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An insight into a gneiss core of the Orlica–Śnieżnik Dome, NE Bohemian Massif: new structural and U-Pb zircon data

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The Orlica–Śnieżnik Dome in the Sudetes, the NE Bohemian Massif, embraces two formations of felsic gneisses of controversial origin and evolution. Our study shows that despite similar geochemical signatures, they carry systematic minor differences in mineral, isotope, zircon and geothermobarometric characteristics. Four variants of the Gierałtów gneisses include migmatites and have a longer structural history than the Śnieżnik augen orthogneisses. U-Pb SHRIMP analyses yielded U-Pb ages of ~500 Ma for cores and ~498 Ma for wide outer parts of zircon grains in the twice-folded Gierałtów gneisses, and an age of ~500 Ma for a discordant neosome vein. Neoproterozoic metasediments were among precursors of the lithologically diversified Gierałtów Gneiss Formation. First deformation, metamorphism, and migmatisation of these rocks occurred at 515–475 Ma and overlapped with the development and emplacement of a porphyritic S-type granite precursor to the Śnieżnik Gneiss Formation. The metagranite (= Śnieżnik augen orthogneiss) embraced migmatitic xenoliths. Zircon grains from such xenoliths revealed distorted and replaced cores which yielded U-Pb ages that dispersed around 507–487 Ma, whilst wide darker poorly zoned outgrowths yielded ages from ~343 Ma to ~325 Ma (mean ~340 Ma). These outgrowths were interpreted as a record of Carboniferous metamorphism assisted by rich Zr- and U-carrying fluids. The Variscan metamorphic overprint was heterogeneous, and variously affected rocks of the two gneiss formations.

Keywords: Cambrian, migmatites, Variscan orogeny, SHRIMP, Sudetes.

INTRODUCTION

The Orlica–Śnieżnik Dome (OSD) is a tectonostratigraphic unit in the Sudetes, SW Poland, the geological evolution of which remains debated and not fully understood (see review in Żelaźniewicz et al., 2014a). A variety of quartzo-feldspathic gneisses that appear in the core of the dome are among most controversially viewed issues. They were originally subdivided into Precambrian migmatitic gneisses of Gierałtów type and "Caledonian" metagranites of Śnieżnik type (Fischer, 1936). Such crude lithostratigraphy – Gierałtów type older than Śnieżnik type – was then contested based on various arguments (reviews in Don et al., 1990; Żelaźniewicz et al., 2002). Don (1964) proposed to reverse the order because during the field mapping he observed that the Śnieżnik type gneisses were locally cut by the mobilized Gierałtów migmatites. In contrast, detailed petrographic observations led Smulikowski (1973, 1976) to conclude that all gneisses were derived from sedimentary protoliths by variably intense solid-state metamorphic granitisation, the Śnieżnik type being the most advanced product of that process. Later geochemical and geochronological data furnished the base for a hypothesis that all gneisses in the dome came from a single ~500 Ma granitic protolith. The original granites were to become substantially transformed and eventually diversified during Variscan deformation and migmatisation between 360 Ma and 340 Ma, then cooled at 340–330 Ma (Maluski et al., 1995; Turniak et al., 2000; Lange et al., 2002, 2005; Gordon et al., 2005; Bröcker et al., 2009, 2010; Štípská et al., 2012) and zonally sheared at ~321 Ma (Marheine et al., 2002).

In the western limb of the OSD, however, the structural and isotopic data were found which suggested that at least some gneisses underwent high-temperature deformation prior to the Variscan events (Přikryl et al., 1996; Redlińska-Marczyńska, 2011; Redlińska-Marczyńska and Żelaźniewicz, 2011) and were migmatised as early as 488 Ma (Żelaźniewicz et al., 2006). Such findings hinted that the OSD likely evolved in a more complex way than assumed in a number of papers (Aleksandrowski et al., 2000; Turniak et al., 2000; Don, 2001; Lange et al., 2002, 2005; Don et al., 2003; Štípská et al., 2004). To further explore this option we have re-examined the relationships between augen gneisses and migmatitic gneisses that crop out in the Międzygórze Antiform (Fig. 1) and performed U-Pb isotopic analyses of zircons retrieved from the samples

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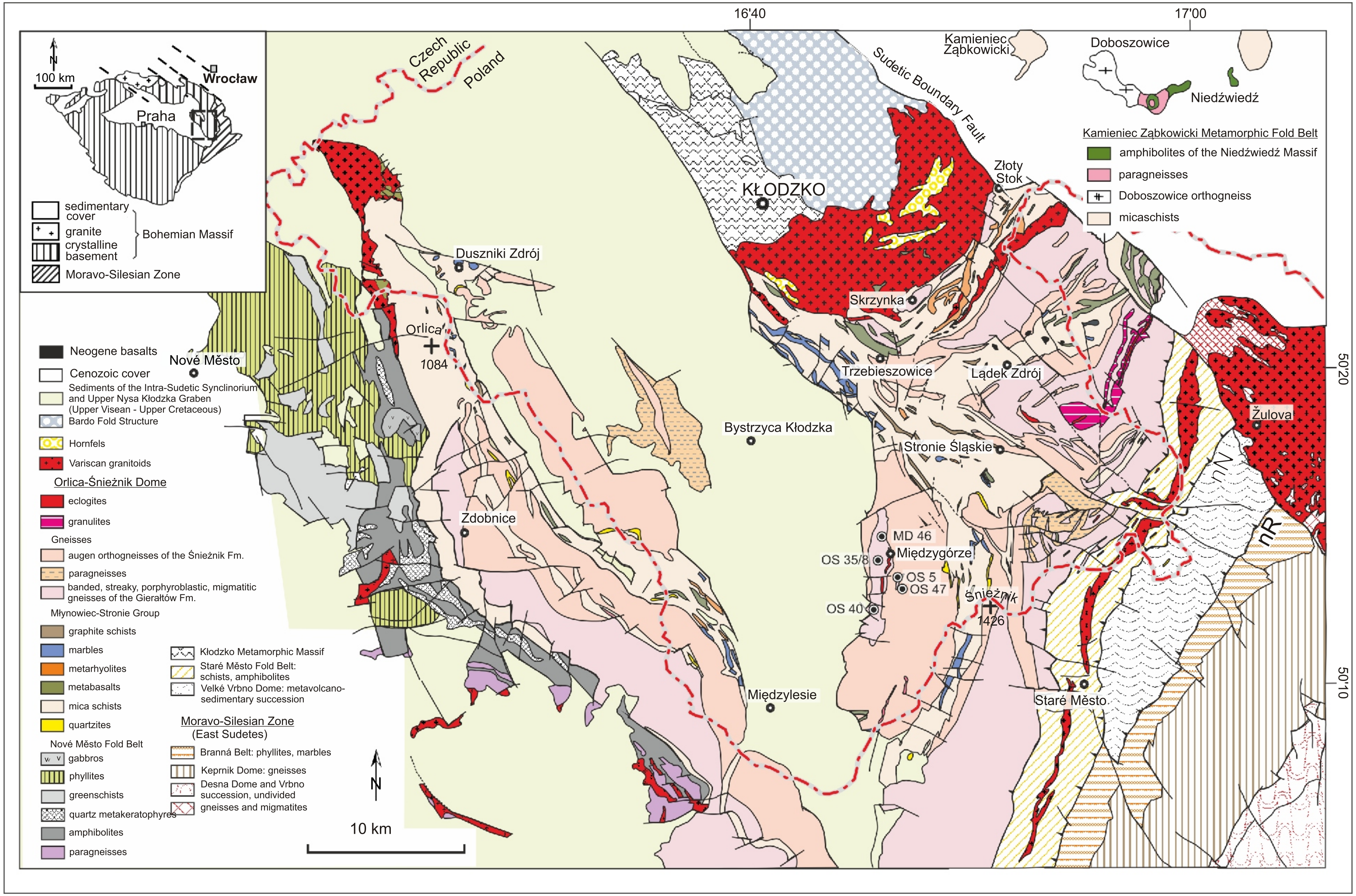

Fig. 1. Geological map of the eastern part of the Orlica–Śnieżnik Dome; inset shows its position in the Bohemian Massif (after Sawicki, 1995; Żelaźniewicz et al., 2014a; modified)

with known structural position and history. In this paper, we summarize the results of structural and petrological re-examination, report new results of the U-Pb SHRIMP datings, and discuss local and regional implications of the collected data.

GEOLOGICAL FRAMEWORK

The Orlica–Śnieżnik Dome (OSD) is the easternmost unit of the Lugian domain (*sensu* Suess, 1912), in the NE part of the Bohemian Massif (Fig. 1). Lithostratigraphic and tectonometamorphic characteristics of the OSD are used to show affinity alternatively with the Saxothuringian or Moldanubian terranes (zones) of the European Variscides (see Franke et al., 1993; Aleksandrowski and Mazur, 2002; Żelaźniewicz et al., 2006; Jastrzębski et al., 2010; Mazur et al., 2012, 2013; Štípská et al., 2012). In the Orlica–Śnieżnik Dome, the gneissic core is mantled by a ~6000 m thick metasedimentary succession of Ediacaran–Early Paleozoic age, referred to as the Młynowiec–Stronie Group (Gunia, 1974; Gunia and Wierzchołowski, 1979; Jastrzębski et al., 2010; Mazur et al., 2012; Żelaźniewicz et al., 2014b). The $F_{(1\text{-}n)}$ or $D_{(1\text{-}n)}$ labelled successive stages of the deformational stories of the OSD rocks which have been proposed in the literature differ remarkably between various authors (reviews in Don et al., 1990; Żelaźniewicz et al., 2002, 2014a). However, there is almost a consensus that (1) the main tectonism in the OSD was controlled by the Variscan collision between the two terranes, namely Saxothuringia/Moldanubia and Brunovistulia, both ultimately of peri-Gondwana descent, and (2) the main fold structures strike generally in the N–S direction. The oldest foliation that followed bedding planes in the metasedimentary mantle rocks was folded and transposed to the subvertical axial planar foliation due to an early E–W subhorizontal shortening and then refolded during subvertical shortening. Such tectonic template is favoured by most authors although identification and labelling of consecutive structures differ in details (Dumicz, 1979; Jastrzębski, 2005, 2009; Murtezi, 2006; Skrzypek et al., 2011, 2014; Chopin et al., 2012a, b). Similar structural succession is often assumed for the core gneisses, which seems controversial and not necessarily correct (Żelaźniewicz at al., 2014a, b). This topic will be addressed below.

CHARACTERISTICS OF GNEISSES

TWO GNEISS FORMATIONS

The original subdivision of the OSD gneisses into two types, Gierałtów and Śnieżnik, appeared too general for purposes of detailed mapping, thus required further subdivisions (e.g., Don et al., 2003). However, the descriptive criteria, such as grain-size, colour, or kind of lamination/layering, turned out sometimes to be ambiguous and even misleading (Dumicz, 1989; Don et al., 1990; Żelaźniewicz et al., 2002). Based on combined field relationships and petrographical as well as structural characteristics, Redlińska-Marczyńska and Żelaźniewicz (2011) proposed to distinguish six lithological variants easily identifiable in the field: (1) augen (ortho)gneisses, (2) migmatites, (3) layered and streaky gneisses, (4) banded gneisses, (5) porphyroblastic gneisses, and (6) mylonites to ultramylonites. Augen gneisses (1) were assigned to the Śnieżnik Gneiss Formation. Varieties (2) to (5) were assigned to the Gierałtów Gneiss Formation. Mylonitic gneisses (6) developed at the expense of rocks of either formation. Actually, we do support the long established subdivision of gneisses in the Orlica–Śnieżnik Dome into two major types, herein referred to as the Śnieżnik and Gierałtów formations (Figs. 2–4). In the Miedzygórze Antiform, the outcrop pattern and field relationships clearly depict a map view of an inlier of the Gierałtów Formation rocks within the Śnieżnik gneisses (Fig. 1). In our opinion, the antiform is a folded, large-scale enclave of the high-grade migmatitic gneisses set in the porphyritic metagranite. There is a "transitional zone" (Teisseyre, 1973; Don et al., 2003) between the two types where most variants occur side by side (Redlińska-Marczyńska and Żelaźniewicz, 2011; Żelaźniewicz et al., 2014b).

One of important differences between the two gneiss formations lies in rocks enclosed in them. HP eclogite, retroeclogite/amphibolite, and granulite bodies of various dimensions occur exclusively within the Gierałtów Gneiss Formation. In the Śnieżnik Gneiss Formation, there are xenoliths of

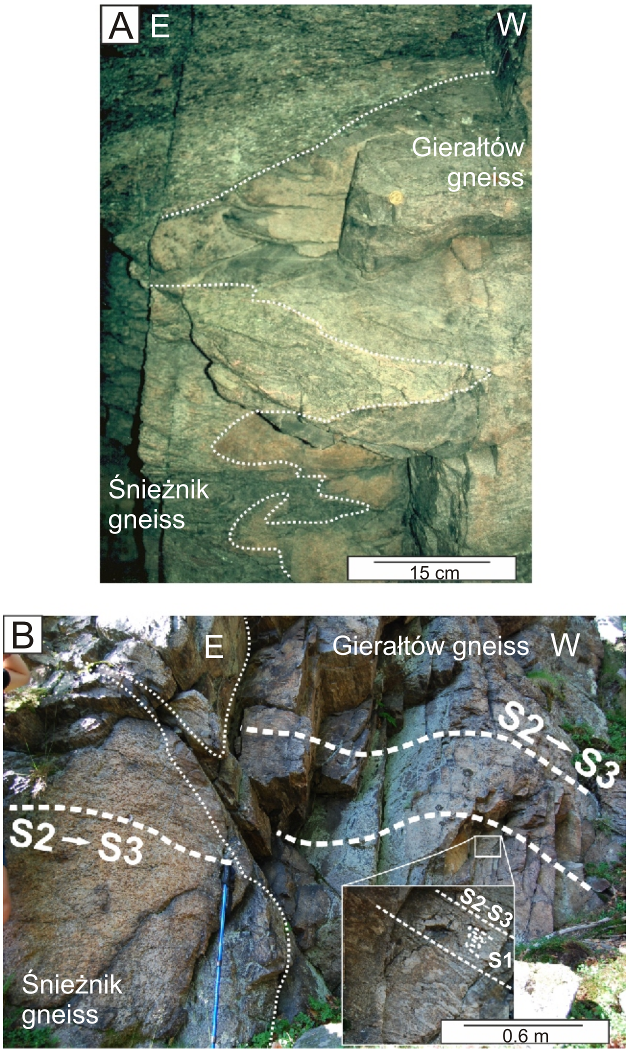

Fig. 2. Relic primary intrusive contacts between the Gierałtów gneisses and Śnieżnik gneisses (see also Fig. 4C)

A – originally steep intrusive interface between the gneisses was subjected to later deformations; **B** – both rocks were deformed in common during D3 shearing, when S2 planes were rejuvenated in the Gierałtów gneisses (S2 S3) whereas in the Śnieżnik gneisses the first foliation set developed and became folded (see also Figs. 3F and 4C), thus the structural history of the latter was evidently shorter than that of the former

