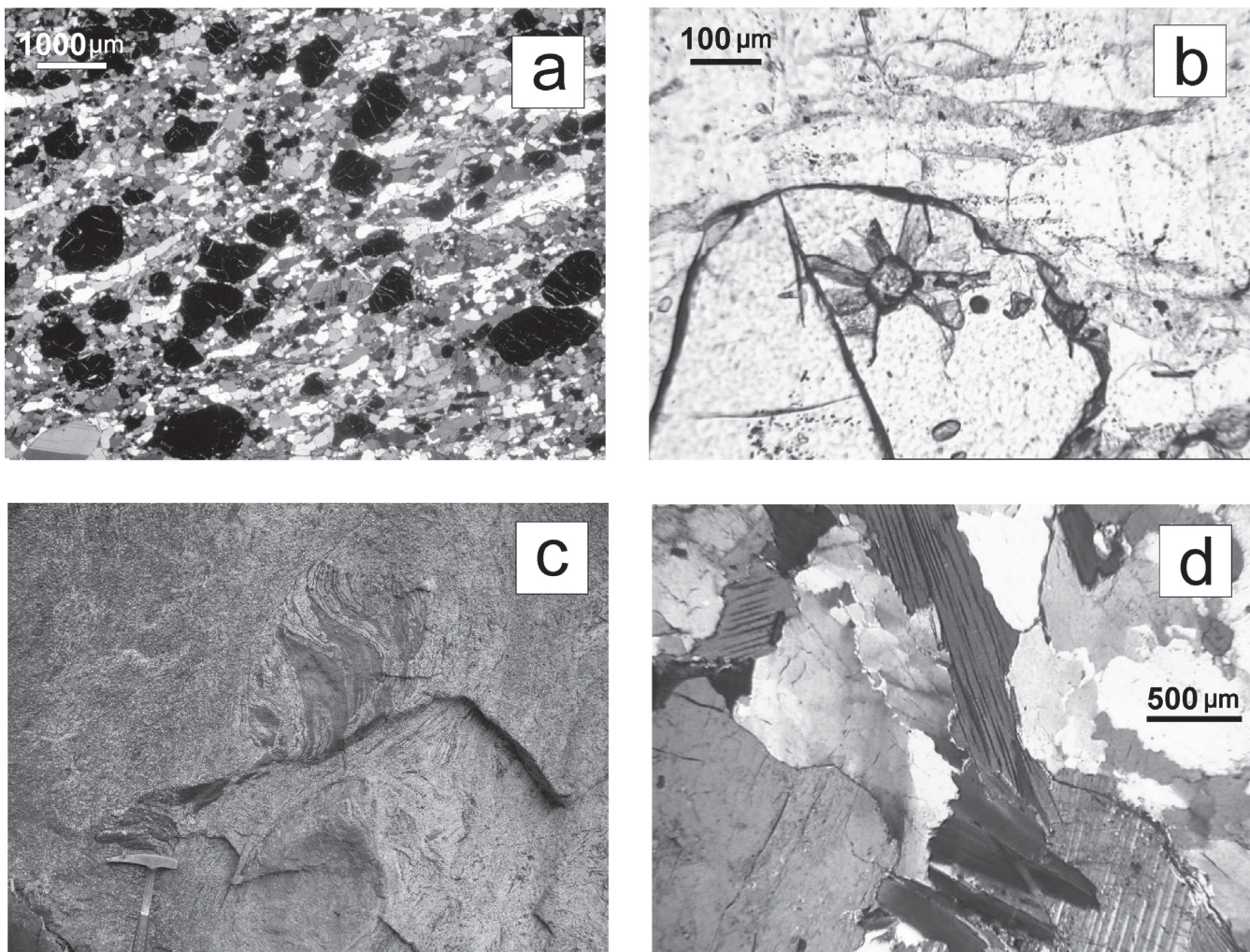


Fig. 2: Photomicrographs of felsic granulite: (a) typical porphyroblastic texture: garnet (black) in a matrix dominated by quartz and feldspars (crossed polars); (b) oval zircon inclusion in garnet (plane polarized light). Migmatite (diatexite) at Potoczek, central part of the Góry Sowie Block: (c) typical nebulite appearance; (d) granitic texture of the diatexite (crossed polars).

Recently, Gordon *et al.* [9] have provided new ion microprobe Th-Pb, and electron microprobe total-Pb monazite ages, together with complementary U-Pb zircon results, on amphibolite-facies gneissic and migmatitic samples from both the Góry Sowie Block and Orlica-Śnieżnik Dome. In their model, the GSB granulites attained the peak PT conditions of the granulite facies at c. 400 Ma, and then were exhumed to mid-crustal levels at 380-370 Ma, generally in line with the previously published data.

3. Petrological notes

The petrology of the GSB migmatites and granulites has been described in detail in several papers [17,25,27,35, and refs. therein]. Herewith, we present: (a) petrographic details of the samples on which SHRIMP geochronology was performed, and (b) a review of the P-T paths of the rocks studied based on earlier published data.

3.1. Felsic granulite from Zagórze

The sample for SHRIMP zircon dating Fre1x comes from the well-known locality of Zagórze Śląskie (Zagórze in short), which is a road cut several metres long, along the south bank of the Jezioro Bystrzyckie (Bystrzyca Lake) in the central north part of the GSB (c. 11 km SWS of the city of Świdnica; Fig. 1).

The specimen selected, collected in the centre of the exposure, represents a fresh, not strongly retrograded, felsic granulite (Fig. 2a,b). It is a pale grey, pink-tinged, fine- to medium-grained rock, with mostly distinct colour banding reflecting various concentrations of felsic and mafic minerals. The main components are quartz, plagioclase, K-feldspar, garnet and kyanite, whereas accessories are represented by rutile, ilmenite, zircon, apatite and monazite. Secondary (at least in part) biotite clusters around garnet, and obviously retrogressive white mica typically rims kyanite crystals. Quartz is usually platy in shape, defining the foliation of the rock. Plagioclase, ranging

between An₂₂ in cores to An₂₅ in rims, displays antiperthitic intergrowths, as does less abundant K-feldspar with a common perthitic texture. Garnet forms subidiomorphic porphyroblasts, locally with distinct cores filled with numerous tiny inclusions, and inclusion-free rims. It is chemically zoned, with a strong decrease in grossularite contents from core to rim, compensated by moderate increases in pyrope, almandine and spessartine molecules. Kyanite, up to several mm in size, is very common, and rutile is also a frequent accessory.

3.2. Migmatite (diatexite) from Potoczek

The sample of diatexitic migmatite (nebulite) Pot Vb comes from the old village of Potoczek in the central part of the GSB, c. 11 km WSW of the town of Dzierżonów (Fig. 1). The specimen was collected from a large crack on the E side of the road, 200 m S of the parking site.

In the exposure, the dominant type is a granite-like rock, grey in colour, with a medium-grained and generally massive texture (Fig. 2c,d). This homogeneous mass contains mostly loaf-shaped inclusions of darker gneisses and layered migmatites, usually darker and finer-grained compared with the granitic matrix. Apart from the well-defined inclusions, the granite-like rock displays locally diffuse “shadows” of not completely “digested” foliated gneisses.

The studied sample represents a homogeneous, grey, massive, granitoid-like portion of the Góry Sowie migmatites. The major components include quartz, plagioclase and biotite, with subordinate and generally locally distributed K-feldspar, garnet and muscovite. Sillimanite is rare, whereas apatite, zircon and monazite are common accessories [25,38,39]. The plagioclase is characteristically idio- to subidiomorphic, displaying weak chemical zonation, with An contents around An₃₀ decreasing from core to rim. Biotite is randomly oriented, often associated with garnet porphyroblasts, up to 1 cm in size. The garnet is slightly zoned, with decreasing Grs contents from core to rim of grains. The observed textures, together with other petrographic features (*e.g.* normal zonation in plagioclase, [25]) indicate that the migmatites were formed through intense anatexis melting (diatexis).