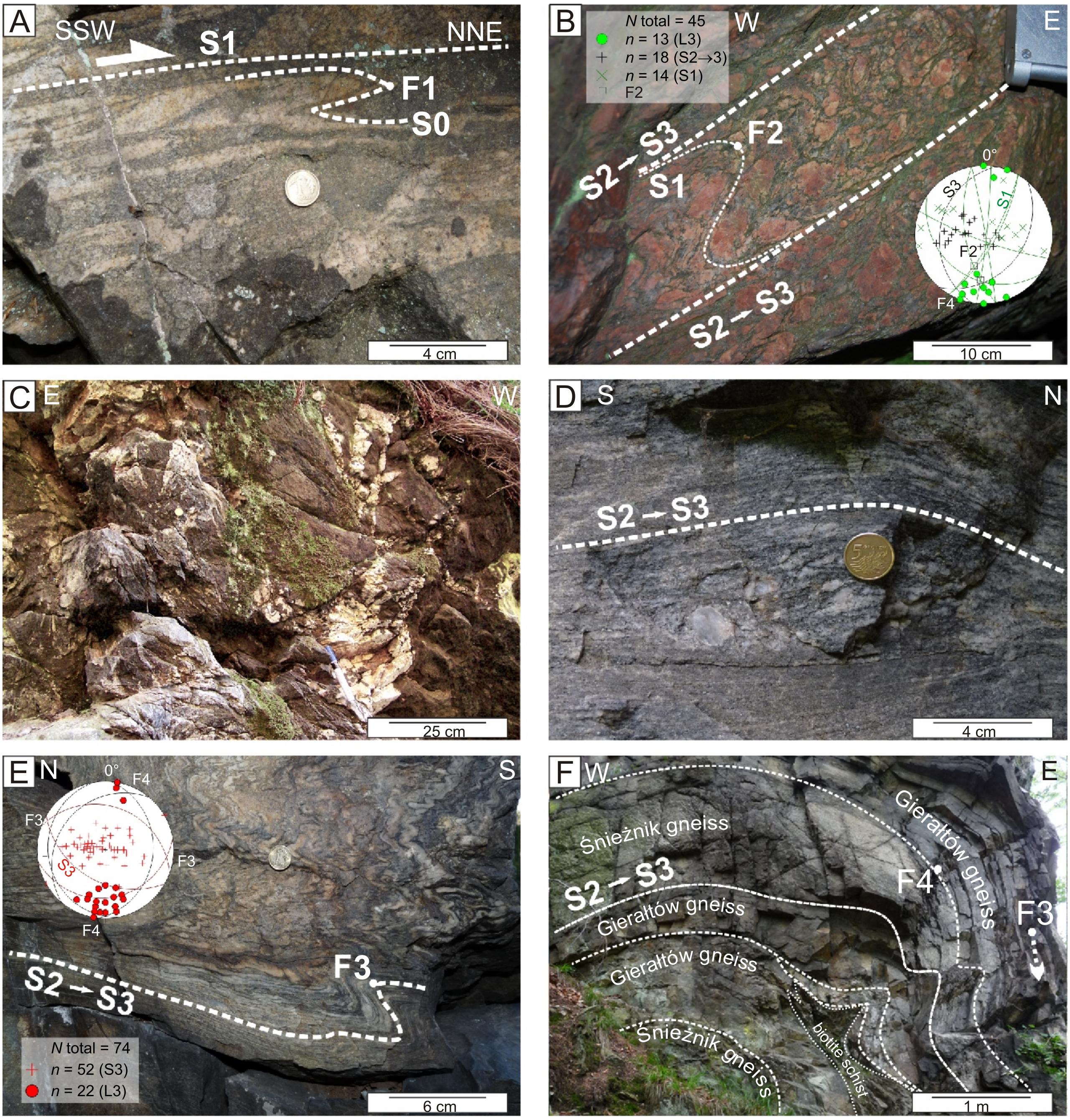

Fig. 3. Structural characteristics of gneisses in the Międzygórze Antiform
(stereographic projections on the lower hemisphere, equal angle net)

A – Gierałtów gneiss: compositional banding (S0) involved in F1 folds and subsequent shearing along S1, which brought about intrafolial folds; **B** – Gierałtów gneiss: porphyroblastic variant with K-feldspar and polymineral quartz-feldspar blasts nucleated intra- to post-kinematically with respect to small-scale folds F2; **C** – Gierałtów migmatitic gneiss: unfoliated, irregular leucocratic veins (leucosome nests) that cut discordantly the twice foliated host gneiss; **D** – D3 sheared migmatitic Gierałtów gneiss: note less deformed pod with relic magmatic fabric surrounded by anastomosing mylonitic foliation, top-to-the N vergence; **E** – Śnieżnik augen gneiss: details of F3 fold in S2 S3 foliation (diagram shows folds F3 and F4); **F** – Śnieżnik/Gierałtów gneiss transitional zone (*sensu* Teisseyre, 1957, 1973): alternation of banded migmatitic gneisses (Gierałtów) and augen gneisses (Śnieżnik), both strongly sheared in S2 S3 and involved successively in F3 and F4 folds, note sheared biotite schist relict within the migmatite

fine-grained biotite gneisses, migmatitic gneisses and schists (Grześkowiak and Żelaźniewicz, 2002; Redlińska-Marczyńska and Żelaźniewicz, 2011). The xenoliths indicate that a porphyritic granite precursor to the Śnieżnik gneisses must have been genetically linked with migmatitisation and that some migmatites were older or broadly coeval with that granite. Moreover, relic discordant intrusive contacts are in evidence, which clearly shows that the porphyritic granite, now the poorly foliated Śnieżnik gneiss, was originally emplaced into well-foliated migmatitic gneiss of Gierałtów type (Fig. 2).

On a geochemical ground, all gneisses carry similar peraluminous, calc-alkaline granite signatures and limited vari-

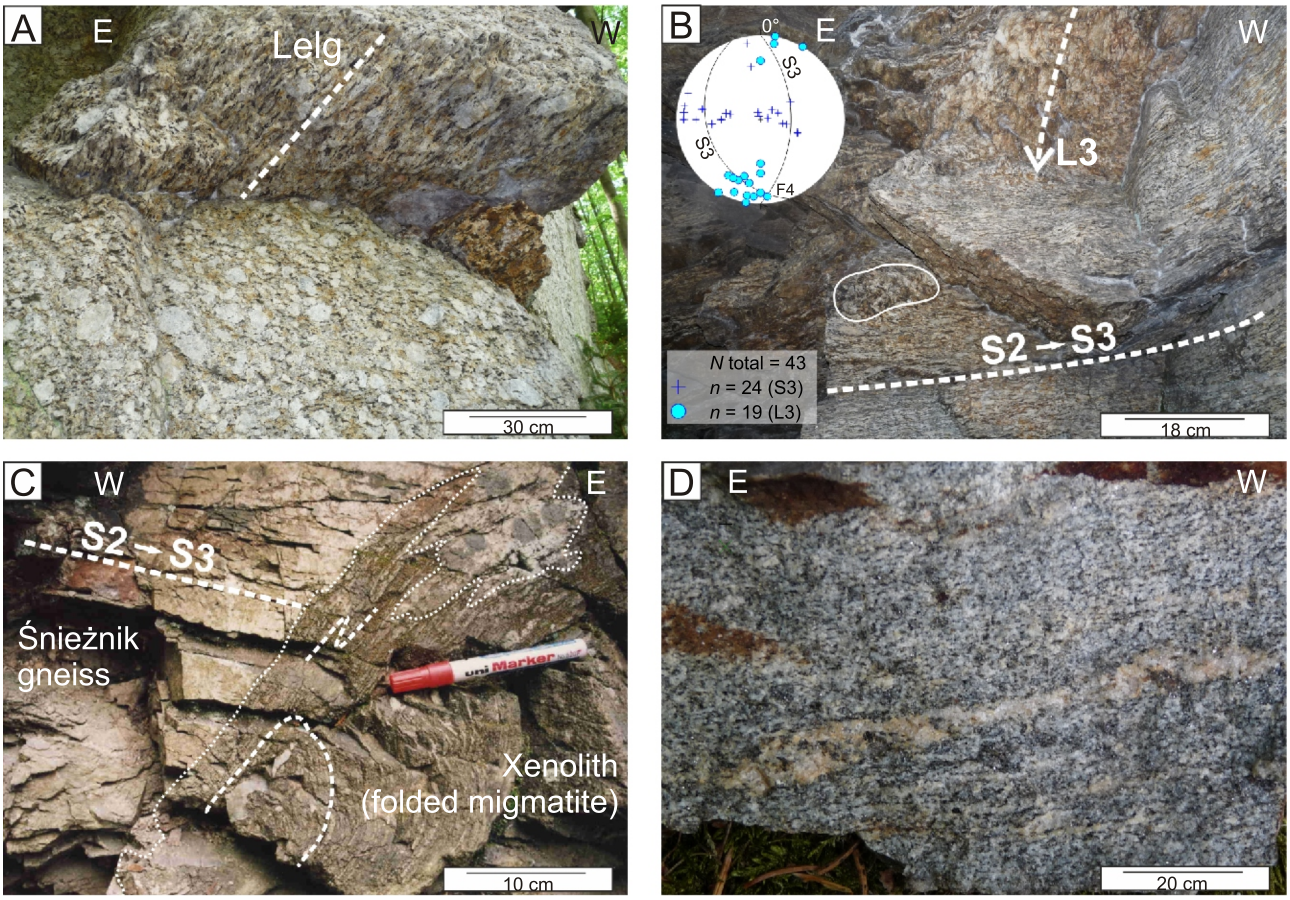

Fig. 4. Structural features of gneisses of the two formations

A – L > S augen gneiss as in sample OS47; **B** – Śnieżnik orthogneiss with genuine augens (K-feldspar porphyroclasts), stretching lineation L3 and mylonitic foliation (L < S-tectonite), note less deformed pods of the initial coarse-grained porphyritic granite elongated in the L3 (Lelg) direction and subjected to flattening in S2 S3 (diagram shows folding by E-vergent F4 folds); primary intrusive contact between the Gierałtów gneiss (folded and migmatised) and the Śnieżnik (meta)granite; **C** – folded migmatitic gneiss xenolith within the Śnieżnik augen gneisses which contain the single foliation set equivalent to S2 S3 planes in the Gierałtów gneisses, the pictured interface is a small-scale model of the primary contacts between the Śnieżnik granite and folded Gierałtów gneisses; **D** – migmatitic gneiss xenolith as in sample OS5

ations in the REE concentrations. The existing differences were found by many authors to be insufficient to distinguish between the protoliths of the Śnieżnik and Gierałtów gneisses (Maluski et al., 1995; Kröner et al., 2000; Turniak et al., 2000; Lange et al., 2005; Bröcker et al., 2009). Therefore, all the gneisses have often been interpreted as coming from one igneous suite, derived from identical source rocks. However, meticulous studies performed by Borkowska et al. (1990) and Borkowska (1994, 1996) showed that the protoliths of the two main gneiss types noticeably differed in their geochemistry with the amount of major (Si, Al, Mg, Na) and trace (Ba, Sr) elements and Rb-Sr systematics. For such reasons, two separate protoliths were inferred by the latter authors, or, alternatively, one protolith, albeit chemically diversified by intrusive processes. Indeed, the similarities in geochemistry strongly suggest derivation from a similar rock complex, which does not necessarily imply that the Śnieżnik and Gierałtów gneisses originated from one magma body or that their protoliths passed all through a magma stage.

MINERAL, ISOTOPE, ZIRCON AND GEOTHERMOBAROMETRIC CHARACTERISTICS

Despite geochemical similarities of the Gierałtów and Śnieżnik formations, microscopic studies reveal some systematic variations in modal compositions between gneisses of the two formations and migmatite xenoliths found within the Śnieżnik gneisses (details in Redlińska-Marczyńska, 2011; Redlińska-Marczyńska and Żelaźniewicz, 2011). Utilizing >13,000 microprobe analyses, statistically significant differences have been demonstrated for these rocks and briefly compared in Table 1.

Minor differences between the two types of gneisses were observed in the isotope characteristics (Lange et al., 2005; Pin et al., 2007). Generally, values of Nd_{500} are up to 3 times more scattered in the Gierałtów (–0.3 to –7.1) than in the Śnieżnik (–3.5 to –5.2) gneisses, which also display a narrower range of T_{DM} ages (1.6–1.5 Ga). Initial $^{87}Sr/^{86}Sr$ ratios are again more scattered in the Gierałtów gneisses. Such values indicate that the Śnieżnik gneisses represent less heterogeneous rocks than the Gierałtów gneisses (Redlińska-Marczyńska and Żelaźniewicz, 2011). Indeed, modal composition of the latter rocks, xenoliths inclusive, is statistically more diversified and heterogeneous than that of the Śnieżnik metagranite (Table 1). Such trend is consistent with the evolutionary tendency of granitic melts that acquire less diversified (lithological, petrographical, isotopic and structural) features than the source rocks. Consequently, the Śnieżnik magma is assumed to be an advanced product of the processes that also produced the

Table 1

Summary of mineral and modal compositions of gneisses of the two formations (~13,000 analytical spots in ~150 thin sections – for details see Redlińska-Marczyńska, 2011 and Redlińska-Marczyńska and Żelaźniewicz, 2011)

Item/characteristics		Śnieżnik Augen Gneiss Formation	Xenoliths in the Śnieżnik gneisses	Gierałtów Gneiss Formation
Alkali/K-feldspar	Mode	26–36 vol%	16–30 vol%	16–34 vol%
Plagioclase normally zoned	Mode	20–30 vol%	22–45 vol%	20–40 vol%
	An content	6–23	6–34	6–38
Biotite	Ti content	< 0.39 a.p.f.u.	<0.56 a.p.f.u.	<0.56 a.p.f.u.
White mica	$Fe_{[tot]}$/Mg	<1.4	<3.7	<3.5
	Si	3.0–3.37 a.p.f.u.	3.05–3.43 a.p.f.u.	3.0–3.43 a.p.f.u.
Garnet	Almandine	45–67%	44–70%	43–70%
	Grossular	30–53%	15–56%	30–52%
	Spessartine	0–20%	0–20%	0–8%
	Pyrope	1–7%	0–1.5%	0–7%
	Andradite	0–2%	0–1.5%	0–4%
Titanite	X_{Al} = [Al/(Al+Ti)]	<0.18 a.p.f.u.	<0.37 a.p.f.u.	<0.41 a.p.f.u.

migmatitic Gierałtów gneisses or it was derived by melting from these or alike rocks. The mentioned geochemical similarities between the gneisses are not in conflict with such assumption and are in line with the preserved intrusive contacts.

Such model can also explain why garnet in both types of gneisses and in xenoliths is generally similar, though with large compositional scatter. Indeed, inherited metamorphic garnet is present in numerous garnetiferous plutons, especially peraluminous ones, which occur in metamorphic terranes (Chamberlain and Lyons, 1983; Plank, 1987; Lackey et al., 2006).The composition of garnet xenocrysts may depend solely on the bulk composition and metamorphic grade of the source rock (Spear, 1993; Owen and Marr, 1999). The grossular content is controlled by the bulk composition and increases (at the expense of Mn) with the depth of crystallisation, but the increasing spessartine content of garnet stabilizes this mineral to low pressures (Miller and Stoddard, 1978, 1981). It is worth to note that high-Al titanite is also stable over a wide P-T range even under high-grade conditions (Markl and Piazolo, 2004; Lucassen et al., 2010). Therefore, such metamorphic minerals can be expected to occur in felsic magmatic rocks developed via partial melting of crustal sources. The above-briefed differences in the spessartine content in garnet, Si content in white mica, or ilmenite and titanomagnetite microgrowths observed in the studied rocks are in line with such expectations (Redlińska-Marczyńska, 2011; Redlińska-Marczyńska and Żelaźniewicz, 2011).

Turniak et al. (2000) studied typology of zircon grains in 17 gneiss samples and found that the zircons from the Śnieżnik gneisses resemble those from S-type granites, whereas the zircons from the Gierałtów gneisses point to I-type granitoids. In the former, the {211} bipyramid dominates over the {101}, which is opposite to the Gierałtów zircons, yet in both gneisses the {110} prism is better developed than {100}. Such observations are basically valid in our samples too, though we did not conduct a systematic typology study of a greater number of zircon populations. Nevertheless, differences in precursors of the two types of gneisses can be reasonably expected.