3.3. Summary of metamorphic P-T conditions

Pressure and temperature conditions for the GSB granulites were calculated using ternary feldspar and biotite-garnet thermometry, GASP barometry for the felsic rocks, and selected garnet-clinopyroxene-orthopyroxene equilibria for the pyroxene-bearing varieties. The results were verified applying the TWQ programme [17, and refs. therein]. The mineral core compositions yielded very high temperatures, between 900 and 1050 °C at pressures between 15 and 20 kbar. Similar values have also been reported by O'Brien *et al.* [14], and they are considered to reflect the peak granulite facies event. The mineral rim compositions gave considerably lower pressures, within the range of 4 to 6 kbar, at temperatures that had dropped to c. 630–750 °C. The later decompressive event is strongly reflected

by mineral chemical zonation (*e.g.* grossularite decrease from core to rim in garnet) and textures (*e.g.* decomposed perthitic feldspars, plagioclase + orthopyroxene coronas around garnet porphyroblasts in clinopyroxene-bearing granulites).

A P-T path of migmatites from Potoczek was calculated by Kryza & Pin [40] using biotite-garnet and GASP thermobarometry. An earlier stage of metamorphism recorded in the migmatites, inferred from the mineral core compositions, took place at around 850 °C and c. 10 kbar. That stage was followed by a later event, evidenced in rims of grains, at still rather high temperatures of around 700 °C and significantly lower pressures of c. 4–6 kbar. Very similar estimates were obtained for coronitic metagabbros in the same area [40].

Summing up, the GSB granulites experienced an early granulite facies peak metamorphism at high pressures (15–20 kbar) and temperatures (above 900 °C). This was followed by a decompressive re-equilibration under still high temperatures (630–750 °C) but evidently lower pressures (4–6 kbar). In contrast, the surrounding migmatites bear records of a still pressure-dominated (but at significantly lower P) early phase of metamorphic evolution (c. 10 kbar and 850 °C, evidenced also by the widespread relict kyanite). An important feature is that both the granulites and hosting migmatites experienced profound re-equilibration at roughly the same metamorphic conditions at c. 630–750 °C and 4–6 kbar (see Fig. 7).

4. SHRIMP zircon geochronology

Zircon grains for the SHRIMP analysis were obtained by the standard separation procedures: crushing, sieving, heavy liquid (sodium polytungstate) and paramagnetic separation. The zircons were finally hand-picked under a binocular microscope from the grain-size fraction of 60 to 300 μm and, afterwards, mounted in epoxy and polished in the form of standard thin sections. Cathodoluminescence (CL) SEM images were made for all mounted zircons to enable selection of grains and domains for analysis. The U, Pb, Th and isotopic analyses were done using the Sensitive High Resolution Ion Microprobe (SHRIMP II) at the Australian National University; each analysis consisting of six scans through the mass spectrum. The data have been reduced in a manner similar to that described by Williams [41, and references therein], using the SQUID Excel Macro of Ludwig [42]. The Pb/U ratios for the zircons have been normalised relative to a value of 0.1859 for the ²⁰⁶Pb/²³⁸U ratio of the FC1 reference zircon, equivalent to an age of 1099 Ma [see 43]. Uncertainties given for individual analyses (ratios and ages) are at the 1σ level, while the uncertainties in calculated weighted mean ages are reported as 95% confidence limits. Tera and Wasserburg [44] concordia plots and weighted mean ²⁰⁶Pb/²³⁸U ages were carried out using ISOPLOT/EX [45].

4.1. Felsic granulite

The zircon grains from this sample range from elongate subhedral crystals (*e.g.* grains 1, 3, 9, 12, 14 and 15 in Fig. 3)

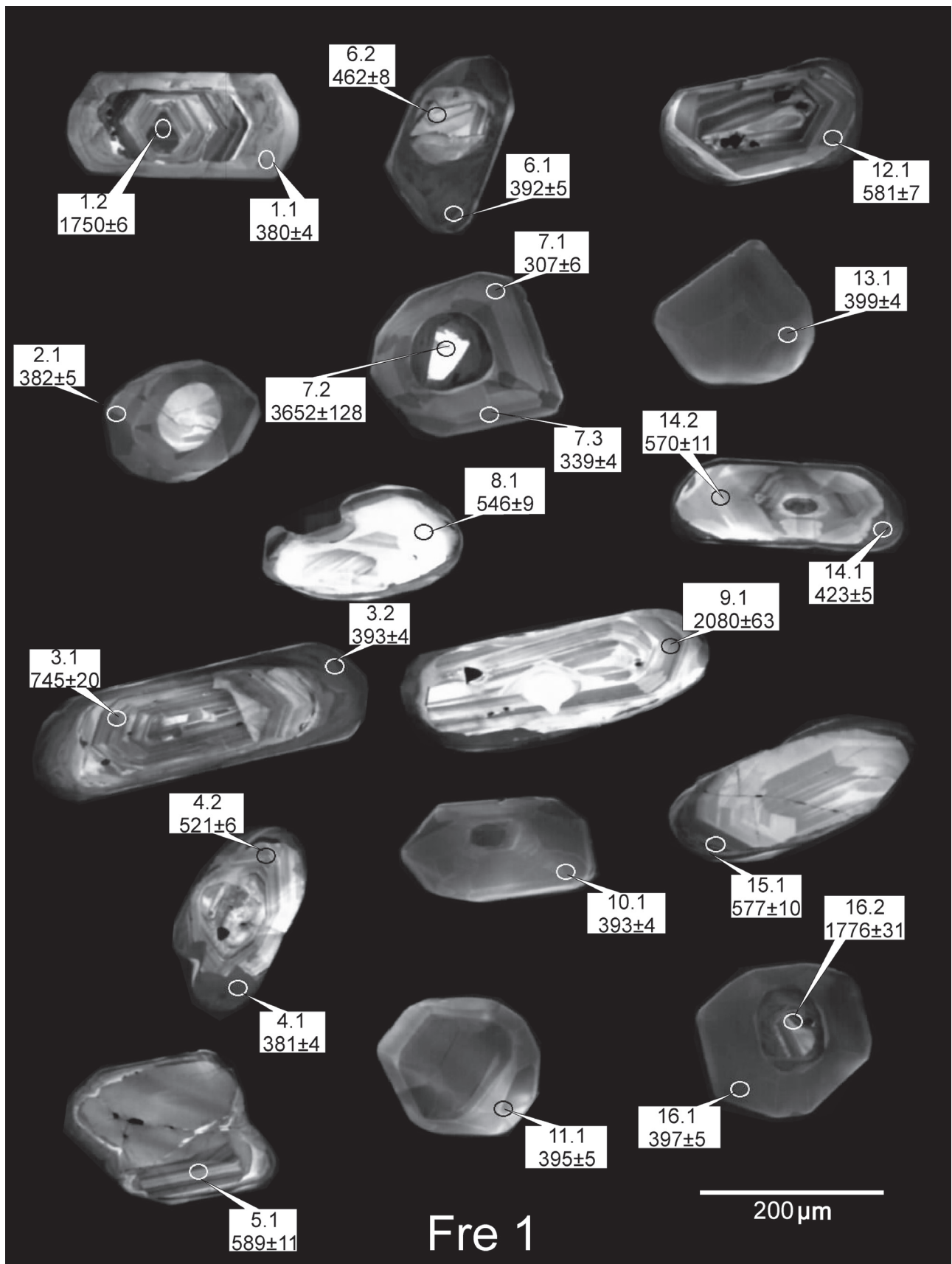
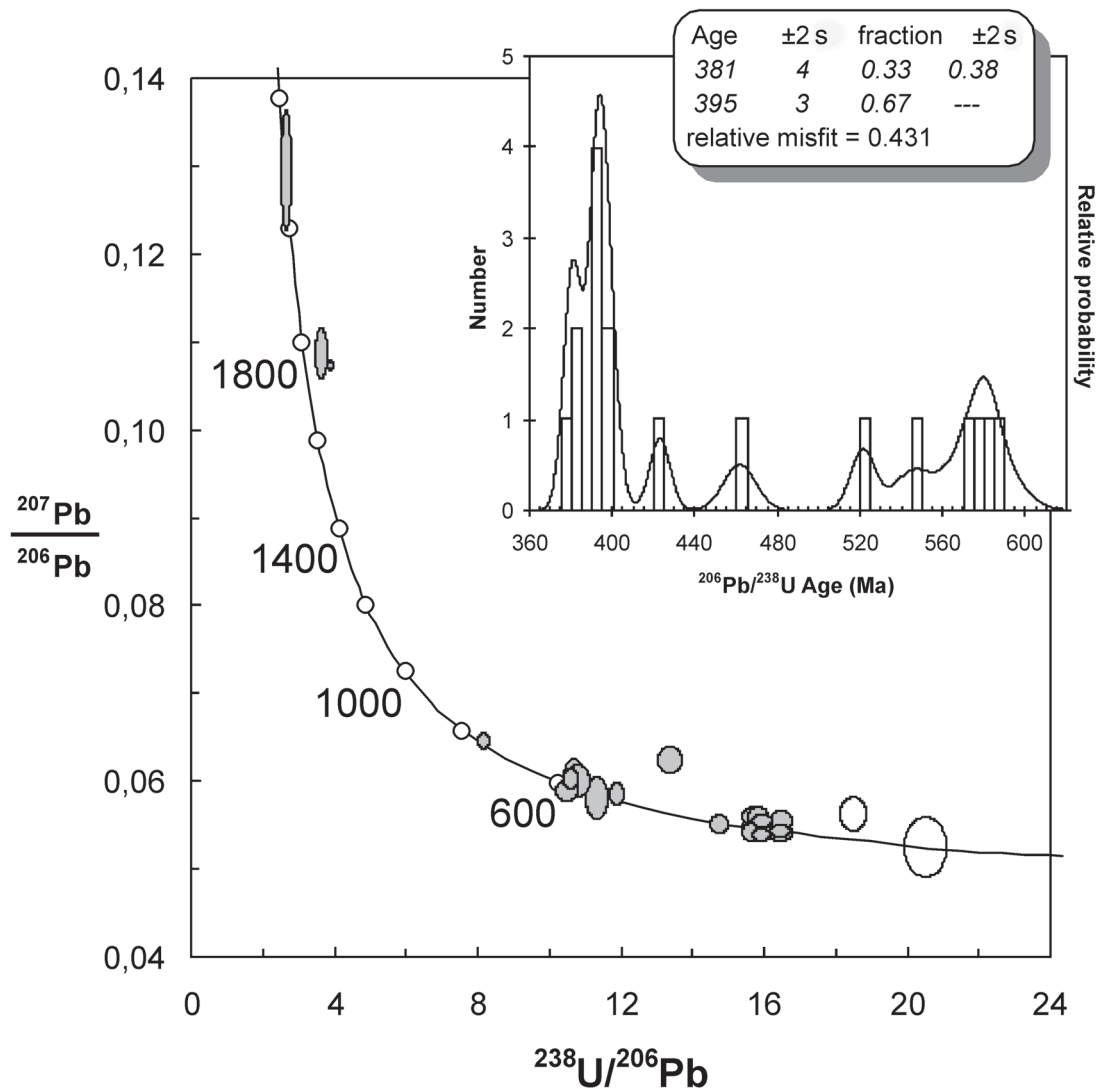


Fig. 3: Cathodoluminescence images of the zircon grains analysed from the felsic granulite from Zagórze. The circles indicate spots analysed, and the labels give the $^{206}\text{Pb}/^{238}\text{U}$ ($^{207}\text{Pb}/^{206}\text{Pb}$ for Precambrian) ages from Table 1.

Fig. 4: Tera and Wasserburg (1972) concordia plot of SHRIMP analyses for the Zagórze granulite showing the total $^{207}\text{Pb}/^{206}\text{Pb}$ ratios vs. the calibrated $^{238}\text{U}/^{206}\text{Pb}$ ratios, uncorrected for common Pb. Inset shows a relative probability plot, with stacked histogram (using Ludwig 1999) of the radiogenic $^{206}\text{Pb}/^{238}\text{U}$ ages for the zircon analyses with ages below 600 Ma. The modelling calculation is for the first two age peaks, Tera and Wasserburg (1972)[44] (using Ludwig 1999 [45]).



to equant round morphologies with the classic “soccer-ball” shape of deep crustal zircons (grains 2, 7, 8, 11, 13 and 16 [e.g., 46-48]). Even under transmitted light the grains can be seen to be structured. A number of the elongate grains have a central component that dominates the grain and has abundant tiny inclusions of apatite, rutile and other optically unidentifiable phases. These are overgrown by clear zircon rims. The CL images reveal the true complex internal structure (Fig. 3). The majority of the grains have zoned magmatic-type interiors, interpreted to reflect igneous sources for the zircons. The rims to the elongate grains, and the main areas of the more equant grains are dark under CL and likely of a metamorphic origin. In some cases the metamorphic rim is not well developed and so the grain is dominated by the protolith zircon component.

Twenty four areas have been analysed on 16 grains (Fig. 3, Table 1). The three analyses of grain 7 are all anomalous with respect to the rest of the data-set. There were clear machine problems during the analysis of area 7.2, the core of grain 7. The two analyses of the rims (7.1 and 7.3) are considered to be discordant and are not considered further.

Analyses of the zoned magmatic areas yield a range of ages from Ordovician to Palaeoproterozoic with no clear grouping. Four of these zircon core areas record $^{206}\text{Pb}/^{238}\text{U}$ ages between ~ 570 Ma and ~ 590 Ma indicating an important Cadomian (Panafrikan) source for the zoned zircon inherited components. However, the overall range in inherited ages suggests that the protolith is heterogeneous and that the rock is of a sedimentary derivation.

Analyses of the metamorphic (and/or anatectic ?) rims similarly do not define a single age grouping, nor do they follow “folk-lore” that metamorphic zircon rims have low Th/U ratios (less than 0.01). The analyses of the metamorphic rims to grains 1, 3, 4, and 6 are truly depleted in Th (<5 ppm Th) and have Th/U ratios of 0.01 or less. The $^{206}\text{Pb}/^{238}\text{U}$ ages however range from approximately 380 to 395 Ma, in excess of experimental uncertainty, and so do not define a unique metamorphic crystallisation age. Other metamorphic rim areas analysed do not show Th depletion and have Th/U ratios between 0.1 and 0.3. The $^{206}\text{Pb}/^{238}\text{U}$ ages range from ~ 380 Ma to ~ 400 Ma overlapping with those from the low Th/U metamorphic rims. It is not uncommon for metamorphic zircon growths to reflect the protolith zircon chemistry

Table 1: Summary of SHRIMP U-Pb zircon results for sample Fre 1.r.