For gneisses of the Międzygórze Antiform, regardless of methods used, the geothermobarometric calculations range between 4–11 kbar/600–650°C (Klemd et al., 1995) and 4–14 kbar/500–570°C (Grześkowiak, 2004; Redlińska-Marczyńska, 2011). Higher values of <15kbar/<700°C to 19–20 kbar/>700°C were recently obtained from P-T pseudosections and compositional isopleths for various minerals by Chopin et al. (2012a) who, however, did not refer to the classification of gneisses into the Śnieżnik and Gierałtów types. The highest values were determined for the Gierałtów type gneisses which were interpreted by these authors as an ultramylonite derived from the augen orthogneiss of Śnieżnik type. Although our observations also repeatedly show that the Śnieżnik metagranite (= augen gneiss) was metamorphosed at lower temperature and pressure conditions than the Gierałtów gneisses and that rocks of the two formations were zonally mylonitised, we do not see arguments which would substantiate the relationship proposed by Chopin et al. (2012a).

Summing up, the above review indicates that rocks of the Gierałtów and Śnieżnik formations systematically differ in many respects, starting from their protoliths. Although minor, all these differences are clearly in conflict with the assumption that they come from one igneous suite derived from identical source rocks. Our observations concur with those performed by Borkowska et al. (1990) and Borkowska (1994, 1996).

PREVIOUS ISOTOPIC AGE DATA FOR GNEISSES WITH BASIC REFERENCE TO OTHER ROCKS

An early isotopic study of the Śnieżnik augen gneiss yielded the Rb-Sr whole-rock age of 487 ± 11 Ma, which was interpreted to indicate the time of emplacement of its granitic precursor (van Breemen et al., 1982). Later studies performed by Borkowska et al. (1990) yielded Rb–Sr whole-rock isochron ages of 395 ± 35 Ma for the Śnieżnik gneisses and of 464 ± 18 Ma for the Gierałtów gneisses. These authors, based on the field relationships, the presence of retrograded eclogite bodies and unusually composed garnet, concluded that the Gierałtów gneisses were metamorphosed and deformed before "having been penetrated by the Śnieżnik porphyroid granite intrusion".

Lange et al. (2005) performed more Rb-Sr analyses and having recalculated the results of Borkowska et al. (1990) came to the dates of 471 ± 35 Ma (*n* = 7; MSWD = 29) for the Śnieżnik and of 449 ± 5 Ma (*n* = 21; MSWD = 43) for the Gierałtów gneisses. They confirmed earlier observations of variations in the Rb–Sr isotope systematics throughout the dome and, considering the high MSWD values, suggested primarily a heterogeneous source for the gneisses and/or disturbances in the Rb-Sr system being accomplished during subsequent metamorphism. The latter conclusion presumably also extends to other isotope systems studied in the OSD rocks.

The Rb-Sr phengite and biotite ages for gneisses of the two formations range between 335 Ma and ~319 Ma (Borkowska et al., 1990; Lange et al., 2005) and are well compatible with the Ar-Ar ages determined between 341 Ma and 320 Ma (Maluski et al., 1995; Marheine et al., 2002; Glascock et al., 2003; Schneider et al., 2006). These are cooling ages, yet often considered to reflect the timing of Variscan metamorphism in the gneisses.

A database of U-Pb zircon ages for the gneisses, still small though larger than the Rb-Sr database, shows three discrete age groups revealed mainly by SHRIMP analyses: (1) 560–530 Ma and older up to 2.6 Ga, (2) 515–480 Ma, and (3) ~350–330 Ma (Oliver et al., 1993; Klemd and Bröcker, 1999; Kröner et al., 2000; Turniak et al., 2000; Lange et al., 2002, 2005; Štípská et al., 2004; Grześkowiak et al., 2005; Bröcker et al., 2009, 2010). Group (1) is taken to represent inherited components, group (2) – magma formation and granite emplacement, group (3) – metamorphism and deformation of granites to gneisses. Such clear-cut picture is distorted by far less frequent ages around 450 Ma and 370 Ma, yielded mainly by ID-TIMS analyses. These can be likely discarded as geologically meaningless mixed ages (groups 1 and 2) being derived from zoned single grains (Lange et al., 2005). However, disturbances in the U-Pb system during later metamorphism cannot be ruled out as the age numbers coincide with the Rb-Sr ages of ~460-450 Ma, which apparently resulted from disturbances in the Rb-Sr system.

The Th-Pb analyses of monazite from the gneisses disclose four age groups: (1) ~500 Ma, (2) ~370–360 Ma, (3) ~345–330 Ma and (4) ~300 Ma (Gordon et al., 2005; Schneider et al., 2006). Groups (1) and (3) agree with magmatism in the Late Cambrian and subsequent metamorphism in the Early Carboniferous as inferred from other isotope systems. The ages of ~370–360 Ma and 300 Ma are not observed in the U-Pb zircon dataset for the gneisses.

Although (U)HP rocks are beyond the scope of this paper, yet the Gierałtów gneisses enclose granulites whose garnet yielded Lu-Hf age of 382 Ma (Anczkiewicz et al., 2007) hinting to the Devonian HP event. Budzyń et al. (2015) inferred, however, from the Th-U-total-Pb dating of monazite and P-T estimations that granulites were under temperature >900°C by 349 ± 2 Ma. Under such conditions, the isotope systems in most minerals must have been reset. Thus the ~350 Ma ages may only reflect the time of the resetting or the end of the metamorphic climax at best. Strikingly similar conclusion was reached by Brueckner et al. (1991) who studied the Sm-Nd system in eclogites and found that they were actually on the retrograde P-T path between 350 Ma and 329 Ma.

The age of ~350 Ma is also identical with the metamorphic climax after the main deformational event in mica schists that occurred at ~352–346 Ma (Gordon et al., 2005; Jastrzębski, 2009; Jastrzębski et al., 2010) and at ~360 Ma in rocks of the borderland between the Saxothuringian/Moldanubian and Brunovistulian terranes along the eastern margin of the Orlica–Śnieżnik Dome (Jastrzębski et al., 2015). Relicts of the blueschist facies metamorphism in the western limb of the dome would imply that at least part of the metasedimentary rocks, which mantle the gneissic core of this unit, was subjected to HP conditions of ~20–21 kbar at 500–550°C (Faryad and Kachlík, 2013) prior to the thermal peak metamorphism at lower pressures.

As follows from the above, the timing and details of metamorphism and deformation in the OSD rocks are still not fully understood, thus should be debated (see Żelaźniewicz et al., 2014a, b). Almost all isotopic studies yielded ages between 350 Ma and 330 Ma, which suggests that the main tectonometamorphic processes in the dome occurred in the Early Carboniferous. However, the view presented in recent years, that all the following: prograde metamorphism up to HP-HT conditions associated with multiple folding and nappe emplacement, migmatisation, shearing and mylonitisation may have occurred almost contemporaneously with cooling of all rock types – requires many a priori assumptions and far more evidence. Moreover, having considered the presence of HP-HT eclogite and granulite enclosures in the Gierałtów gneisses, the former can be expected to be older or of the same age as the latter (Żelaźniewicz and Bakun-Czubarow, 2002). Actually, similar ages may indicate just common cooling of different rock units in the same time span.

GNEISS SAMPLES AND STRUCTURAL TEMPLATE

For the isotopic study, five samples were collected in the Międzygórze Antiform area (Fig. 1). They were selected to cover key variants of the two formations, each with different characteristics, structural position and evolution. Three samples represent the Gierałtów Gneiss Formation: OS40 – streaky gneiss (N50°12'11.34" E16°45'36.28"), MD46 – porphyroblastic gneiss (N50°14'1.74" E16°46'5.62"), OS35/8 – leucocratic neosome from migmatitic gneiss (N50°13'44.53" E16°45'26.81"). Two samples come from the Śnieżnik Gneiss Formation: OS47 – weakly deformed rodded augen gneiss (L>S tectonite; N50°13'21.18" E16°46'48.47"), and OS5 – enclave (xenolith) of migmatitic gneiss (N50°13'21.21" E16°46'48.39"). The sequence of structures F1S1—F4S4 described below is valid for gneisses in the antiform (Redlińska-Marczyńska, 2011; Redlińska-Marczyńska and Żelaźniewicz, 2011).

Two Gierałtów gneiss samples (OS40, MD46) represent rocks with compositional banding (S0) followed mimetically by the earliest metamorphic foliation. Both the structures were folded (F1) and transposed (D1 event) to the axial planar foliation (S1) accompanied by shearing and intrafolial folds (Fig. 3A). The S1 was refolded into asymmetric F2 folds with variably oriented axial planar foliation S2 (Fig. 3B). In the hinge areas of F2 folds, there are K-feldspar (porphyro)blasts and/or leucocratic aggregates/neosomes composed of quartz, K-feldspar, white mica (and minor plagioclase, biotite, apatite). The presence of such structurally controlled blasts and neosomes is one of the characteristic and distinctive features of the Gierałtów Formation (Fig. 3B; see also Redlińska-Marczyńska and Żelaźniewicz, 2011: fig. 2.3). They appear as streaky porphyroblastic to migmatitic gneisses in which the leucosome was extracted in situ (nests) and/or injected as irregular veins in the axial planar or discordant manner (Fig. 3C, sample OS35/8). The migmatisation occurred syn- to post-kinematically with respect to disharmonic folding F2 (D2 event). Such tectonometamorphic edifice of the Gierałtów gneisses was then subjected to shear deformation and mylonitisation along S3 planes, which often were the rejuvenated or transposed S2 foliation (Fig. 3D). The shearing was associated with folding F3 (Fig. 3E) on roughly W–E to NW–SE axes and accompanied by stretching lineation (Fig. 4A, B) in the N–S to NE–SW direction (D_3 event in both types of gneisses). In the Międzygórze Antiform, the subsequent event brought about conspicuous E-vergent folds F4 with amplitudes up to a few tens of metres (Fig. 3F), which resulted in subhorizontal and steep dips of the earlier S-planes (in both types of gneisses).

Sample OS35/8 is a leucocratic, unfoliated rock that comes from a subvertical vein which cuts discordantly the twice folded migmatitic gneiss of Gierałtów type (Fig. 3C). The vein continues as leucosome nests in these gneisses.

Sample OS47 is the rodded Śnieżnik gneiss with augens being K-feldspar porphyroclasts (Fig. 4A). In general, the augen gneisses developed from a porphyritic granite (Fig. 3A, B) with local pre-existing primary fabric (Żelaźniewicz 1984, 1988, 1991; Redlińska-Marczyńska, 2011). The granite was then heterogeneously deformed, some parts transformed into rodding gneiss (L > S to L > S tectonites) with varied overprint (Fig. 4A, B). This type of strain may have occurred in the hinges of F2 folds (Żelaźniewicz et al., 2013). Field observations show that such L to L > S fabric was then subjected to shearing which produced L < S to S-type tectonites (Fig. 4B, C) thus changed the porphyritic granite to augen gneiss in which the shear zones widened as the deformation progressed. It was the very shearing that produced D_3 structures in the Gierałtów gneisses. In augen orthogneisses, the deformational history was evidently shorter and the first foliation-forming event in the Śnieżnik metagranite (Fig. 4A–C) did overprint the earlier folds and planar fabrics (S1 and S2) in the Gierałtów rocks (Fig. 3B, D, F). In the latter, the D3 shearing often rejuvenated the S2 foliation, which resulted in the spatial coincidence of the S2 and S3 planes.

Sample OS5 (Fig. 4D) comes from a large enclave (~10 m 15 m) enclosed by the rodded L > S augen orthogneiss of OS47 type (Fig. 4A). This is a coarse- to even-grained stromatitic migmatite with monomineral (K-feldspar or quartz) or polymineral (quartz + K-feldspar ± plagioclase) blasts, nests and pods that overgrew at random the folded migmatic fabric of this rock (Redlińska-Marczyńska, 2011).

U-Pb ZIRCON STUDY

METHODS

Zircon samples were retrieved from the five gneiss samples featured above, 5–7 kg each. They were prepared using standard procedures. Cathodoluminescence imaging was used to identify internal structure of zircon grains. The U-Th-Pb analyses were carried out using a SHRIMP II facility at the Research School of Earth Sciences, Australian National University, following the methods described by Williams (1998). 108 spots have been analysed in 97 zircon grains from five samples (Fig. 1). Each analysis consisted of six scans through the mass range, with the Temora reference zircon grains analysed for every three unknown analyses. The data have been reduced using the SQUID Excel Macro of Ludwig (2001). The Pb/U ratios have been normalised relative to a value of 0.1859 for the Duluth Gabbro FC1 reference zircon, equivalent to an age of 1099 Ma (see Paces and Miller, 1993). Uncertainty in the reference zircon calibration was ± 0.21% (2) for the analytical session. Uncertainties given for individual analyses (ratios and ages) are at the one sigma level (Appendicies 1–5*). Correction for common Pb was either made using the measured ^{204}Pb/^{206}Pb ratio in the normal manner, or for grains younger than 800 Ma (or those low in U and radiogenic Pb) by the ^{207}Pb correction method (see Williams, 1998). When the ^{207}Pb correction was applied it was not possible to determine radiogenic ^{207}Pb/^{206}Pb ratios or ages. In general, the radiogenic ^{206}Pb-^{238}U age for grains younger than 800 Ma was used with correction by the ^{207}Pb method. Tera-Wasserburg concordia plots, probability density plots with stacked histogram, and weighted mean ^{206}Pb-^{238}U age calculations (Tera and Wasserburg, 1972) were carried out using *ISOPLOT/EX* (Ludwig, 2003); see Figures 5–9. Weighted mean ^{206}Pb-^{238}U age calculation uncertainties are reported as 95% confidence limits.

ZIRCON SAMPLES

Zircon from porphyroblastic gneiss (Gierałtów Gneiss Formation): sample MD46. The zircon grains are 50 to 300 μm long but many are short and almost isometric with bipyramidal terminations (Fig. 5). The CL images show grains with differently zoned interiors and less densely oscillatory zoned outgrowths (# 1, 2, 6 and 7). In core domains, oscillatory, sector and planar zonal structures are in evidence (# 1, 5 and 14). Discontinuities between core and rim zones suggest discrete episodes of zircon crystallisation (# 5, 6, 7, 9 and 15) and resorption (# 15). Other grains have low-luminescent central domains surrounding old grains or inclusions (# 4, 7, and 9), and localised recrystallisation can be seen (# 5) around the latter. “Soccer-ball” zircon is also part of the population (# 8).

Zircon from streaky gneiss (Gierałtów Gneiss Formation): sample OS40. Most grains are subhedral, subequant to slightly elongate (~1:2). The CL images reveal complex internal structures of most grains that contain at least two different components (Fig. 6). Many grains display older, inherited, igneous or metamorphic cores (e.g., # 11, 14) and oscillatory zoned rims (e.g., # 3, 4, 11, 14), others have unzoned, clearly metamorphic rims (e.g., # 5, 9, 10, 15, and 16), but no high-U, dark rims have been observed. When seen under transmitted light, many grains are cracked and dark and some have mottled surfaces, which, along with rounded shapes (e.g., # 1, 5), suggest surface transport and detrital provenance.

Zircon from a discordant leucocratic vein in the Gierałtów migmatitic gneiss: sample OS35/8. They are predominantly very clear, slender prismatic (aspect ratio 1:3 to 1:6), euhedral grains (Fig. 7). The presence of numerous long prismatic crystals (# 3, 8, 10, 12 and 16), mainly with poor planar or sector zoning, differs this population from other two zircon samples retrieved from rocks of the Gierałtów Formation. Most grains have the {110} prism faces that may imply crystallisation from relatively cold, H_2O- and alumina-rich magmas and emplaced close to the place of extraction (Vavra, 1994). These would be in line with leucocratic neosome origin of their host vein. The CL images show oscillatory zoned internal structures. Discontinuities in such zoning are frequent, suggesting multiple zircon crystallisation episodes during growth of those grains. In some grains, there are clearly older inherited components in central areas which underwent dissolution. Other grains have a very poor CL response (greyish or whitish) and structure obliterated by metamict alterations. Slightly darker or CL bright overgrowths are less or quite poorly zoned. Few grains have thin dark CL rims (grains 18, 19, and 21).