Grain spot	U (ppm)	Th (ppm)	Th/U	Pb* (ppm)	$\frac{^{204}\text{Pb}}{^{206}\text{Pb}}$	f_{206} %	Total Ratios		Radiogenic Ratios				Age (Ma)					
							$\frac{^{238}\text{U}}{^{206}\text{Pb}}$	\pm	$\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$	\pm	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	\pm	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	\pm	$\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$	\pm	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	% Disc
1,1	232	2	0,01	12,1	0,000090	0,16	16,445	0,191	0,0555	0,0008	0,0607	0,0007	0,0607	0,0007	379,9	4,3		
1,2	527	342	0,65	117,5	0,000017	0,03	3,853	0,051	0,1073	0,0004	0,2594	0,0034	3,829	0,052	0,2594	0,0034	0,968	15
2,1	373	77	0,21	19,6	-	<0,01	16,404	0,214	0,0541	0,0006	0,0610	0,0008	0,0610	0,0008	381,5	4,9		
3,1	261	192	0,74	27,5	0,000118	0,21	8,154	0,117	0,0646	0,0006	0,1226	0,0018	1,083	0,019	0,0641	0,0006	0,837	0
3,2	688	4	0,01	37,2	0,000022	<0,01	15,902	0,169	0,0540	0,0004	0,0629	0,0007	0,0629	0,0007	393,4	4,1		
4,1	660	4	0,01	34,5	-	0,01	16,415	0,175	0,0543	0,0005	0,0609	0,0007	0,0609	0,0007	381,2	4,0		
4,2	213	133	0,63	15,4	0,000003	0,10	11,858	0,137	0,0586	0,0009	0,0842	0,0010	0,0842	0,0010	521,4	5,9		
5,1	248	45	0,18	20,4	-	<0,01	10,458	0,196	0,0589	0,0008	0,0957	0,0018	0,0957	0,0018	589,2	10,8		
6,1	684	3	0,00	36,9	0,000002	0,12	15,943	0,190	0,0555	0,0005	0,0626	0,0008	0,0626	0,0008	391,7	4,6		
6,2	156	30	0,19	10,0	0,000195	0,76	13,364	0,231	0,0624	0,0010	0,0743	0,0013	0,0743	0,0013	461,8	7,8		
7,1	277	44	0,16	11,6	-	0,01	20,499	0,387	0,0526	0,0022	0,0488	0,0009	0,0488	0,0009	307,0	5,8		
7,2	40	28	0,69	6,9	-	<0,01	5,012	0,437	0,3377	0,0283	0,1995	0,0174	9,291	1,123	0,1995	0,0174	0,721	68
7,3	361	50	0,37	16,8	-	0,38	18,474	0,243	0,0563	0,0013	0,0539	0,0007	0,0539	0,0007	338,6	4,4		
8,1	73	51	0,70	5,6	-	<0,01	11,327	0,197	0,0581	0,0015	0,0883	0,0016	0,0883	0,0016	545,6	9,3		
9,1	85	38	0,44	27,7	0,000060	0,09	2,650	0,082	0,1295	0,0046	0,3771	0,0117	6,692	0,316	0,3771	0,0117	0,656	1
10,1	292	39	0,13	15,8	-	<0,01	15,926	0,180	0,0543	0,0007	0,0628	0,0007	0,0628	0,0007	392,7	4,4		
11,1	249	49	0,20	13,5	0,000038	0,18	15,816	0,182	0,0560	0,0008	0,0631	0,0007	0,0631	0,0007	394,6	4,5		
12,1	204	193	0,95	16,5	-	0,10	10,596	0,122	0,0602	0,0007	0,0943	0,0011	0,0943	0,0011	580,8	6,5		
13,1	277	56	0,20	15,2	0,000046	<0,01	15,667	0,177	0,0543	0,0007	0,0639	0,0007	0,0639	0,0007	399,1	4,4		
14,1	332	43	0,13	19,3	0,000031	<0,01	14,743	0,176	0,0551	0,0006	0,0678	0,0008	0,0678	0,0008	423,1	5,0		
14,2	120	108	0,90	9,6	0,000244	0,12	10,801	0,209	0,0601	0,0012	0,0925	0,0018	0,0925	0,0018	570,2	10,8		
15,1	486	158	0,33	39,1	-	0,14	10,676	0,182	0,0604	0,0014	0,0935	0,0016	0,0935	0,0016	576,5	9,6		
16,1	412	57	0,14	22,5	-	0,18	15,722	0,204	0,0561	0,0007	0,0635	0,0008	0,0635	0,0008	396,8	5,1		
16,2	350	128	0,37	83,1	-	<0,01	3,616	0,096	0,1086	0,0018	0,2765	0,0073	4,140	0,130	0,2765	0,0073	0,842	11

Notes:

1. Uncertainties given at the one sigma level.
2. Error in FC1 reference zircon calibration was 0.39 for the analytical session (not included in above errors but required when comparing data from different mounts).
3. f_{206} % denotes the percentage of ^{206}Pb that is common Pb.
4. For areas older than ~800 Ma correction for common Pb made using the measured $^{204}\text{Pb}/^{206}\text{Pb}$ ratio.
5. For areas younger than ~800 Ma correction for common Pb made using the measured $^{238}\text{U}/^{206}\text{Pb}$ and $^{207}\text{Pb}/^{206}\text{Pb}$ ratios following Tera and Wasserburg (1972).
6. For % Disc, 0% denotes a concordant analysis.

Table 2: Summary of SHRIMP U-Pb zircon results for sample Pot Vb.r

Grain spot	U (ppm)	Th (ppm)	Th/U	Pb* (ppm)	$\frac{^{204}\text{Pb}}{^{206}\text{Pb}}$	f_{206} %	Total Ratios		Radiogenic Ratios				Age (Ma)		% Disc
							\pm	$\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$	\pm	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	\pm	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	\pm	$\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$	
1,1	179	33	0.18	12.2	0.000076	0.01	12.626	0.153	0.0570	0.0009	0.0792	0.0010	491.3	5.8	
2,1	280	29	0.10	19.7	0.000041	<0.01	12.208	0.137	0.0570	0.0006	0.0820	0.0009	508	6	
2,2	97	33	0.34	6.6	-	0.17	12.680	0.165	0.0583	0.0011	0.0787	0.0010	488.5	6.2	
3,1	238	19	0.08	16.0	0.000139	0.04	12.794	0.145	0.0571	0.0007	0.0781	0.0009	485	5	
4,1	102	53	0.52	6.7	0.000288	0.39	12.918	0.168	0.0598	0.0011	0.0771	0.0010	478.9	6.1	
5,1	99	205	2.07	29.1	0.000025	0.04	2.928	0.126	0.1256	0.0099	0.3414	0.0147	1893.4	70.6	2032 140 7
6,1	274	23	0.09	18.8	0.000079	0.06	12.550	0.142	0.0576	0.0007	0.0796	0.0009	493.9	5.5	
7,1	141	37	0.26	9.7	0.000134	0.15	12.439	0.154	0.0584	0.0009	0.0803	0.0010	497.8	6.1	
7,2	166	16	0.10	34.5	0.000046	0.08	4.126	0.108	0.1182	0.0034	0.2422	0.0063	1398.0	32.8	1919 53 27
8,1	341	46	0.13	24.2	0.000163	0.38	12.133	0.137	0.0606	0.0008	0.0821	0.0009	508.6	5.6	
9,1	189	96	0.51	13.2	0.000087	0.19	12.359	0.146	0.0588	0.0008	0.0808	0.0010	500.6	5.8	
10,1	143	52	0.36	40.0	0.000026	0.04	3.064	0.056	0.1252	0.0017	0.3262	0.0060	1820	29	2026 24 10
11,1	148	59	0.40	10.2	0.000179	0.06	12.432	0.179	0.0577	0.0009	0.0804	0.0012	498.4	7.0	
12,1	192	46	0.24	13.0	0.000120	0.04	12.682	0.168	0.0572	0.0008	0.0788	0.0011	489.1	6.4	
12,2	88	33	0.38	6.0	0.000136	0.06	12.558	0.169	0.0575	0.0012	0.0796	0.0011	494	7	
13,1	141	28	0.20	9.8	0.000283	0.16	12.285	0.151	0.0586	0.0011	0.0813	0.0010	503.7	6.1	
14,1	256	12	0.05	13.9	0.000054	0.06	15.832	0.181	0.0550	0.0007	0.0631	0.0007	394.6	4.5	
14,2	152	52	0.34	10.6	0.000142	0.22	12.357	0.160	0.0590	0.0010	0.0808	0.0011	500.6	6.4	
15,1	188	57	0.31	13.3	-	0.06	12.109	0.142	0.0580	0.0008	0.0825	0.0010	511.2	5.9	
16,1	156	34	0.22	11.2	0.000090	0.05	11.950	0.146	0.0581	0.0009	0.0836	0.0010	517.8	6.2	
16,2	111	60	0.54	7.7	0.000210	0.10	12.339	0.304	0.0580	0.0011	0.0810	0.0020	501.9	12.1	
17,1	106	29	0.27	7.0	0.000150	0.38	12.882	0.178	0.0598	0.0016	0.0773	0.0011	480.2	6.6	
18,1	131	26	0.20	8.9	-	0.20	12.685	0.162	0.0585	0.0010	0.0787	0.0010	488.2	6.1	

Table 3: Compilation of published geochronological data for the Góry Sowie gneisses, migmatites, granulites and associated rocks

Rock types & localities (sample)	Ages (Ma)	Methods	Refs.
1. Gneisses & migmatites			
1.1. Zagórze Śląskie (dam-lake): layered migmatites	381±2 369±15 (l. intercept) 360±7, 372±7	U-Pb Mnz U-Pb Zrn unabraded Rb-Sr Bt model age	[28] [28] [28]
layered migmatites PL4	483.7±1.7 (mean 3 grains) [1124.9±1.1, 1173.5±0.8, 1324.5±1.2, 2246.4±0.8, 2367.8±1.0]	207Pb-206Pb Zrn single grain evaporation -	[32] -
layered migmatites PL6	485.8±1.7 (mean 3 grains) [1182.2±1.5, 1270.1±1.4, 1699.6±1.2, 1839.7±0.7]	-	-
layered migmatites 1097 & 1098 (leucosome)	362±8, 366±7 (leucosome)	Rb-Sr thin slab	[29]
1.2. Jugowice: gneiss PL14	[2214.7±0.9, 2393.1±0.8, 2395.4±1.4, 2415.8±2.1, 2620.1±1.1]	207Pb-206Pb Zrn single grain evaporation	[32]
1.3. Sokolec: granitogneiss PL16	487.4±1.7 (mean 6 grains) [1937.0±1.3]	207Pb-206Pb Zrn single grain evaporation -	[32] -
augengneiss PL17	482.3±1.7 (mean 4 grains) [1558.3±1.4]	-	-
augengneiss 1100	380 – 384 374±5 380±2, 381±2, 384±3	207Pb-235U Mnz multigrain Rb-Sr internal isochron 207Pb-206Pb Xenotime multigrain	[29] - -
1.4. Potoczek: nebulite (diatexite) nebulite (diatexite) PL11 nebulite (diatexite) 1101 nebulite (diatexite) 1101	461±50-2 (l. intercept) 439.8±1.8 (mean 3 grains) 372±7 c. 379 – 383 (375±3, 379±2, 380±2)	U-Pb Zrn multigrain 207Pb-206Pb Zrn single grain evaporation Rb-Sr thin slab Pb-U Mnz multigrain (207Pb-206Pb Mnz)	[31] [32] [29] -
2. Granite dykes & pegmatites			
2.1. Walim: granite dyke PL15	472.9±1.7 (mean 2 grains) [1267.2±1.2, 2537.2±1.2, 2675.0±1.0]	207Pb-206Pb Zrn single grain evaporation	[32]
granite dyke 1099	372±3	Rb-Sr internal isochron	[29]
granite dyke	378±2 (mean 3 grains)	TIMS U-Pb Mnz	[61]
granite dyke SU46	359±3	40Ar-39Ar Ms single grain and concentrates	[60]
2.2. Zagórze Śląskie (Fregata): pegmatite	370±5, 371±3, 383±5	TIMS U-Pb Xenotime	[61]
2.3. Lutomia Górna: pegmatite	363±4, 374±4, mean: 372±7	Rb-Sr Ms model age	[28]
3. Granulites and ultramafics			
3.1. Zagórze Śląskie (Fregata): felsic granulite	401.5±0.9.9 (mean 19 grains) [446.8±1.6 to 2154.7±1.4]	U-Pb & Pb-Pb Zrn vapour digestion & single grain evaporation	[14]
felsic granulite	388±3	IMS1270 ion microprobe, Mnz	[64]
3.2. Bystrzyca Górna: metaperidotite	402±3	Sm-Nd Grt-Opx-Cpx-whole rock	[18]
4. Others (no precise sample location)			
mylonitized gneiss	319±17, 337±13	40Ar-39Ar Ms & Bt fusion ages	[63]
mylonitized gneiss (Przygórze) SU48	359±3 (Ms), 381±4 (Bt)	40Ar-39Ar Ms & Bt single grain and concentrates	[60]
protomylonite S part of GSB	347±3, 377±5	IMS1270 ion microprobe, Mnz	[63]
gneisses GSB	382±1, 373±0.5	40Ar-39Ar Horn and Mica plateau ages	[64]
Grt-gneiss GS-14 (S Góry Sowie)	375±5	IMS1270 ion microprobe, Mnz	[8]
Bt-granulite-gneiss GS-2 (N Góry Sowie)	388±3, 372±5, 405±7, 415±7	-	-
Mica-granulite GS-19 (east GSB)	355±8, 383±7, 404±14	electron Microprobe total-Pb, Mnz	-
Gneiss GS-11 (west-central Góry Sowie)	358±14, 383±7, 418±14	-	-
Grt-gneiss GS-8 (central Góry Sowie)	360±5, 382±4, 404±5	-	-

[in brackets = ages of xenocryst]

[see for example 49], perhaps an indication of essentially isochemical reconstitution of the zircon from an igneous to a metamorphic form. If this process is only partially effected then it may be possible for some inherited radiogenic Pb to remain, therefore giving rise to a spread in $^{206}\text{Pb}/^{238}\text{U}$ ages as seen in this sample. It is possible to deconvolve, statistically, the $^{206}\text{Pb}/^{238}\text{U}$ analyses into two groups using the mixture modelling algorithm of Sambridge and Compston [50]. The age components suggested by this statistical function are ~ 395 Ma and ~ 380 Ma (Fig. 4). The former is the more prominent ($\sim 65\%$); both contain areas with low Th/U ratios. From the current data-set, we conclude that the timing of the metamorphic zircon occurred no later than ~ 380 Ma in this sample.

4.2. Diatexitic migmatite

The zircons from this sample are dominantly elongate sub- to euhedral crystals, many with bipyramidal terminations (Fig. 5). The grains are remarkably clear under transmitted light, though some grains do have inclusions of apatite. A few grains are more equant, multifaceted soccer-ball types and considered to be high-grade metamorphic or anatectic zircons. The CL images show a dominantly simple oscillatory zoned, magmatic internal structure. Some of these grains do have more complex internal structure, with distinct cores overgrown by zoned (magmatic) rims (e.g. grain 7). The rare soccer-ball type grains usually have rather indistinct cores and fairly homogeneous rims (grains 2 and 5 in Fig. 5).

Twenty three areas have been analysed on 18 zircon grains (Fig. 5, Table 2). The analysis of the central areas to grain 7 and those for grains 5 and 10 yield Proterozoic $^{207}\text{Pb}/^{206}\text{Pb}$ ages of approximately 1900 to 2030 Ma. These are interpreted as inherited components in this rock. The analysis of the tip to grain 14 yields a $^{206}\text{Pb}/^{238}\text{U}$ age of ~ 395 Ma which is anomalously young for this migmatite sample. The CL of this area is dark, indicating a possible metamorphic origin. The grain, however, has euhedral terminations. Whilst the Th/U ratio of ~ 0.05 of this area is lower than all other areas analysed, the Th and U concentrations are not anomalous. This single young analysis may reflect a metamorphic event that post-dates the dominant zoned igneous zircon.