Zircon from rodded (L > S) augen orthogneiss of the Śnieżnik Formation: sample OS47. The zircon grains are elongate to almost equant, sub- to euhedral, ~100–300 μm

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* Supplementary data associated with this article can be found, in the online version, at doi: 10.7306/gq.1287

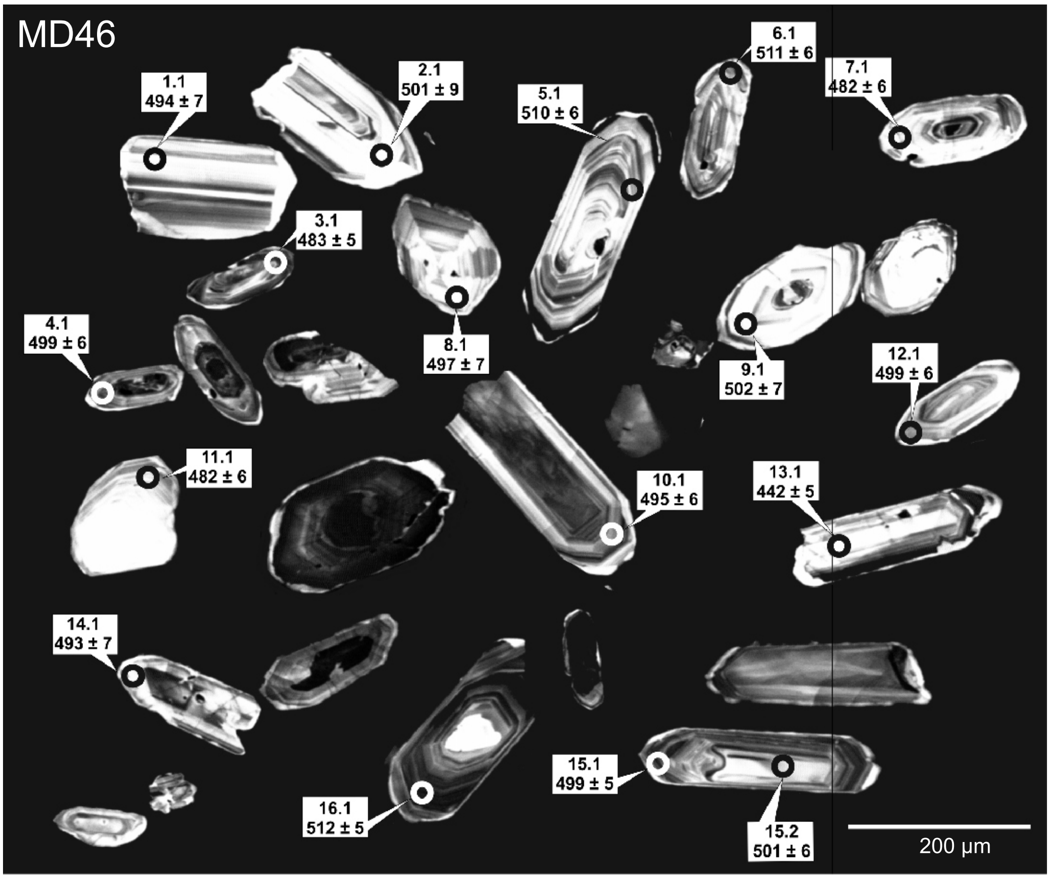

Fig. 5. Cathodoluminescent images of zircons from sample MD46

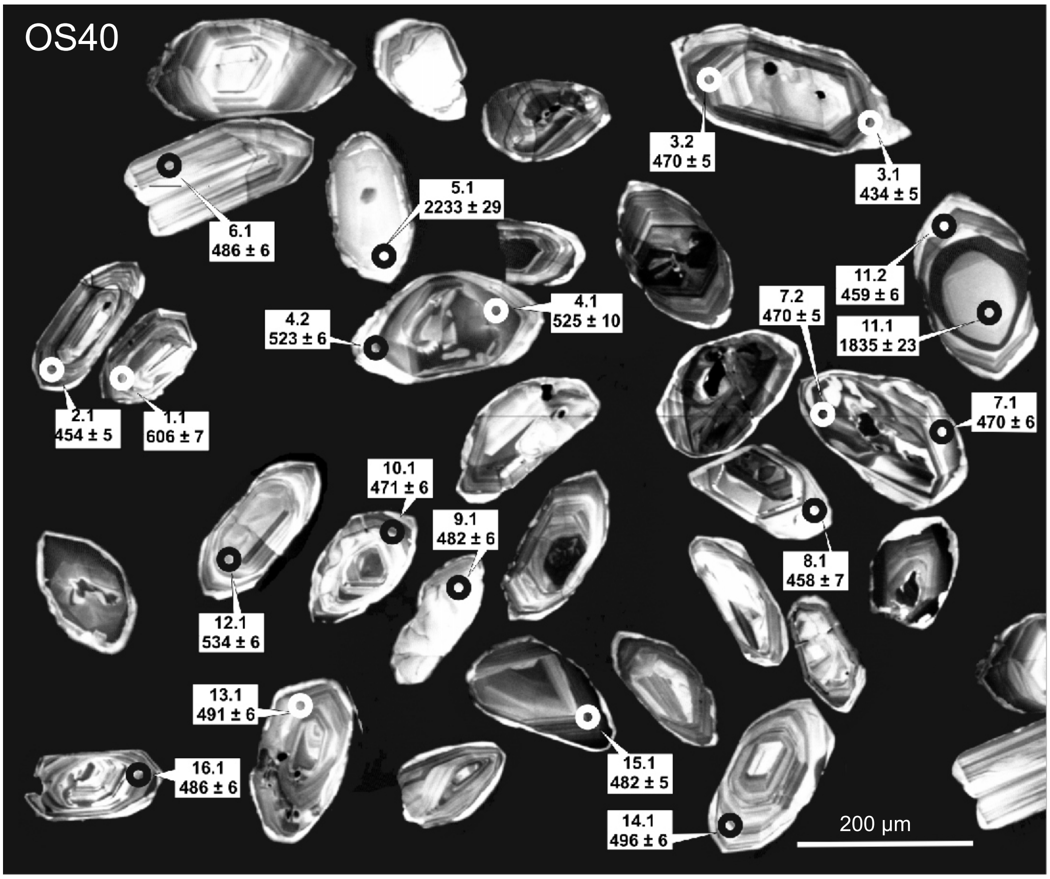

Fig. 6. Cathodoluminescent images of zircons from sample OS40

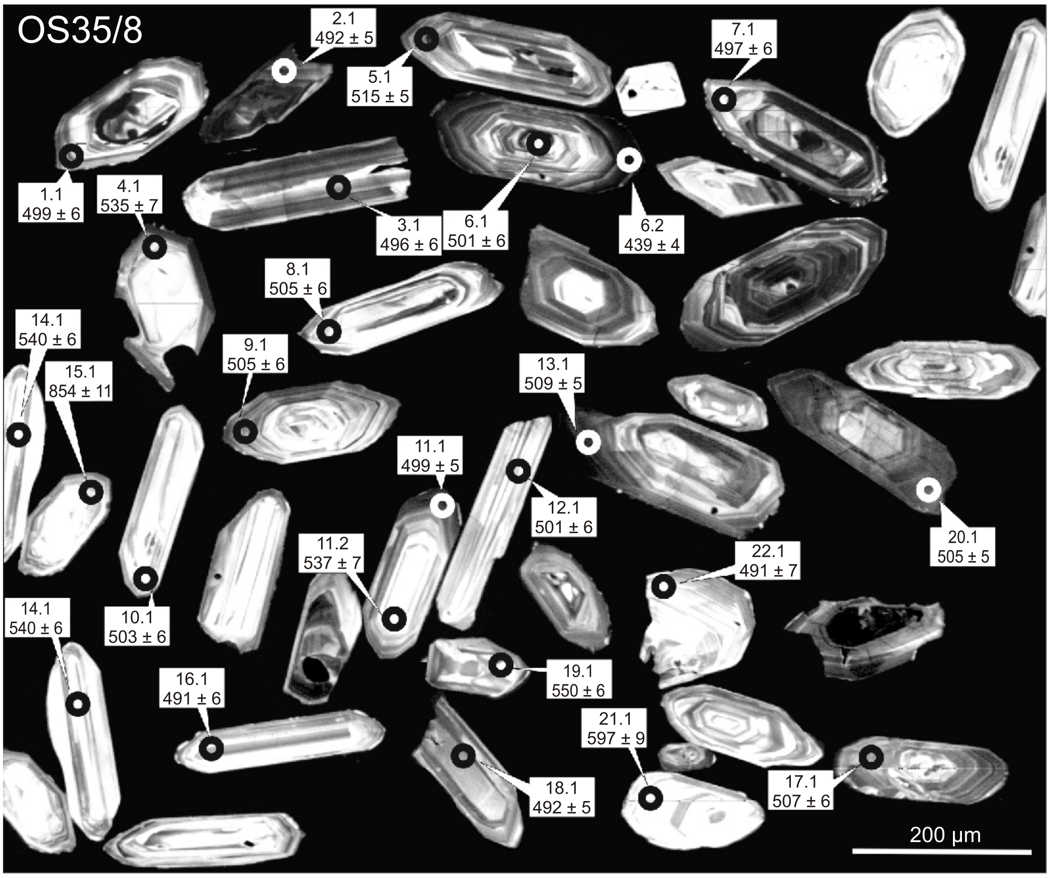

Fig. 7. Cathodoluminescent images of zircons from sample OS35/8

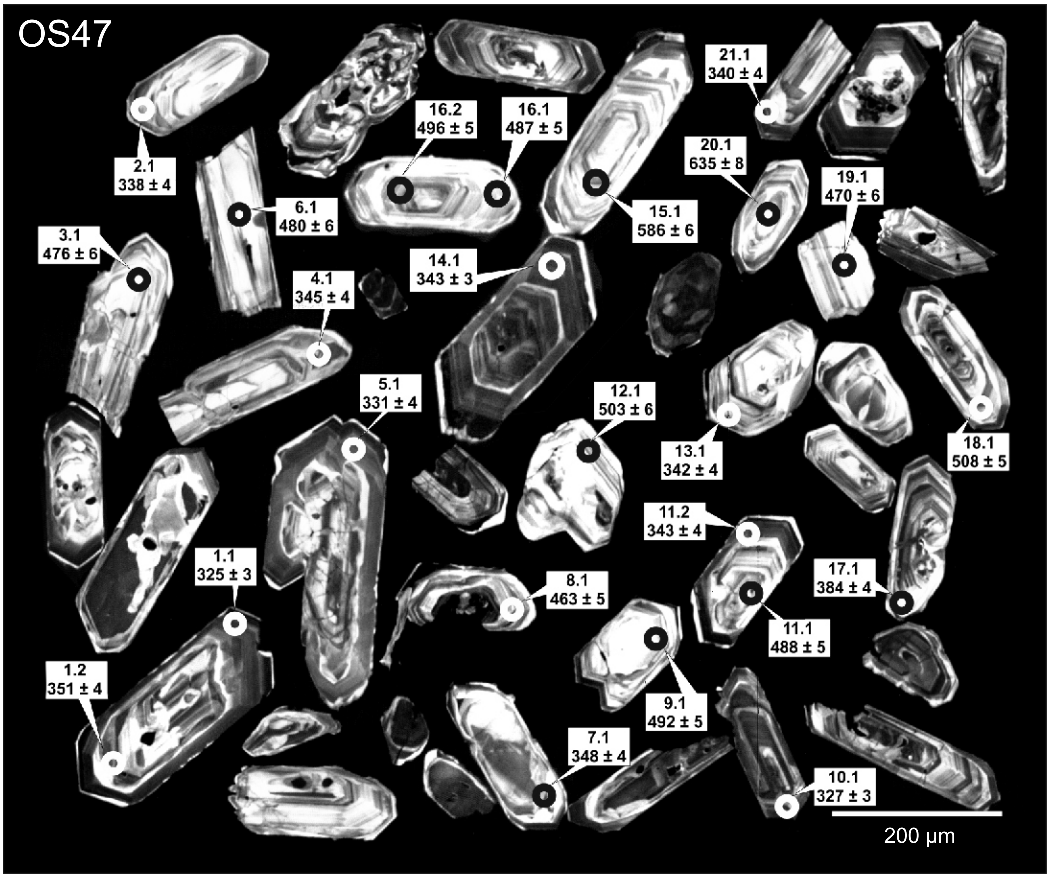

Fig. 8. Cathodoluminescent images of zircons from sample OS47

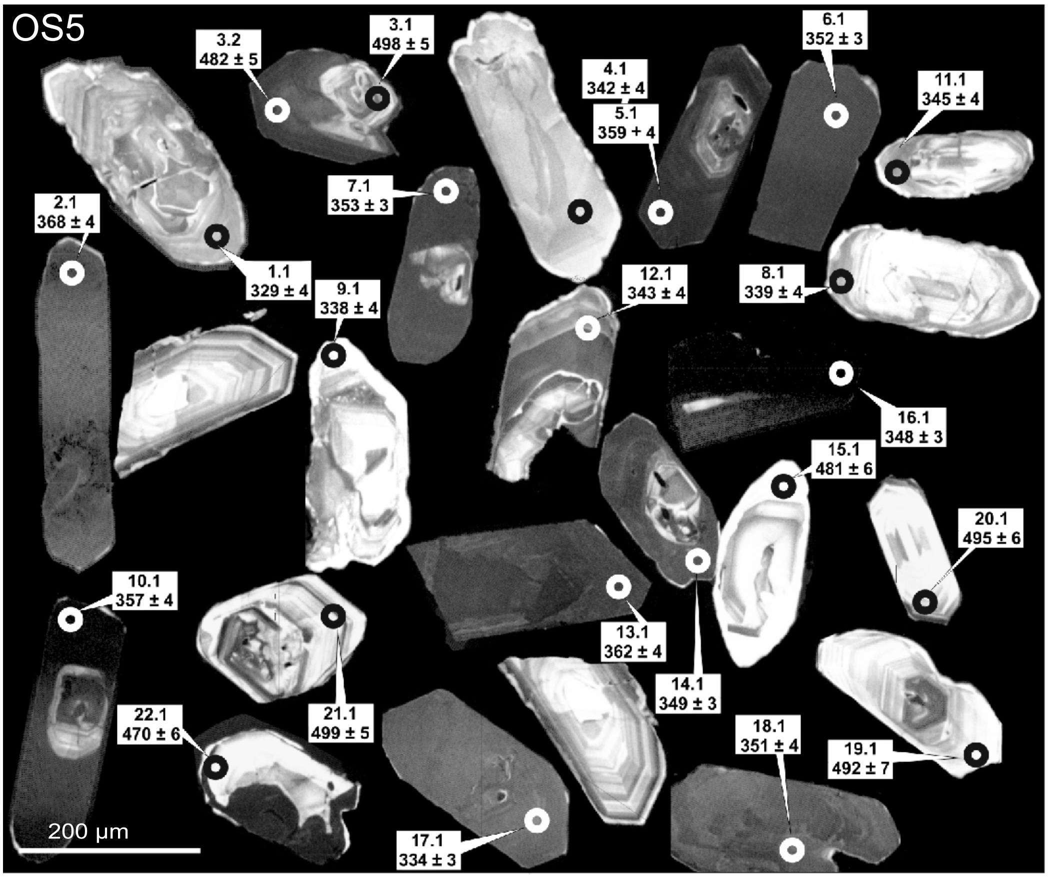

Fig. 9. Cathodoluminescent images of zircons from sample OS5

long, with both the {101} and {211} bipyramids (Fig. 8). Subround terminations (e.g., # 15, 16) might be caused by metamorphic processes. Like in the OS35/8 leucosome, dominant {110} prisms are in evidence. Many euhedral grains have irregularly structured or zoned inherited cores and oscillatory zoned outgrowths often darker in CL (e.g., # 4, 5 and 14). The complex CL structure of the inner parts may indicate repetitive fluid or melt interactions that recrystallised and embayed the original inherited zircon component.

Zircon from migmatitic xenolith in the rodded augen orthogneiss of the Śnieżnik Formation: sample OS5. The zircon grains are 100–300 µm long with variable aspect ratio 1.3:1 to 5:1 (Fig. 9). They differ from other samples by dullness due to metamictisation and strong dissolution of cores which have acquired very irregular outlines. Similarly to sample OS47, there are crystals terminated with the {101} and {211} bipyramids. In grains which have poor CL response (greyish or whitish), it is difficult to determine their structure. Some grains have bright oscillatory zoned centres and dark to black CL overgrowths.

RESULTS

Porphyroblastic gneiss (Gierałtów Gneiss Formation): sample MD46. In this sample, retrieved from the porphyroblastic gneiss, 17 oscillatory zoned areas were analysed on 16 zircon grains (Appendix 1 and Figs. 5, 10, 15). On the Tera-Wasserburg plot, the analyses form a single group around 500 Ma (Fig. 10A). On a probability density plot, 10 analyses form a dominant age peak at 499 ± 5 Ma, with 3 analyses each on the older and younger age side (Fig. 10B). The former, slightly older, could be considered as inherited zoned igneous zircon (i.e. the 3 older analyses at about 510 Ma) and the latter analyses likely relate to the loss of small amounts of radiogenic Pb (i.e. the 3 younger analyses at about 485 Ma). The analysis of grain 13 is significantly younger and we interpret the area analysed to have lost radiogenic Pb. For the main oscillatory zoned component a weighted mean ^{206}Pb^{238}U age of 498.1 ± 4.1 Ma (*n* = 10, MSWD = 0.21) provides an estimate for the time of major zircon crystallisation (see discussion below).

The analytical data show varying Th/U ratios from 0.06 to 0.72, of which 3/4 (12 of 17) is below 0.3, thus in the range of metamorphic zircons rather than magmatic, though unambiguous discrimination requires caution (Hoskin and Schaltegger, 2003). In the Tera-Wasserburg plot, the dispersed radiogenic ^{206}Pb-^{238}U ages show a prominent grouping along a line that intersects the concordia at about 500 Ma (Fig. 10A). However, no single igneous crystallisation event can be unambiguously inferred. The discontinuities in the oscillatory zoning indicate more than one crystallisation episode, whilst evidence of recrystallisation and resorption of central domains, and poorly zoned outgrowths suggest the importance of high-grade metamorphic processes. In grain 15, an age difference of 2 Ma, almost negligible if to consider error limits, would suggest a relatively short duration of such processes concurrent with the growth of oval, soccer ball-shaped crystals. This concurs with the host rock which is folded gneiss with K-feldspar porphyroblasts and polymineral aggregates located in the fold hinges due to incipient migmatitic/partial melting phenomena.

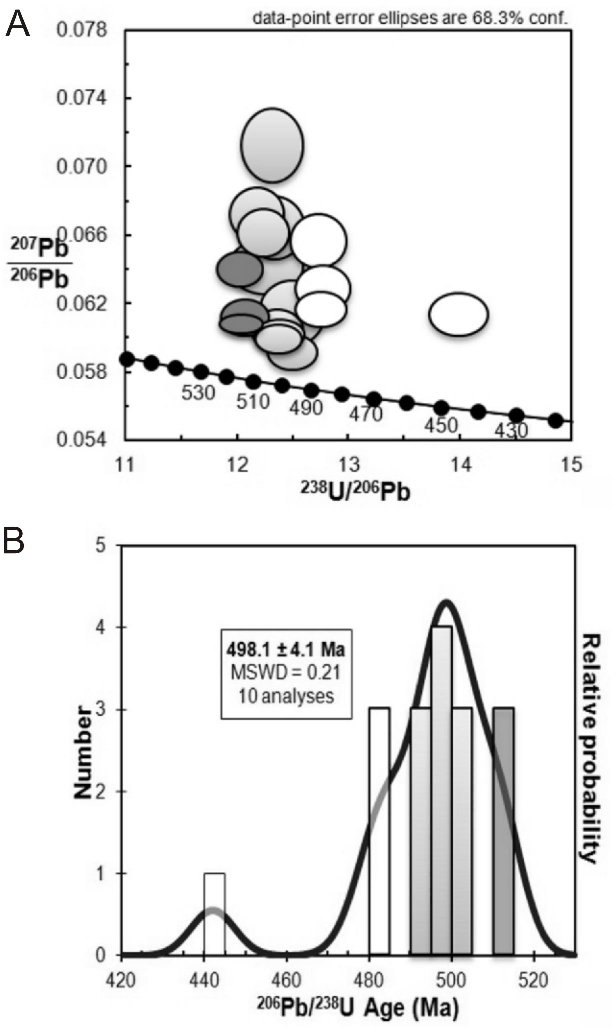

Fig. 10. Tera-Wasserburg concordia diagram (A) and probability density diagram (B) for sample MD46

This and the following T-W plots show the calibrated, total ratios; i.e. uncorrected for common Pb, whereas the probability plot shows corrected ages (2sigma). Each age grouping is represented by a different shade of grey

Such conditions likely promoted growth of zircon outer domains with oscillatory zoning as expected for the crystallisation from melt. Characteristically, the Th/U ratios in such outgrowths vary remarkably from the lowest, “metamorphic” ratios (<0.1) as old as ~512 Ma to the highest, “magmatic” (> 0.5) as observed in the rim of grain 14.1 dated at ~493 ± 7 Ma. There are some legible relationships between age, texture and Th/U ratios in zircons. Younger grains or domains tend to have higher Th/U ratios, which presumably reflects the trend from metamorphic to migmatitic/magmatic conditions at the ~500 Ma event. Again, this is well-illustrated by grain 15, in which slightly older, homogenous yet partly resorbed core (Th/U = 0.09) is overgrown by oscillatory zoned outgrowth (Th/U = 0.26). The high common Pb content (>1%) in 1/3 of the analyses, ranging between 0.25% and 1.74%, apparently did not make them useless.

Streaky gneiss (Gierałtów Gneiss Formation): sample OS40. For this study, 20 areas were analysed on 16 zircon grains (Appendix 2 and Figs. 6, 11, 15), coming from a streaky gneiss. In contrast to sample MD46, which also comes from the Gierałtów gneiss, no single age grouping is recorded. On the Tera-Wasserburg plot, the analyses scatter between ~540 and ~440 Ma (Fig. 11A), as a consequence of variable ^{206}Pb-^{238}U ages and variable amounts of common Pb. The latter is >1% in 13 areas, which impedes any precise age determination and the analyses around 440 Ma are apparently too young (Fig. 11B).

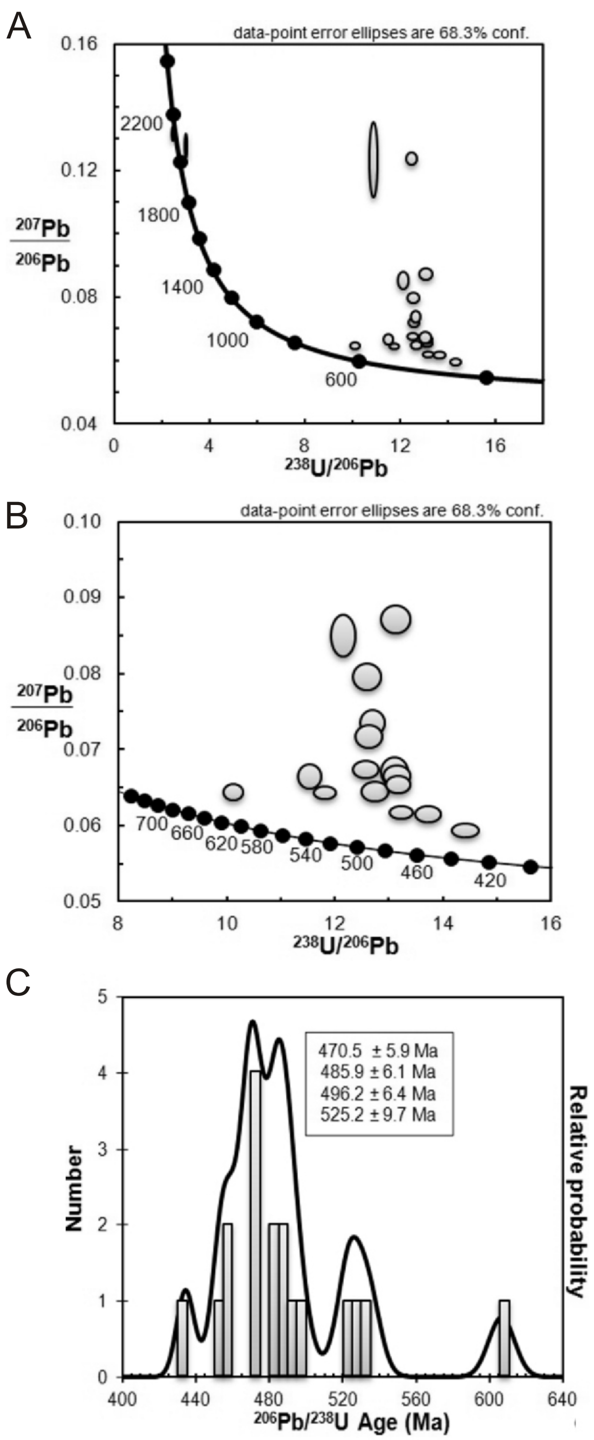

Fig. 11. Tera-Wasserburg concordia diagram (A), U-Pb concordia diagram for younger grouping (B), and probability density diagram (C) for sample

However, the strong dispersion in dates and correlation between CL structure and age, nor U, Th and Th/U ratios, indicate the presence of a strong initially heterogeneous zircon population, coupled with superimposed metamorphic processes that gave rise to variable radiogenic Pb loss. Moreover, low Th/U in almost all grains suggests that the complex structured zircon grains are metamorphic, which is in line with the observed convolute zoning and non-zoned or poorly zoned outgrowths in most grains. In this sample, like in MD46, no grain or rim was found which might record a Carboniferous event around ~340 Ma. Based on the data in hand, there is no reason to assume that such profound metamorphic disturbances were caused by the event which did not left behind any legible trace. Although some conditions during metamorphism may impede or even prevent zircon recrystallisation, there is a poor reason to assume that they selectively operated only in the Gierałtów gneisses and not in the adjacent Śnieżnik gneisses (see samples OS47 and OS35/8). The complex nature of the OS40 zircon population along with the grains as old as 2.2 Ga and 1.8 Ga, and the inferred detrital provenance of many grains allow us to conclude that the protolith to the studied Gierałtów gneiss is a metasedimentary rock with the maximum provenance age of 606 Ma (# 1) and possibly the youngest component of ~540 Ma. It seems reasonable to infer that the protolith OS40 was metamorphosed in the span 540–440 Ma, most likely around 500 Ma like other samples of the Gierałtów gneisses (Fig. 11C). Despite high common Pb, the integrated information on sample OS40 allows interpreting it as a high-grade paragneiss metamorphosed and deformed in Late Cambrian–Early Ordovician times. It is noteworthy that despite high U and high common Pb in many analyses the obtained age estimates fit exactly the ages provided in the literature by other authors for the Gierałtów and the Śnieżnik gneisses.

Discordant leucocratic vein in the Gierałtów migmatitic gneiss: sample OS35/8. From the leucocratic vein crosscutting the migmatite, 24 areas were analysed on 22 zircon grains (Appendix 3 and Figs. 7, 12). The Tera-Wasserburg plot shows distinct age groupings (Fig. 12A). For the main group, a weighted mean gives a ^{206}Pb-^{238}U age of 500 ± 3 Ma (n = 15, MSWD = 1.08), which constrains the time of zircon crystallisation in the host leucocratic vein. Another group, represented by older grain cores, yields, as it might be expected, older ^{206}Pb-^{238}U ages of about 540 Ma (n = 4). These analyses revealed >1% of common Pb and do not provide precise age determination. The apparently youngest ^{206}Pb-^{238}U age of ~440 Ma was determined for a high-U rim on grain 6. It likely lost radiogenic Pb due to later metamorphic processes. The darker CL outgrowths with poor structure (# 6, 13 and 20), which have between ~1200 and ~2000 ppm U, display Th/U ratios between 0.04 and 0.08 as typical for metamorphic zircon. However, they may represent late-crystallizing igneous zircon from a U rich magmatic pulse. The remaining areas analysed have rather poor oscillatory zoned structure and these, except two, have Th/U ratios between 0.05 and 0.43, thus <0.5 value over which zircon is typically assigned as igneous (Hoskin and Schaltegger, 2003). On the other hand, it is known that the Th/U ratio itself is not an unambiguous criterion. Interestingly, the long prismatic crystals which differ from other grains in the population, almost invariably yielded ages, within errors, around ~500 Ma (e.g., # 3,10,12,16), though they contain high common Pb > 1%. Grain 11 developed the ~500 Ma outgrowth on the ~540 Ma central domain and the 500 Ma outgrowths occur on other crystals, the cores of which have not been dated. The age of the cores and older grains is in the range from ~600 to ~535 Ma, which sufficiently documents the inherited zircon even with imprecise timing. No legible evidence for a tectonothermal Carboniferous event occurs in the studied population. Narrow black rims on few grains are too thin and too U-rich to be dated (# 6.2).

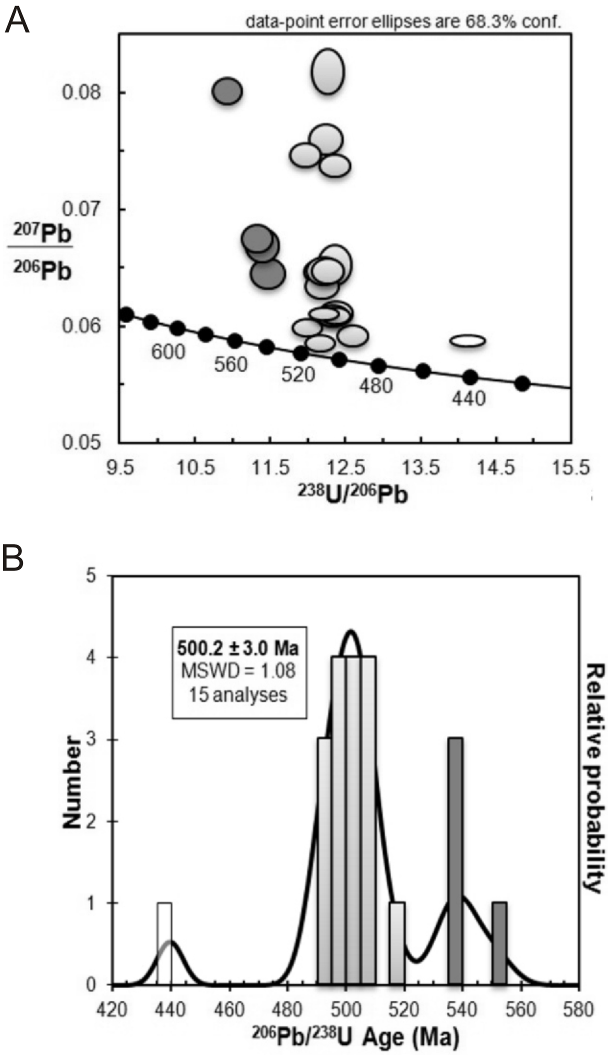

Fig. 12. Tera-Wasserburg concordia diagram (A) and probability density diagram (B) for sample OS35/8

Integrating the zircon data with the structural position of the host rock, a leucocratic unfoliated vein that discordantly intersects folded migmatitic gneiss of the Gierałtów Formation (Fig. 3C), the following inferences can be made: (1) discordant vein is younger than the deformed host gneiss; (2) zircon is inherited from the protolith with significant ~600–540 Ma component; (3) some old grains have no outgrowth or merely very thin CL black rims, which suggests that they have never been in an effective contact with the magmatic melt; (4) crystallisation from melt produced new, dominantly slender, prismatic grains and outgrowths on older grains at 500 Ma; leucocratic melt developed via partial melting of the host gneisses or rocks similar to them and represented larger portions of the mobilized migmatitic neosome; (5) zircon crystals dominated by the {110} prisms typical of granites crystallised from H_2O-rich, "cold" magmas (Vavra, 1994); (6) such conditions likely characterized the neosome formation in the course of migmatisation observed in sample MD46, and presumably in the Gierałtów gneisses in general. Incipient migmatisation was accomplished under structural control, as evidenced by the fold-hinge located porphyroblasts, leucocratic aggregates and leucosome segregations or injections; (7) lack of signs of strain in the cross-cutting vein rock does not support the possibility that the twice folded host Gierałtów migmatite and the vein itself might have developed during the ~340 Ma episode of deformation and metamorphism of the ~500 Ma granite, as assumed by Turniak et al. (2000) and other authors following such view. Under some conditions, migmatisation may not bring about outgrowths on zircons, but it would be rather hard to assume that these occurred exclusively in the Gierałtów gneisses and not in the Śnieżnik gneisses which contain the 340 Ma components, as exemplified by the two samples discussed below.