The remaining 19 areas analysed, including those of the deep crustal zircon (grain 2) cluster close to or within uncertainty of the Tera and Wasserburg Concordia at about 500 Ma. In detail, there is a range in the $^{206}\text{Pb}/^{238}\text{U}$ ages, from ~ 480 Ma (4.1) to ~ 518 Ma (16.1) and the relative probability plot shows a broad age peak that is skewed from a peak near 500 Ma towards the older side (Fig. 6). Whilst it may be possible to deconvolve this using the Sambridge and Compston [50] mixture modelling algorithm there is no clear mathematical solution. If the oldest and youngest analyses are excluded, a weighted mean for 17 analyses has excess scatter (MSWD = 2.1) giving an age estimate of 497 ± 5 Ma. From the current data this is interpreted as the crystallisation age for the dominant oscillatory zoned magmatic zircon separated from this sample.

5. Discussion and conclusion

Geochronological studies of the GSB metamorphic rocks have been performed for c. 30 years and a compilation of the available data is given in Table 3. Particular rock types in the same localities have been studied several times by different techniques and some of the results have been controversial. However, the increasing amount of data obtained by various authors using differing methods allows the definition of several tectonothermal events in the evolution of the GSB rock complex. In the following discussion, we should keep in mind that part of the previously published results were obtained by conventional multi-grain or single-grain (but still “whole-grain”) zircon analyses, and some of them may represent mixed ages that are geologically rather meaningless.

5.1. The inherited zircons

In the granulites, a wide range of inherited zircon ages have been obtained [14, and this study], up to the (problematic) oldest at ~ 3650 Ma (Tables 1 and 3). Apart from the distinct age group of 570–590 Ma, which may correspond to the age of a major Cadomian (Panafrican) alimentary source, three clusters of Precambrian zircons can be defined, each comprising 4 to 5 individual measurements:

- (a) 1.0 to 1.1 Ga (4 analyses),
- (b) 1.7 to 1.8 Ga (4 analyses),
- (c) 2.0 to 2.2 Ga (5 analyses).

In the gneisses, migmatites and anatectic granites, the ages of inherited zircons are dispersed between c. 1.1 and 2.7 Ga (Tables 2 and 3). Here, as in the granulites, the ages of the older zircons tend to cluster within three groups, each comprising 4 to 6 analyses:

- (a) 1.1 to 1.3 Ga (6 analyses),
- (b) 1.9 to 2.0 Ga (4 analyses),
- (c) 2.3 to 2.4 Ga (4 analyses).

Comparing the gneisses and migmatites with the granulites, the zircon ages of c. 1.0 and 1.3 Ga may partly overlap in both rock types, but the detailed age spectra are significantly different. The age group of c. 1.75 Ga in the granulites does not seem to have an exact equivalent in the gneisses, whereas both rock types contain important populations of zircons of 1.9 to 2.2 Ga. Finally, the abundant early Proterozoic/Archean ages found in the gneisses and migmatites, from 2.4 to 2.7 Ga, do not have counterparts in the granulites.

Summing up the age data compiled on the inherited zircons, the following conclusions can be drawn:

1. The here reported coherent group of magmatic zircon ages of 570–590 Ma in the granulites reflects a major Cadomian source contribution to their protoliths (e.g., granitoids such as described by Oberc-Dziedzic *et al.* [51]).
2. Zircon ages scattered between 600 and 900 Ma: a few analyses of this age range obtained in the granulites correspond to the Pan-African orogenic cycle [cf., 52-55]. No such ages have yet been found in the gneisses and migmatites in which there seems to be a gap in ages between 500 Ma and 1.1 Ga.

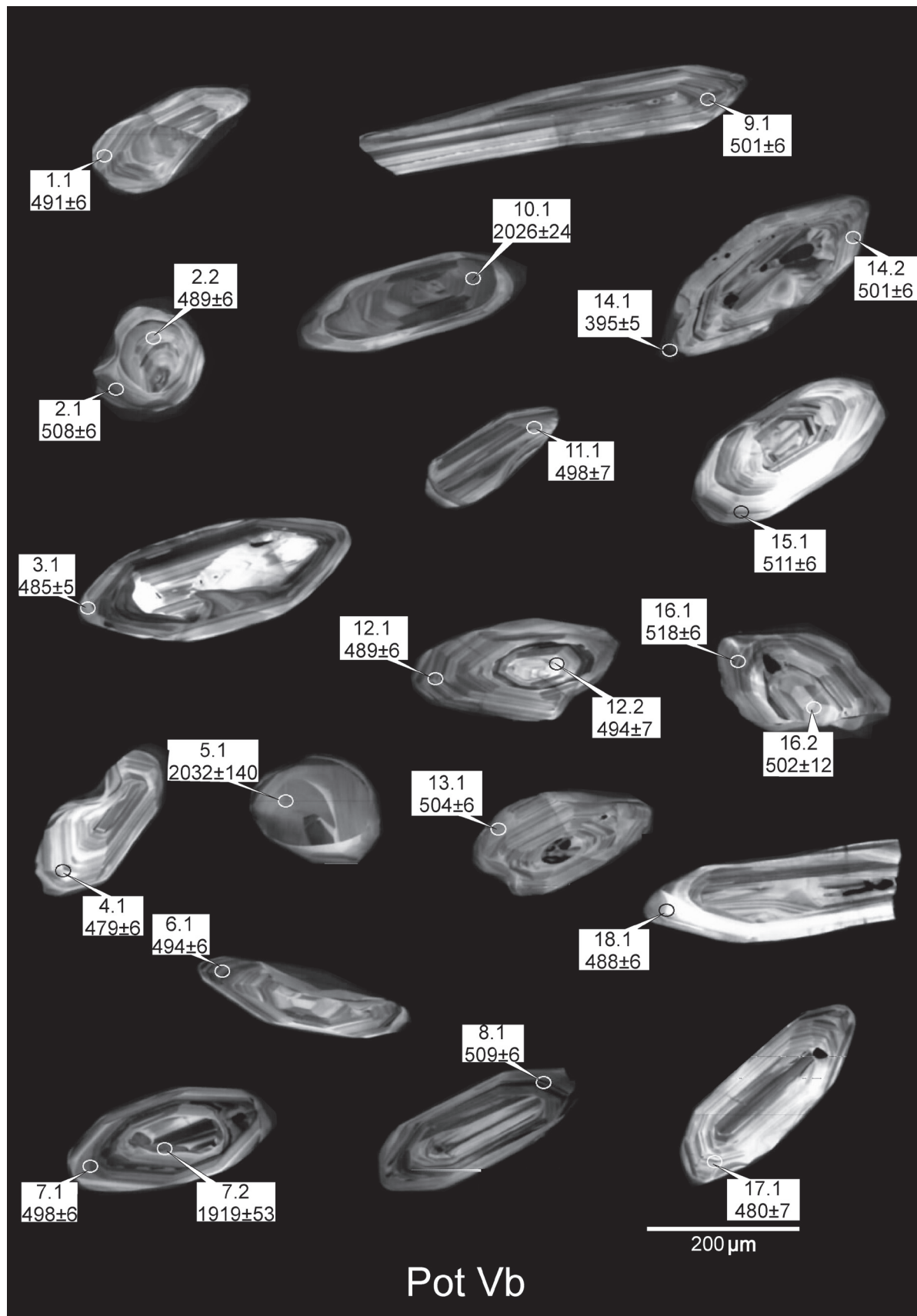


Fig. 5: Cathodoluminescence images of the zircon grains analysed from the diatexic migmatite from Potoczek. The circles indicate spots analysed, and the labels give the $^{206}\text{Pb}/^{238}\text{U}$ ($^{207}\text{Pb}/^{206}\text{Pb}$ for Precambrian) ages from Table 2.