Rodded (L > S) augen orthogneiss of the Śnieżnik Formation: sample OS47. In the sample retrieved from the Śnieżnik augen orthogneiss, 24 areas were analysed on 21 zircon grains (Appendix 4 and Figs. 8, 13). Two grains have old cores, 586 ± 6 Ma (# 15) and 635 ±8 Ma (# 20), and those ages indicate inherited components. The ages obtained from core parts of other grains disperse around 507–487 Ma and also represent inheritance, yet younger. In grain 11, the core yields an age of 488 ± 5 Ma with a Th/U ratio of 0.353 Ma, whilst the dark rim is distinctly younger being dated at 343 ± 4 Ma with a Th/U ratio of 0.007. Similar relationships are displayed by grain 1. In these two grains, the core domains are distorted and embayed by darker and poorly zoned zircon of younger outgrowths. Such strong resorption of cores is even more obvious in other grains (# 3, 4, 5, 7, 8 and 9) and is a predominant feature of most core-rim structured pairs. Th/U ratios in these rims are low, varying from 0.002 to 0.28, with some systematic relationship between the ^{206}Pb-^{238}U age and this ratio: the smaller Th/U ratio and higher U-contents the smaller age number (Fig. 13C).

In general, the low Th/U ratios may be indicative of either growth from a partial melt being enriched in U, growth under high-grade metamorphic conditions, or growth from U-rich metamorphic fluids. The wide oscillatory zoned CL structure in the rims suggests, yet does not prove unambiguously, an igneous crystallisation event.

The high-U, low-Th dark CL rims (# 5, 10, 14, 21) with low Th/U ratios <0.01 yielded Carboniferous ^{206}Pb-^{238}U ages that overall range from ~343 Ma to ~325 Ma with overlaps within errors. However, most analyses revealed high common Pb. The dates are not precise, but we do not discard them as they fit well the age range determined by other authors for the OSD gneisses. The youngest ages do not necessarily always result from loss of radiogenic Pb. In grain 1, the analysed area in the outgrowth (# 1.1) is richer in Pb* than the outer core. Within the 343–325 Ma group there is no clear relationship between age and contents of Pb* or common Pb and these values differ considerably between grains.

A question arises as to whether the brighter CL, oscillatory zoned zircon with Th/U ratios of 0.016–0.023 crystallised at about the same time as the darker CL, <0.01 Th/U zoned rims. The age ranges overlap, but on the probability density plot of the youngest ^{206}Pb-^{238}U ages there are two peaks, one at about 328 Ma and another at ~343 Ma. On the Tera-Wasserburg concordia plot (of the calibrated, total ratios; i.e. uncorrected for common Pb) the three youngest analyses do not plot within uncertainty of the concordia curve but are elevated due to slight enrichment in common Pb, and the possible radiogenic Pb loss cannot be excluded (Fig. 13A). The fact that there is overlap in ^{206}Pb-^{238}U ages for the two components may indicate that the dominant weighted mean ^{206}Pb-^{238}U age of 343 ± 3 Ma (*n* = 7, MSWD = 0.73) is the best estimate for the time of crystallisation of the poorly zoned outgrowths.

In view of the above, a question arises about the origin of 343–325 Ma outgrowths: are they igneous or metamorphic fluid-assisted? As there is no grain with Carboniferous core, hence large amount of melt at that time seems improbable. The high U coupled with the dark and clouded nature of a number of

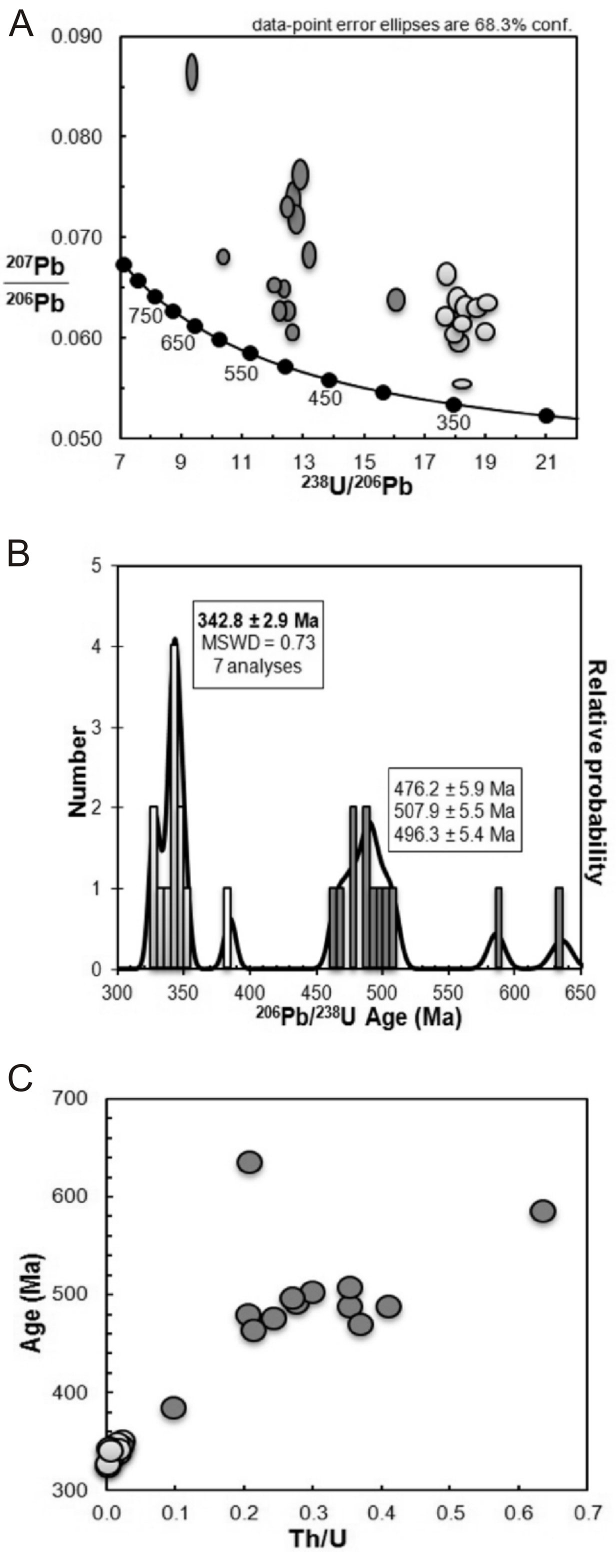

Fig. 13. Tera-Wasserburg concordia diagram (A), probability density diagram (B), and Th/U ratio vs. age [Ma] diagram (C) for sample OS47

zircon grains in this population (though not for the areas analysed) is suggestive of metamorphic alteration and fluid activity. The corroded embayed outlines of usually strongly disturbed cores are in line with such option as are the low Th/U ratios.

It is noteworthy that an age group of 508–480 Ma in the Śnieżnik metagranite (OS47), well-represented by the weighted mean ^{206}Pb-^{238}U age of 497 ± 6 Ma (*n* = 4, MSWD = 0.24), is similar to that shown by the zircons from the discordant leucocratic vein OS35/8. Indeed, in both rocks there are (1) inherited zircon components around 600 Ma and (2) double core-rim structure of ~500 Ma grains with predominantly oscillatory zone inner parts and poorly zoned outgrowths.

A difference between samples OS35/8 and OS47 lies in the presence of the ~340 Ma zircon outer domains which were not observed in the former. In sample OS47, many ~500 Ma grains have cores distorted and resorbed (e.g., # 5, 9), which must have happened at the time when the ~340 Ma outgrowths were developing. Such resorption is absent from sample OS35/8 just because it was not affected by the ~340 Ma event (or less probably - conditions were unfavourable for the zircon to grow), and thus no trace of it is found there. The first statement is also evident from the concordia plots (Figs. 12 and 13). In the Tera-Wasserburg diagram for sample OS47, there is a group of analyses from undistorted grains with common Pb <1% (e.g., # 16, 18) that plots along a line which intersects the concordia at ~500 Ma. Close to it there is another arrayed group of analyses of the distorted cores, often with common Pb >1%, from the core-rim grains. These show slightly younger ages in the range ~488–463 Ma for the cores in the grains that possess the ~340 Ma outgrowths. It is clear that such younging of the distorted cores was due to alteration caused by later Zr-carrying fluids. In view of the above, the fluids were metamorphic rather than igneous. Indeed, neither the host rodded augen gneiss specimens, nor their microscopic images carry any evidence of the presence of magmatic melt which is unlikely to develop easily in such coarse-grained, poorly deformed metagranite (Fig. 4A).

Migmatitic xenolith in the rodded augen orthogneiss of the Śnieżnik Formation: sample OS5. Twenty-three areas were analysed on 22 zircon grains (Appendix 5 and Figs. 9, 14, 15) coming from a migmatitic xenolith enclosed within the Śnieżnik augen orthogneiss. As it was mentioned above (zircon sample section), the zircon population of grains is unlike in other four samples. The very irregularly textured central areas and those that are clouded by metamict alteration products have not been analysed. One third of the population (# 3, 15, 19–22) yielded ^{206}Pb-^{238}U ages between ~500 and ~480 Ma for outer parts of the grains which have either oscillatory zoned igneous-looking cores (# 19, 21) or complex poorly zoned to non-zoned, highly distorted, metamorphic-looking cores (# 3, 22). The outer parts are mainly poorly zoned. All these areas have high common Pb >1% and Th/U ratios 0.14 (up to 0.4), which is in the range observed for both igneous zircon and metamorphic zircons, yet not precise enough to permit unambiguous discrimination. Such characteristic is similar to that of sample OS47 from the Śnieżnik gneiss. These analyses do not yield precise dates, but we should not discard them. They are informative enough to discern a group of zircons that possess poorly zoned metamorphic-looking rims developed at ~500 Ma age, which were dissolved and strongly distorted during younger metamorphic overprint.

In grains with strongly distorted cores, the outer areas yield Carboniferous ^{206}Pb-^{238}U ages and have Th/U ratios mostly 0.011, but with some ranging up to 0.05. The U concentrations in these grains/areas are quite variable in accord with the CL response. The dark CL areas mostly have more than 3000 ppm U, ranging up to about 6500 ppm, whilst the bright areas gener-

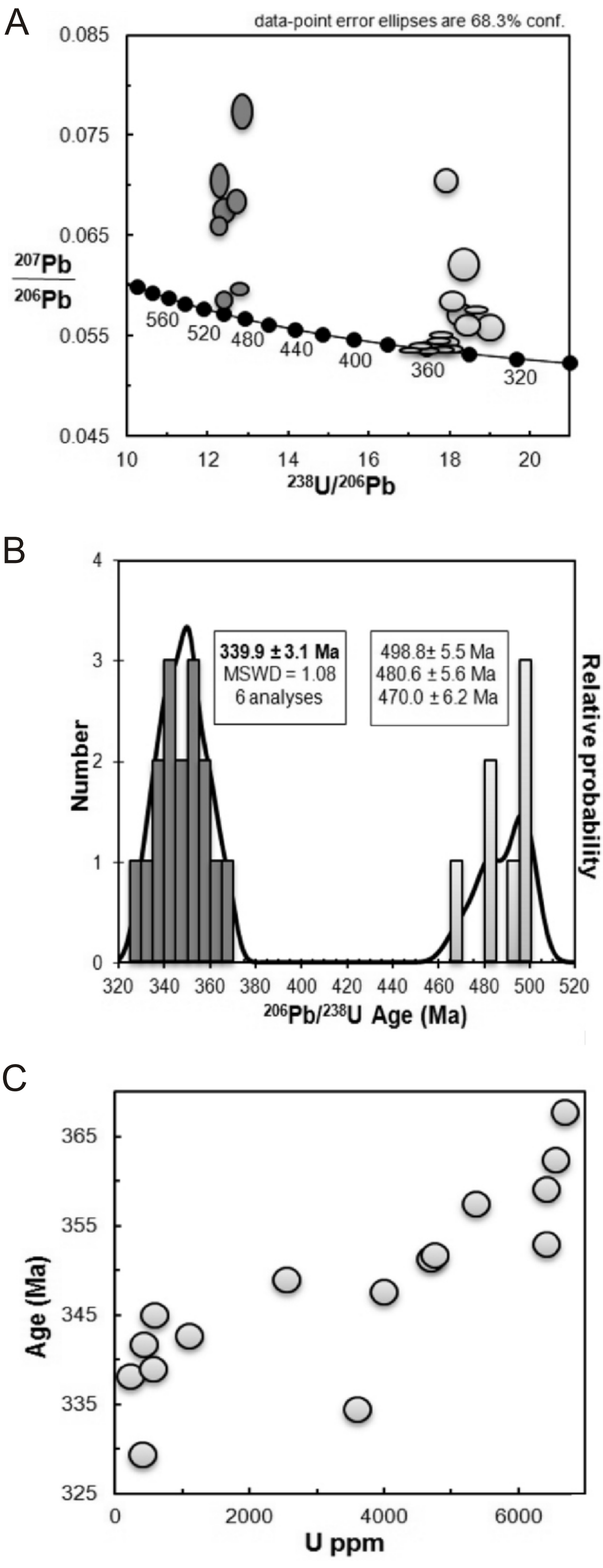

Fig. 14. Tera-Wasserburg concordia diagram (A), probability density diagram (B), and U ppm vs. age [Ma] diagram (C) for sample OS5

ally have less than 600 ppm. On a plot of U ppm *versus* ^{206}Pb-^{238}U age (Fig. 14C) there is a positive correlation between ^{206}Pb-^{238}U age and U ppm (starting from ca. 4000 ppm of U), though opposite to that found in sample OS47. This is a common feature observed in SHRIMP analyses of very high-U zircons (see Williams and Hergt, 2000); there is a sputtering bias with Pb preferentially enriched over U in such extremely U-rich zircon areas. It is also likely that there has been radiogenic Pb loss in such high-U areas and this may counter the sputtering bias such that arbitrarily useful U-Pb dates can be obtained. Notwithstanding this fortuitous situation, if the extreme U-rich areas are excluded, a weighted mean ^{206}Pb-^{238}U age of 340 ± 3 Ma (*n* = 6, MSWD = 1.08) provides an estimate for the rim and overgrowth components in this sample. The analysis of grain 1 at ~330 Ma is younger and the area analysed is interpreted to have undergone radiogenic Pb loss. However, it should be noted that this spot has the lowest Th content (~2 ppm).