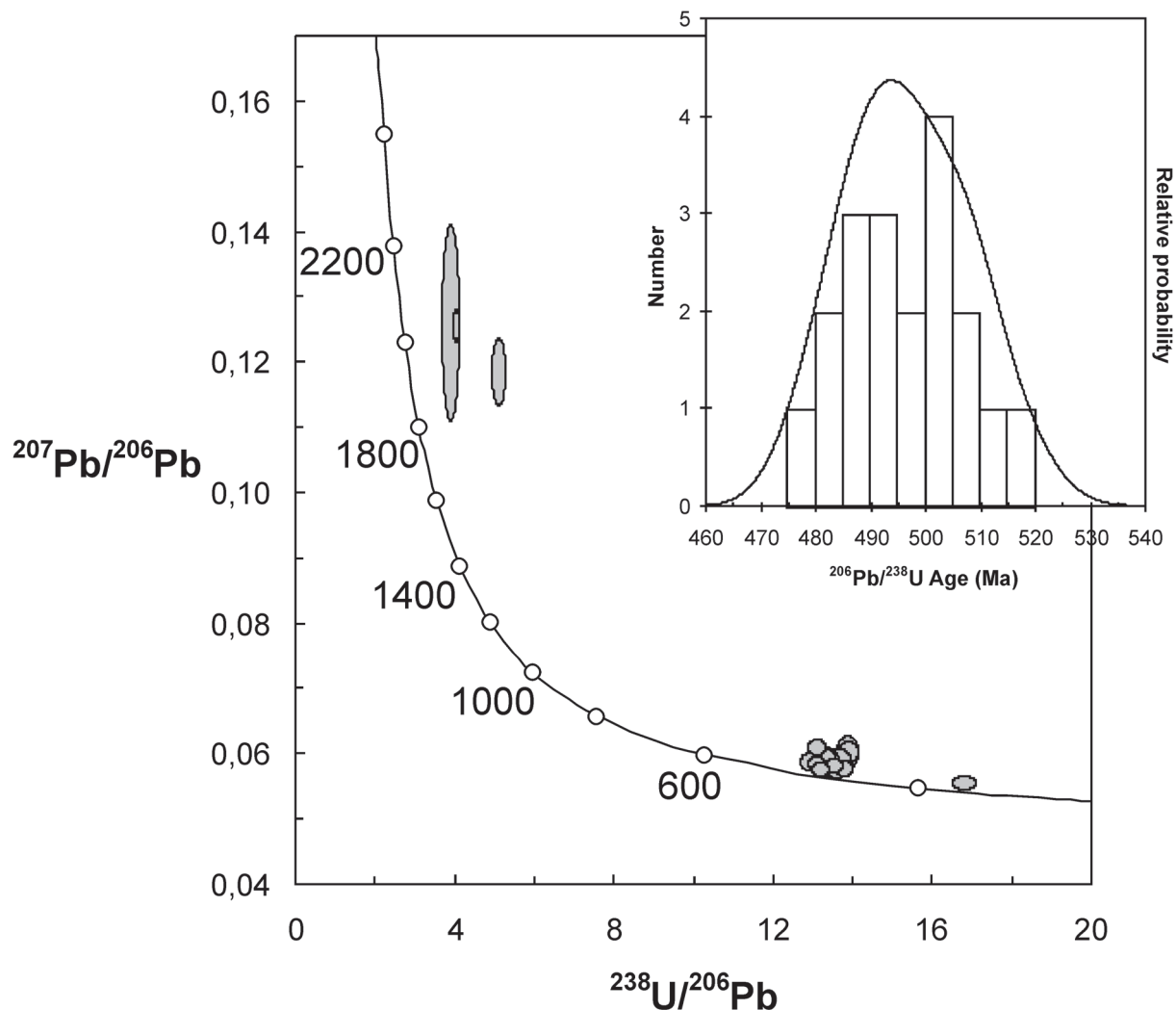


Fig. 6: Tera and Wasserburg (1972) concordia plot of SHRIMP analyses for the diatexic migmatite from Potoczek showing the total $^{207}\text{Pb}/^{206}\text{Pb}$ ratios vs. the calibrated $^{238}\text{U}/^{206}\text{Pb}$ ratios, uncorrected for common Pb. Inset shows a cumulative probability plot of the radiogenic $^{206}\text{Pb}/^{238}\text{U}$ ages for the zircon analyses with a calculated age of 497 ± 5 Ma.

3. C. 1.0–1.1 Ga zircons define a coherent age group in the granulites. This zircon growth event may be related to an orogeny at around 1.0 Ga, evidence of which is recorded in the “Armorican terrane assembly” [56]. In the gneisses and migmatites, an important group of similarly old zircons of 1.1 to 1.3 Ga partly overlaps with that in the granulites and extends to somewhat older dates. All these ages were obtained by the zircon evaporation technique [32] and have not yet been verified by within grain analyses, using, for example, a SHRIMP.
 4. C. 1.75 Ga zircon ages in the granulites are represented by two conventional zircon evaporation analyses and by two SHRIMP analyses. Together with single zircon ages dispersed between 1.1 and 1.7 Ga, these may indicate, *e.g.*, a South American or similar type source area for these zircons [cf., 57].
 5. C. 2.0–2.2 Ga zircons are common in both the granulites, and gneisses + migmatites (obtained by both evaporation and SHRIMP methods). As shown by Zeh *et al.* [58], c. 2 Ga old zircons are typical inherited components in portions of the Variscan crust, indicating intense continental crust-producing processes at that time [56,59].
 6. The oldest zircon ages from the GSB gneisses and migmatites range between 2.2 and 2.7 Ga (evaporation technique, Kröner & Hegner [32]) and correspond well to the oldest reliable age information from zircons from various units of the Variscan Belt [56,59].
- Concluding the discussion on the inherited zircons, we have to stress, once again, that part of the available data has been obtained by the whole-grain evaporation method and, thus, would need verification by more reliable microanalytical techniques (*e.g.* SHRIMP); consequently, the above conclusions should be treated with caution.

5.2. Main populations of zircons

5.2.1. The granulites

The ages of the main populations of zircons in the granulites differ sharply from those in the gneisses and migmatites. Vapour digestion of small zircon fractions and single grain evaporation U-Pb zircon dating [14] provided a

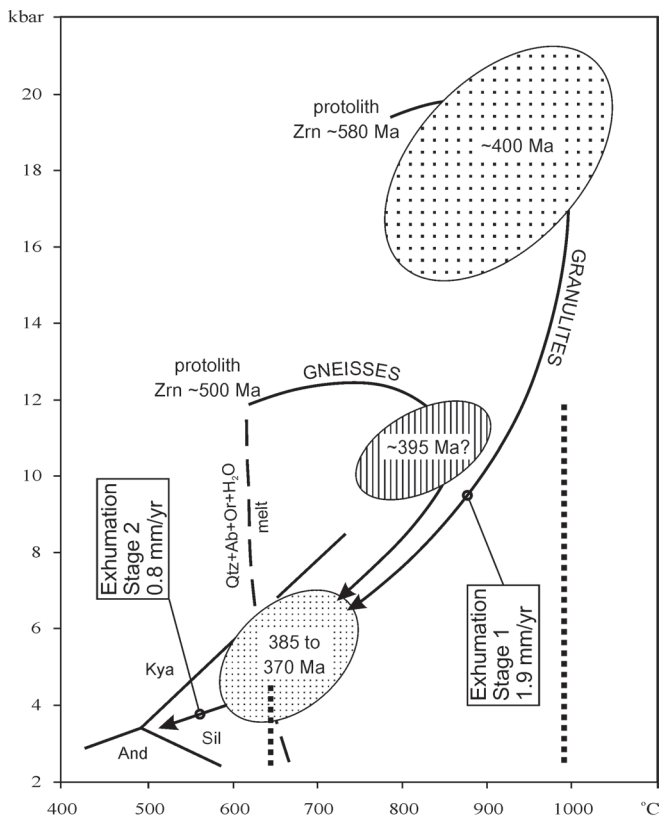


Fig. 7: P-T-t path for the Góry Sowie granulites and gneisses.

mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 401.5 ± 0.9 Ma which is identical, within analytical error, to the 402 ± 3 Ma Sm-Nd age of the associated meta-ultramafites [16].