Summing up the observations collected in sample OS5, this is exactly what may have occurred and be expected in a migmatised paragneissic xenolith that was entrapped on intruding granitic magma (age of ~500 Ma) and then subjected to metamorphic overprint at ~340 Ma. It is to be stressed that OS5 is not part of the Gierałtów Gneiss Formation. It is the xenolith of the migmatitic gneiss which is similar to Gierałtów, but does belong to the Śnieżnik Formation.

DISCUSSION

ZIRCON MORPHOLOGY

Most of the zircon grains analysed by us show core-to-rim oscillatory zoned structure. The xenocrystic cores range from clear, uniform prismatic grains with oscillating zonation to subround grains with relics of oscillatory, sector or planar zoning. Newly formed zircon rims may be in optical continuity or separated from the cores by more or less legible discontinuities, across which they differ in crystallographic orientation. Such discontinuities may have developed during interactions between crystal faces and younger fluids, whether magmatic or metamorphic. The activity of the latter was possibly enhanced by tectonic deformation.

Moreover, there are differences between samples from the Gierałtów and Śnieżnik formations. In the Śnieżnik augen gneiss (OS47) and in the migmatitic xenolith (OS5) enclosed within it, numerous grains have cores with distorted internal structure and convolute, sector or oscillatory zonation. These cores have highly irregular, embayed or broken outlines being surrounded by dark or bright in CL, poorly oscillatory zoned to non-zoned outgrowths (Figs. 8 and 9).

Such features are usually taken to indicate resorption, corrosion and dissolution processes occurring before and/or during the development of the overgrowths under both magmatic and metamorphic conditions. Having considered isotopic data, CL images of zircons, petrological characteristics, field relationships and structural features of the host rocks, we are in favour of the metamorphic/migmatitic conditions to explain the evolution of the host rocks for samples OS47 and OS5.

In general, the above features can also be linked to various stages of complex magma evolution from the initial formation by source melting, migration through the crust, to magma mixing, fractional crystallisation and differentiation. In case of the Śnieżnik orthogneisses, the extensive presence of the ~340 Ma new zircon outgrowths interpreted as the product of magmatic crystallisation would require that the Śnieżnik magma intruded at that time. Such corollary is entirely incompatible with the local geology and other results of isotopic studies. Conversely, all these features can also develop during various stages of crystallisation from a locally derived melt (migmatitic) or hot supercritical fluids (in this case U-rich) interacting with the rock at the peak or high-grade metamorphic conditions, usually in the presence of an active aqueous phase (see Gebauer et al., 1997; Corfu et al., 2003; Geisler et al., 2007). In very fluid-rich systems, newly formed components will crystallise with usual characteristics of magmatic zircon; i.e. with similar morphology (euhedral/subhedral shape) and zoning (oscillatory). Morphology and textures of magmatic and migmatitic zircons in peraluminous rocks may be undistinguishable (Hoskin and Schaltegger, 2003) and we do not have a simple distinguishing criterion for the origin of dated zircons. Therefore, we see the need for integrating data collected along various lines of evidence. In our opinion, all the collected data favour the migmatitic hypothesis for the zircon origin in the three studied samples from the Gierałtów Gneiss Formation.

In view of the above and the absence of noticeable traces of the ~340 Ma components in the three samples from the Gierałtów Gneiss Formation studied by us, we suggest that metamorphic transformations in the gneisses of the Międzygórze Antiform were not a wholesale process and thus they varied within this structure, being strongly assisted by hot, U-rich fluids. Our observations show that such fluids were likely to be more easily channelized through the coarse-grained metagranite with strong constrictional fabric (L > S tectonite) than through the multiply deformed Gierałtów gneisses with the twice folded planar fabrics. Such explanation is in line with the lack or scarce presence of very thin dark CL rims, which might record weak Carboniferous overprint in these rocks.

STRUCTURAL RECORD *VERSUS* GEOCHRONOLOGY

The brief structural review presented in this paper (see above) indicates that the Gierałtów (migmatitic) Gneiss Formation has undergone more complex evolution (D1–D4) than the Śnieżnik augen orthogneisses (D2?/D3–D4). Samples of the streaky (OS40) and porphyroblastic (MD46) Gierałtów gneisses (Fig. 3B, D) represent twice folded rocks, accompanied by syn- to post-tectonic migmatisation with respect to D2 (Redlińska-Marczyńska, 2011). The latter produced leucosomes of various shapes, leucocratic veins (sample OS35/8) and aggregates as well as K-feldspar blasts located in F2 fold hinges, and giving a porphyroblastic outlook (MD46) to streaky (OS40) or flaser Gierałtów gneisses.

Besides the differences between the Gierałtów and Śnieżnik gneisses in the features of zircon grains, also observed in zircon typology (Turniak et al., 2000), these rocks further differ with the presence of skeletal Ca-garnets (inherited xenocrysts), Si-rich phengites, ilmenite and high-Al titanomagnetite. The latter can be interpreted as indicators of HP-HT episode inferred for the Gierałtów Gneiss Formation (Borkowska et al., 1990; Bröcker and Klemd, 1996; Grześkowiak, 2004; Stawikowski, 2006; Redlińska-Marczyńska and Żelaźniewicz, 2011; Chopin et al., 2012a) and thus in migmatitic xenoliths enclosed within the Śnieżnik metagranite.

In the twice folded and migmatised Gierałtów gneisses, the zircons yielded the mean ages of 500 ± 3 Ma and 498 ± 4 Ma for wide outer parts of the grains. As only few grains have very thin, dark in CL, metamorphic rims – probably of Carboniferous age – the question arises as to which of these zircon overgrowths reflect metamorphism and migmatisation in the gneisses: extremely thin and Th/U low rims, or rather voluminous, oscillatory zoned (igneous/metamorphic in appearance and higher Th/U ratio) ~500 Ma mantles. Again, having considered isotopic data, CL images of zircons, petrological characteristics and field relationships of the host rocks, the discordant leucocratic vein OS35/8 inclusive, we find the option of migmatisation of the Gierałtów gneisses at ~340 Ma rather unlikely and therefore we are in favour of the option of migmatisation at ~500 Ma. Naturally, this does not preclude Carboniferous metamorphic overprint in rocks of the Międzygórze Antiform, however, more localized and less pervasive than is commonly thought (Turniak et al., 2000; Štípská et al., 2004; Lange et al., 2005; Bröcker et al., 2009). We do not support the view that the petrographic and mineral compositional variability of gneisses was mainly caused by modifications accomplished during deformation and migmatisation, as assumed by those authors.

The Śnieżnik augen gneiss in sample OS47 is L > S tectonite, with genuine augen porphyroclasts derived from original K-feldspar phenocrysts during gneissification (Figs. 4A and 15). It developed at lower metamorphic conditions than those recorded by the Gierałtów migmatitic gneisses as indicated by higher Mn content in garnets, lower Al content in titanites, and lower Si content in phengites. Magmatic origin of this weakly deformed rock is evident from its mesoscopic and microscopic structural and petrographic features, which is corroborated by morphology of zircon grains, being oscillatory zoned and bright under CL (Figs. 8 and 15). Both cores and most of overgrowths in such grains yielded ~500 Ma age, interpreted to record the emplacement of a granitic precursor to the Śnieżnik augen gneiss. Similar results were obtained for the zircons from the migmatitic gneiss xenolith (sample OS5) enclosed within the Śnieżnik rodded (L > S) orthogneiss. As xenoliths are to be at least slightly older than the host igneous rock, the observed geological relationships directly suggest that in the xenolith which was entrapped in the granite magma, most of the zircon grains carried by the gneiss became entirely resorbed, thus no inheritance was detected in the studied population. However, quite probably that more analyses would reveal older components too. Having confronted both the estimated age and features of the discussed zircons against the migmatitic nature and geological position of the gneiss xenolith, the corollary is that the latter must have undergone thorough zircon recrystallisation around ~500 Ma, thus coevally with the formation and emplacement of the porphyritic precursor of the Śnieżnik augen gneiss. In case of the Międzygórze Antiform, this directly confirms the presence of rocks metamorphosed and migmatised at ~500 Maand indirectly the original differences between gneisses of the two formations, the view advocated by Redlińska-Marczyńska and Żelaźniewicz (2011).

Important information rendered by sample OS40 is that the Gierałtów Gneiss Formation is lithologically heterogeneous and comprises metasediments. Such conclusion sheds new light on the ongoing discussion on the origin of gneisses in the Orlica-Śnieżnik Dome and invalids the hypothesis about one magmatic source.

CAMBRO-ORDOVICIAN TECTONOTHERMAL EVENT ACCOMPANIED BY MIGMATISATION

The problem of Cambro-Ordovician event in the Orlica–Śnieżnik Dome was discussed by Lange et al. (2005), who did not find enough arguments to support migmatisation at that time. However, Přikryl et al. (1996) reported evidence for the pre-Variscan HT deformation and metamorphism in gneisses in the western part of the dome. Then Żelaźniewicz et al. (2006) described twice folded, fine-grained migmatitic gneisses which carried a later shear overprint at the contact with the Śnieżnik augen orthogneiss at the village of Zdobnice (Fig. 1). It was the very shearing that built up foliation in the metagranite. Deformation history of the latter is evidently shorter than in the migmatite. Such critical field relationships provide straightforward evidence that deformation and neosome formation in the migmatite occurred earlier than the common, yet heterogeneous shearing experienced jointly by the two types of gneisses. Elsewhere in the dome, such shearing was constrained with various methods to a span of 340–325 Ma (review in Żelaźniewicz et al., 2014a, b). In Zdobnice, additional constraint comes from a discordant unfoliated syenite vein dated (U-Pb zircon) at 326 ± 3 Ma (Żelaźniewicz et al., 2006), thus the shearing there and the foliation build-up in the metagranite took place before 326 Ma, most probably between ~340 and ~330 Ma. In view of the integrated field, structural and zircon data (Żelaźniewicz et al., 2006), it is rather unlikely that migmatites might have been selectively developed, folded, then sheared and dynamically recrystallised in the same time span. Therefore, an U-Pb age of 489 ± 12 Ma ($n = 12$, MSWD = 6.5) for the poorly zoned outgrowths, some dark in CL, on older (Ediacaran–Early Cambrian) cores in zircon grains from a granitic neosome in the Zdobnice migmatite is interpreted as a record of migmatisation in the Late Cambrian–Early Ordovician. Although the precision of the date is not high, it is still good enough to indicate that the outgrowths can only be linked with tectonothermal processes which occurred at those times. Such view concurs with the fact that the studied zircon population does not contain evidence for any younger events which would lead to zircon mobilisation.

Bröcker et al. (2009) doubted the early migmatisation in Zdobnice by suggesting that the zircon grains in the neosome are residual and retained from the migmatised source rocks. This is probably very true and in no way invalidates the conclusion about the Cambro-Ordovician migmatisation in the twice folded gneisses from which the granitic neosome was derived. Although in the studied grains only ~500 Ma outgrowths were found. They provide the unambiguous evidence that zircon grains in these gneisses were extensively recrystallised at that time, because the rocks were just undergoing metamorphic transformations including migmatisation.

The above-mentioned situation in the Zdobnice migmatite (= Gierałtów gneiss) is similar to that observed in the studied samples from the Gierałtów Formation. The discordant leucocratic vein of sample OS35/8 is equivalent to the granitic neosome of the Zdobnice migmatite, whilst samples OS40 and MD46 represent the residuum or palaeosome. We reckon that correct interpretation of partially melted rocks requires not only U-Pb zircon age and morphology information but also careful examination of the field relationships and structural history of the rocks under study. Such appropriately multi-aspect approach is particularly important while dealing with the complex gneiss core of the Orlica–Śnieżnik Dome with prolonged history (Fig. 15).

CARBONIFEROUS EVENT

In several recent papers that report results of the isotopic analyses of gneisses in the Orlica–Śnieżnik Dome, the general conclusion, based on isotopic age and chemistry, is that these rocks: (1) had common metasedimentary protolith, (2) came, possibly in a few batches, from a single magma source, (3) intruded to form an extensive granite body at ~500 Ma, (4) were

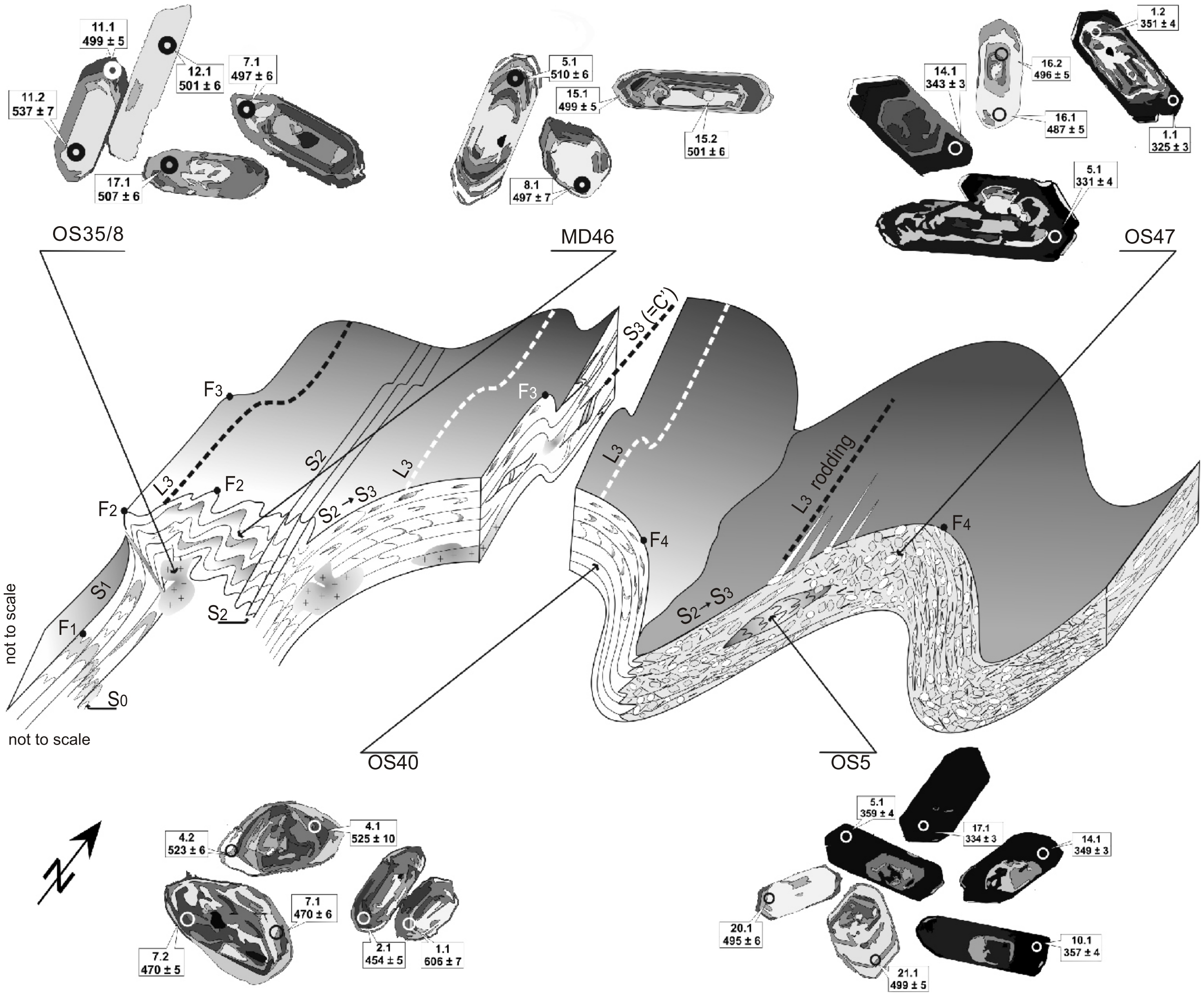

Fig. 15. Structural diagram to show interrelationships of successive mesostructures recognized in gneisses of the Międzygórze Antiform (Redlińska-Marczyńska and Żelaźniewicz, 2011), positions of the studied samples and details of the analysed zircons

The Śnieżnik augen gneisses marked in dark grey, all the other gneiss types (the Gierałtów gneisses) in white; S – planar structures; L – linear structures; F – folds; white – quartz, grey – K-feldspar, tonal filling – quartzo-feldspathic segregations (metablasts and leucosome), tonal filling with crosses – leucosome nests; the isotopic data have been interpreted in conjunction with all transformed to gneisses from the original granites by diversified deformation, metamorphism and migmatisation that occurred around ~340 Ma (Turniak et al., 2000; Lange et al., 2002, 2005; Štipská et al., 2004; Bröcker et al., 2009). However, detailed integrated studies of the topics under point (4) are scarce. Very few papers present structural characteristics of the gneisses (Cymerman, 1997; Chopin et al., 2012a; Żelaźniewicz et al., 2013) and each deals with another aspect of it. A more integrated approach was attempted by Redlińska-Marczyńska (2011) and Redlińska-Marczyńska and Żelaźniewicz (2011), and needs to be continued.