The major population of oval zircons in the granulites statistically can be subdivided into two age sub-maxima of c. 395 and 380 Ma (see Fig. 4). These are interpreted to reflect, respectively, granulite facies metamorphism (roughly the same or slightly younger than that obtained by O'Brien *et al.* [14]), and a subsequent decompressive high-T overprint (Fig. 7). However, the observed chemical variations (*e.g.* Th/U ratios) in both age groups may, alternatively, indicate that the older ages are from zircons that partly preserved composition of earlier precursors and retained some inherited radiogenic Pb. This hypothesis needs verification by further systematic studies.

5.2.2. The gneisses and migmatites

The widely dispersed zircon ages from these rocks reported in previous publications caused much controversy [29,31,32]. The evaporation $^{207}\text{Pb}/^{206}\text{Pb}$ ages around 483–487 Ma, broadly comparable with those from other Sudetic orthogneisses, were interpreted by Kröner & Hegner [32] as the magmatic crystallization age of the granitic protoliths. However, their evaporation $^{207}\text{Pb}/^{206}\text{Pb}$ zircon age from a diatexite from Potoczek provided a much younger date of 439.8 ± 1.8 Ma, interpreted as the age of Ordovician metamorphism. In contrast, our SHRIMP data show older ages for these zircons, 497 ± 5 Ma. Taking into account the characteristic features of these

zircons, the obtained ages, scattered between 480 and 518 Ma, most likely correspond to the magmatic age of granitoids that provided material for these migmatites (either directly or, more probably, in the form of reworked sedimentary materials). The single analysis yielding the date of c. 395 Ma apparently corresponds to a metamorphic zircon growth.

5.3. Timing of P-T paths in the granulites and surrounding gneisses

Our new SHRIMP results for the youngest zircon population in the granulites (c. 380 Ma) correlate well with the main metamorphic event and anatectic migmatization in the gneisses, the latter well constrained by the geochronological data obtained by various methods and oscillating mostly between 370 and 385 Ma (see Table 3 and cited refs.). This strongly confirms that the decompressive re-equilibration in the granulites coincided in time (and in PT conditions, see Fig. 7) with the main amphibolite facies metamorphism and migmatization in the surrounding gneisses. Rather curiously, the high-grade metamorphism is very poorly documented in the SHRIMP zircon data from the diatexite of Potoczek: we have only one single date of c. 395 (analysis 14.1, Table 2). This suggests that the Devonian metamorphism caused only minor zircon growth (thin crystal rims) in the gneisses and migmatites. More SHRIMP data could help to solve this problem. However, the newly formed metamorphic rims are mostly less than 10 microns in width and thus difficult to be analysed.

The problem of separate or (partly) shared metamorphic paths for the HP-HT rocks and their host gneisses has been closely examined as it provides important constraints on exhumation processes and orogenic models. In the GSB, the observed metamorphic-facies contrast between the HP-HT granulites and high-amphibolite facies gneisses and migmatites has been taken by several authors [25,35] as evidence for the exotic character of the granulites. However, the gneisses, migmatites and associated metabasites were found to provide evidence for relatively high metamorphic pressure conditions, within a range of 10–12 kbar, at 750–900 °C [40], but these values may represent only the minimum PT range preserved in these rocks. At this state of knowledge, however, we may assume that the granulites experienced much higher PT metamorphic conditions of 16–20 kbar and 900–1000 °C [17], seemingly at c. 395–400 Ma [14]. These lower-crustal conditions and the ages are in line with the observed mutual association of the granulites with mantle-derived garnet-peridotites of the same age [18].

The granulites, most likely, started their exhumation soon after c. 395 Ma interpreted as recording their peak PT metamorphism, and were tectonically interleaved with gneisses at shallower, mid-crustal levels [25,35,40]. Apparently, subsequent ascent and decompression (with only minor temperature drop to c. 700 °C), rather than isobaric heating, may have been the main cause of migmatization in the gneisses and decompressive re-equilibration in the granulites [17,25]. This stage on the common metamorphic path fell within

the range of 385 – 370 Ma, as documented by Rb-Sr data from the gneisses and migmatites [28,29]. The rapid tectonic unroofing must have continued effectively to shallow crustal levels and, finally, to the Earth's surface, which is indicated by cooling ages (359±3 Ma, $^{40}\text{Ar}/^{39}\text{Ar}$ on muscovite [60]) and the presence of abundant GSB gneiss detritus in late Devonian coarse-clastic sediments of the neighbouring Świebodzice Basin (Fig. 1; [cf. 15 and refs. therein]).

Similar lines of interpretation for the GSB granulites have recently been given by Gordon *et al.* [9]. Their model refers to a two-stage exhumation mechanism as proposed earlier for the HP-HT rocks in the Norwegian Caledonides [8]. The peak metamorphic conditions in the GSB granulites were attained at c. 400 Ma and, subsequently, the rocks were exhumed to mid-crustal levels at c. 380-370 Ma. The following rapid buoyancy-driven ascent was aided by anatexis in the gneisses. The youngest monazite Th-Pb ion probe ages obtained by Gordon *et al.* [9] from the GSB, 347±3 Ma, are among the youngest obtained so far from that area.

The results of Gordon *et al.* [9] also confirm the contrasting ages of the HP-HT rocks of the Orlica-Śnieżnik Dome, with their peak metamorphism at c. 375 Ma, and exhumation to mid-crustal levels at c. 345-330 Ma (the evident differences were also noted in earlier interpretations, *e.g.*, [1,17], but the actual age of the peak HP-HT metamorphism in that area remains controversial [7,20]).

The available thermobarometric and geochronological constraints shown in Fig. 7 as the P-T-t paths of the GSB granulites and migmatites allow to estimate the exhumation rates for these rocks, from deep and mid-crustal levels to the earth surface. We assume the average rock density of 2.8 g cm⁻³ and the following P-T-t constraints for the GSB rocks:

- granulites (peak granulite facies): c. 1000 °C, 18 kbar (64.3 km depth), and 395 Ma (our SHRIMP zircon age),
- gneisses and migmatites: c. 650 °C, 6 kbar (21.4 km depth), and 372 Ma (thin slab Rb-Sr age, [29]),
- cooling of the rock complex: c. 350 °C, 3 kbar (10.7 km depth), and 359 Ma ($^{40}\text{Ar}/^{39}\text{Ar}$ muscovite age, [60]).

Exhumation rates calculated:

stage 1: exhumation of the granulites from c. 64 to c. 21 km depth within 23 Myrs = 1.9 mm/year,

stage 2: unroofing to shallow depths, from c. 21 to c. 10 km, within 13 Myrs = 0.8 mm/year.

The slowdown of exhumation rates with decreasing depth, as that obtained for the GSB rock complex, is typical for regions, where exhumation is tectonically governed [*e.g.* 3].

For the Śnieżnik granulites, it is difficult to estimate the exhumation rates, as the time constraints in these rocks are less clear. However, if the zircon ages of c. 340 Ma in these granulites do correspond to the peak granulite facies conditions [7], and the $^{40}\text{Ar}/^{39}\text{Ar}$ mica cooling ages are within the range of 330-340 Ma [60], the exhumation rate of the Śnieżnik granulites would have to be by an order of magnitude higher. A similar scenario of extremely fast exhumation (10-15 mm/year) is known from the 340 Ma granulites of the Granulitgebirge [12] and Erzgebirge [2,3].

To conclude, the new SHRIMP zircon data provide strong evidence for the existence of the “older” (c. 395 – 400 Ma) HT-HP granulites in the central European Variscides. In the case of the Góry Sowie Block, the granulites went through subsequent decompressive re-equilibration, contemporaneous with the metamorphism and migmatization of the juxtaposed gneisses at c. 380 Ma, followed by moderate uplift and exhumation due to Eo-Variscan orogenic movements.

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