This study shows that the problem of ~340 Ma migmatisation, which does not exist or is very minor in the three samples of the Gierałtów Formation, becomes quite apparent in two samples from the Śnieżnik Formation. In contrast to the Gierałtów samples, both the weakly deformed metagranite (OS47) and migmatitic xenolith (OS5) enclosed in it, rather surprisingly revealed the extensive presence of ~340 Ma zircon components in the form of thick rims. It appears as outgrowths on either undistorted or distorted and resorbed cores dated at ~500 Ma. The most commonly observed features are irregular domains (convolutions, blurs and transgressive lobes) of homogeneous low-U zircon which cuts discordantly across the oscillatory zoned older domains (Figs. 8, 9 and 15). Such features are thought to develop by recrystallisation in the presence of aqueous fluids in deep-seated settings, for instance during late to post-magmatic cooling (Pidgeon and Compston, 1992; Nemchin and Pidgeon, 1997; Schaltegger et al., 1999), due to metamorphic recrystallisation in the solid state (Hoskin and Black, 2000; Corfu et al., 2003) or during the partial melting (Song et al., 2014). Younger ages in the range ~488–463 Ma for cores in such double structured grains were likely due to alteration caused by later Zr-carrying and significantly U-enriched fluids. Our interpretation of the new isotopic data is consistent with the structural observations and is not at odds with current knowledge about zircon behaviour and U-Pb systematics under various crustal processes.

Having reconciled the aforesaid information from the zircon systematics and morphology with the geological situation of these samples, we expect that the fluids were metamorphic rather than igneous. In the weakly deformed rodded augen gneiss and the xenolith, no evidence of the presence of magmatic melt was observed (Figs. 4A, B, D and 15) and the wide oscillatory zoned CL structure in the rims does not prove unambiguously crystallisation from a melt, either. A consequence of the opposite conclusion would be that the Śnieżnik granite crystallised from a melt that intruded at ~340 Ma, which is extremely unlikely.

Following the lithologic-structural criteria for the classification of gneisses in the Orlica–Śnieżnik Dome – the one proposed by Redlińska-Marczyńska and Żelaźniewicz (2011) or even those used by Chopin et al. (2012a), there is no evidence in the Śnieżnik augen gneiss (~"type I" *sensu* Chopin et al., 2012a) that might be taken to support any igneous or partial melting event, or melt extraction after its granite precursor was emplaced in the crust. In contrary, the field evidence shows that migmatitic xenoliths were enclosed in the granitic protolith and these must have developed prior to, or coevally with the host granite, but not later than its final emplacement high in the continental crust.

In view of the above, we reckon that the situation observed in samples OS47 and OS5 is quite instructive. Taking into account the extensive metamorphic recrystallisation of zircon grains in the evidently least deformed and least transformed ~500 Ma metagranite in the Carboniferous, similar processes may be expected to have occurred in other felsic rocks and at other times. We do suggest that this is what actually took place and may be observed in the zircon populations retrieved from the three samples of the Gierałtów Formation, but the degree of recrystallisation and replacement was significantly higher in the Late Cambrian–Early Ordovician. Precursors of the Gierałtów rocks are likely to have been reworked at that time. Rocks akin to those of the Gierałtów Formation occur as xenoliths of various dimensions within the ~500 Ma Śnieżnik (meta)granites transformed to augen orthogneiss during the Variscan event.

COMPARISON WITH PREVIOUS ISOTOPIC RESULTS

It is worth to note that our results partly confirm those obtained by Turniak et al. (2000) for the Śnieżnik and Gierałtów gneisses in the Międzygórze Antiform. The two samples studied by them came from different locations than our samples, but it should be emphasized that sample OS47, although less gneissified, is similar to sample M10 of the Śnieżnik augen gneiss dated by Turniak et al. (2000). However, the ~340 Ma zircon components are much more abundant and more diversely represented in our sample. In their sample, only two analyses of high-U, black CL rims on ~540 Ma cores yielded ages of 327 ± 15 Ma and 336 ± 7 Ma. The latter were interpreted as the timing of Carboniferous metamorphic overgrowths. Such interpretation actually concurs with ours.

In contrast, our results for the Gierałtów Formation rocks significantly depart from that of Turniak et al. (2000). It is not too surprising, given the discrepant gneiss classification used by different authors (review in Żelaźniewicz et al., 2014a, b). Judging from the published photograph and description of localisation, sample M16 collected by Turniak et al. (2000), although fine-grained, is a highly sheared and mylonitised gneiss which differs from the Gierałtów rocks studied by us. This gneiss is actually very similar to "type-III" mylonitic orthogneisses distinguished by Chopin et al. (2012b) but controversially interpreted by them as a HT-HP product of mylonitisation of the Śnieżnik granite. In our opinion, based on the detailed field observations and on the observed structural sequence in the Międzygórze Antiform (Fig. 15), the "type-III" orthogneisses are actually mylonites once entrapped by the Śnieżnik granitic magma and repeatedly sheared later jointly with the host metagranite. In other words, they are enclaves and thus their geological position in the Międzygórze Antiform is actually similar to that of the xenolith OS5. Having acknowledged this observation, the zircon systematics from our sample OS5 and sample M16 of Turniak et al. (2000) appear strikingly compatible. In both there are similar features: sector zoned or unzoned zircon cores, distorted and corroded cores with two age groups ~540–500 Ma and 480–430 Ma due to evident Pb* loss, metamictisation, wide dark CL unzoned outgrowths, and thin black CL rims. Therefore, we propose that the geological reinterpretation for sample M16 may be similar to our sample OS5.

Our criticism to Chopin's et al. (2012b) attempt of classification of gneisses in the Międzygórze Antiform focuses on the unsatisfactory one-sided approach which neglected all earlier proposed classifications, including the major subdivision into the Śnieżnik and Gierałtów types. Three types of gneisses proposed by these authors differ by the amount of deformation and metamorphism in the arbitrarily assumed prograde transformation from initial granite. They estimated that the least deformed orthogneisses (= type I = Śnieżnik augen gneiss) underwent metamorphism at pressures <15 kbar and temperatures <700°C, whereas the other two types, more strongly deformed, equilibrated at ~20 kbar and temperatures >700°C. Not entering the problem of relevant geological models, such results suggest that the gneisses were metamorphosed under different conditions and at different depths. Field observations show, however, that they presently alternate in a single exposure as lenticular bodies even <2 m thick (Fig. 3F), thus the question arises how they got into mutual contacts.

Chopin et al. (2012a) proposed that the three types of gneisses were equilibrated at different P-T conditions along a prograde path during the burial of the continental crust. In contrast, Štípská et al. (2012) suggested that all the gneisses were formed and folded together with eclogites during the HP event and then, in the course of exhumation, were heterogeneously re-equilibrated with metastable leftovers in which HP mineral relicts were preserved. Not sharing fully this proposition, we suggest that such leftovers are among the enclaves once embraced by porphyritic granite magma. Our view is based on the studies of a variety of enclaves occurring within the Śnieżnik augen gneisses (Redlińska-Marczyńska and Żelaźniewicz, 2011). It is also consistent with the striking similarities between the xenolith sample dated by us and the rock analysed by Turniak et al. (2000).

Chopin's et al. (2012a) proposition assumes that gneisses got into the present metasedimentary surroundings by extrusion of migmatitic diapirs through steep crustal channels. Actually, this is a pretty old view, originally expressed by Don (1964) and further explored by Don et al. (1990, 2003), Štípská et al. (2004, 2012), Pressler et al. (2007), Schulmann et al. (2008) or Chopin et al. (2012b). However, the relevant steep or dip-plunging stretching lineation, to which these authors refer, has not been observed by us in the gneisses of the Międzygórze Antiform. In contrast, the subvertically oriented foliation does exist, however not in such channels, as suggested by these authors, but in the short, steep limbs of the E-verging folds (see Figs. 4B and 15; Redlińska-Marczyńska, 2011; Redlińska-Marczyńska and Żelaźniewicz, 2011; Żelaźniewicz et al., 2014a for details), which can hardly support diapirism in the antiform.

In general, our data confirm the earlier results which interpreted the Śnieżnik gneisses as a ~500 Ma S-type granite (with heterogeneous ~340 Ma metamorphic overprint) ultimately derived from the mainly metasedimentary Neoproterozoic crust (600–540 Ma). Dates obtained from the xenocrystic zircon cores in the Gierałtów gneisses also point to the reworking of ~635–535 Ma (Cadomian) crust containing inherited 2.2–1.8 Ga components. Similar age clusters have been reported from the 485 ± 12 Ma Zdobnice migmatites in the western part of the Orlica–Śnieżnik Dome (Żelaźniewicz et al., 2006).

GEODYNAMIC SETTING

Although our analyses point to the significance of the ~500 Ma period, we treat this date as a record of a pronounced mid-term event rather in the process of longer duration. Taking into account other published data, even limited to U-Pb zircon ages only along with the error limits, it appears that the process might have presumably occurred between ~513 Ma (511 ± 2 Ma, Kröner et al., 2000; 495 ± 14 Ma, Turniak et al., 2000; 507 ± 17 Ma, Lange et al., 2005) and 476 Ma (488 ± 12 Ma, Żelaźniewicz et al., 2006; 491 ± 12 Ma, Lange et al., 2005). Such ~40 m.y. long time span is of reasonable duration for an intraplate rifting and subsequent build-up of a magmatic arc accompanied by back-arc extension, which is the scenario commonly used to explain Early Paleozoic history of the Orlica–Śnieżnik Dome in particular, the Sudetes and the NE part of the Bohemian Massif in general. The Palaeo-Tethys Ocean subducted beneath the Gondwana plate, and the future dome was located at its margin in a magmatic arc position.

We expect that the Late Cambrian to Early Ordovician tectonothermal event, which included granitic intrusions and contractional deformation, was more significant and complex than hitherto thought. Similar observation was also reported from other parts in the Bohemian Massif. For instance in the Teplá Crystalline Complex, Peřestý et al. (2015) found evidence that the 505 Ma granite intrusion was followed by regional deformation and metamorphism in the country rocks already at 485 Ma, in a pre-Variscan event.

Given the data and arguments presented above, we propose that the two gneiss formations in the Orlica–Śnieżnik Dome were originally derived from Cadomian crustal rocks accreted to an active margin of northern Gondwana between 635 and 535 Ma. Rifting in a back-arc setting allowed deposition of the Młynowiec–Stronie Group sedimentary-volcanogenic succession, which ceased before the Late Ordovician (Jastrzębski et al., 2010; Żelaźniewicz et al., 2014a, b). The Cadomian crust was thinned and deformed, while mantle-derived heat led to its partial melting, migmatisation and anatexis. This process conceived the Gierałtów Gneiss Formation and eventually gave rise to calc-alkaline, K-rich, porphyritic, S-type granites with the supra-subduction signature (see discussion in Pin et al., 2007) that intruded at ~515–475 Ma as protolith of the Śnieżnik Augen Gneiss Formation. Such a scenario explains both the observed major isotopic and geochemical similarities and numerous minor, yet significant differences between rocks of the two formations. Scarce, yet existing relicts of intrusive contacts of granitic precursor of the Śnieżnik orthogneisses locally emplaced in the Gierałtów migmatitic gneisses (Figs. 2A, B and 4C, details in Redlińska-Marczyńska and Żelaźniewicz, 2011) provide the key geological evidence of the relationships between the gneisses in the Orlica–Śnieżnik Dome. Unfortunately, it may pass unnoticed because of obliterations by later processes. Our structural observations summarized in a model blockdiagram (Fig. 15) easily explain why gneisses of both the formations carry significantly different structural records. They also explain why the Śnieżnik orthogneisses were less deformed and became metamorphosed at P-T conditions lower than those estimated for the Gierałtów gneisses. Eventually, our model observes the rule that granitic melts tend to acquire less diversified aspects, lithological, petrographic, isotopic, and structural or else, than the source rocks.

In a more general view, all the above-mentioned phenomena were likely driven by heat from an upwelling mantle wedge and decompression in the back-arc environment. Having considered also the isotopic ages determined for metarhyolites set in the Młynowiec–Stronie Group (Murtezi, 2006; Jastrzębski et al., 2010, 2015; Mazur et al., 2013), one may assume that this regime was active at least at ~515–475 Ma. Crustal thickening due to the Variscan collision brought about the vertical flattening and resulted in regional metamorphism under amphibolite facies conditions that climaxed at ~340 Ma, as demonstrated by practically all published isotopic studies. We suggest that the OSD gneisses variously responded to those conditions, especially the earlier migmatised and equilibrated Gierałtów gneisses.

CONCLUSIONS

The most important conclusions of this study are as follows:

1. In the Międzygórze Antiform, earlier observations of noticeable differences in derivation and evolution between rocks of the Gierałtów and Śnieżnik gneiss formations have been further confirmed.
2. Among protoliths of the varied Gierałtów rocks are paragneisses, while the compositionally less heterogeneous Śnieżnik rocks are exclusively orthogneisses and their granitic protolith intruded the former and similar rocks at ~500 Ma.
3. Early deformation and metamorphism›migmatisation in the Gierałtów rocks occurred slightly prior to and coevally with the intrusion at ~515–475 Ma; the Śnieżnik rocks have shorter and less complex structural history.

4. In the folded migmatitic Gierałtów rocks, more or less zoned outgrowths, aged ~500 Ma, developed on older zircon xenocrysts, the zonation being furnished by fluids relating to partial melting.
5. Both gneiss formations then underwent jointly a tectonometamorphic episode at ~340 Ma, to which their responses differed to some extent, being controlled by early and later acquired differences.
6. The ~340 Ma event was assisted by Zr-carrying and significantly U-enriched fluids. Their operation was much impeded in the multiply folded, fine-grained migmatitic Gierałtów gneisses that possessed two foliation sets. In contrast, it was significantly enhanced in the coarse-grained augen Śnieżnik gneisses, which acquired then a constrictional L-type fabric in the hinge zones of large-scale folds, and in the accompanying shear zones. Therefore, in the Gierałtów rocks, none or at most very poor U-rich zircon rims developed on the 500 Ma zircon grains, whilst in the Śnieżnik rocks the 500 Ma zircon grains acquired quite extensive, more or less zoned outgrowths.

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