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The Orlica–Śnieżnik Dome, the Sudetes, in 2002 and 12 years later

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Abstract During the 2002 meeting of Czech, Polish and Slovak tectonic community in Żelazno, the Sudetes, the Central European Tectonic Studies Group (CETeG) was established. 12 years ago, participants of the meeting made an excursion to the eastern part of the Orlica–Śnieżnik Dome (OSD), which was focused on a variety of gneisses with inserts of (U)HP eclogites and various enclaves. The 2014 meeting brought members of the CETeG to the OSD again and an accompanying field excursion was dedicated mainly to evolution of metasedimentary and metavolcanogenic rocks in the region. This paper is a short review of the results of the studies undertaken in the OSD by different research groups in the last 12 years. The review is set against a background of what we knew about the geology of the dome in 2002. A significant progress was made. P-T paths were determined for mica schists and marbles as well as for metarhyolites originated from the continental crust and metabasites derived from the mantle. New light was shed on the origin of various types gneisses in the OSD and their genetic and structural relationships. A plethora of isotopic studies helped to better constrain timing of igneous and metamorphic events in the Orlica–Śnieżnik complex. Ages clustered around 350–340 Ma are repeatedly obtained, yet scarcer older ages up to 390 Ma and their geological significance are open to debate. Tectonic evolution of the dome was revised and new geodynamic concepts were proposed. However the new data has created some new problems and some old problems are still to be resolved in the future.

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INTRODUCTION

The 2002 meeting in Żelazno, when the Central European Tectonic Group was established, was accompanied by an excursion to the eastern part of the Orlica–Śnieżnik Dome (OSD). In the guide-book, a short account of the geology of this part of the dome was provided under the title “The Lądek–Śnieżnik Metamorphic Unit – Recent State of Knowledge” (Żelaźniewicz *et al.*, 2002). Such review was intended to help to identify what we knew by that time, what was poorly known and thus remained debatable or controversial, and what was unknown and thus worth to be studied in the future.

Having returned after 12 years in the same region, it is natural to review an advancement of knowledge on a geological evolution of the OSD which has been made over this period owing to the efforts of domestic, foreign and international teams that were interested in this intriguing region. We wish to realize what progress has been made in solving or clearing up and explaining geological problems encountered here.

The 2002 excursion focused more on a variety of gneisses with inserts of (U)HP eclogites and including enclaves. This year we focus more on mica schists, paragneisses, quartzites and bimodal volcanogenic rocks which are assigned jointly to the Młynowiec–Stronie Group. These rocks were progressively metamorphosed up to mid-amphibolite facies conditions, multiply deformed and refolded with gneisses.

The OSD happened to be geologically divided into two parts in the Late Cretaceous when the N–S trending Upper Nysa Graben was formed and then inverted in Santonian/Campanian–Paleocene times (Fig. 1). Although basement rocks continue under the Cretaceous graben, it is practical to refer to the western and eastern parts of the dome that may also be viewed upon as limbs of the dome, respectively. Geology of basement rocks from the two parts will be discussed during a pre-conference excursion. A post-conference excursion will bring participants to Upper Cretaceous rocks and records of tectonic evolution of the Nysa Graben in Late Cretaceous–Cenozoic times.

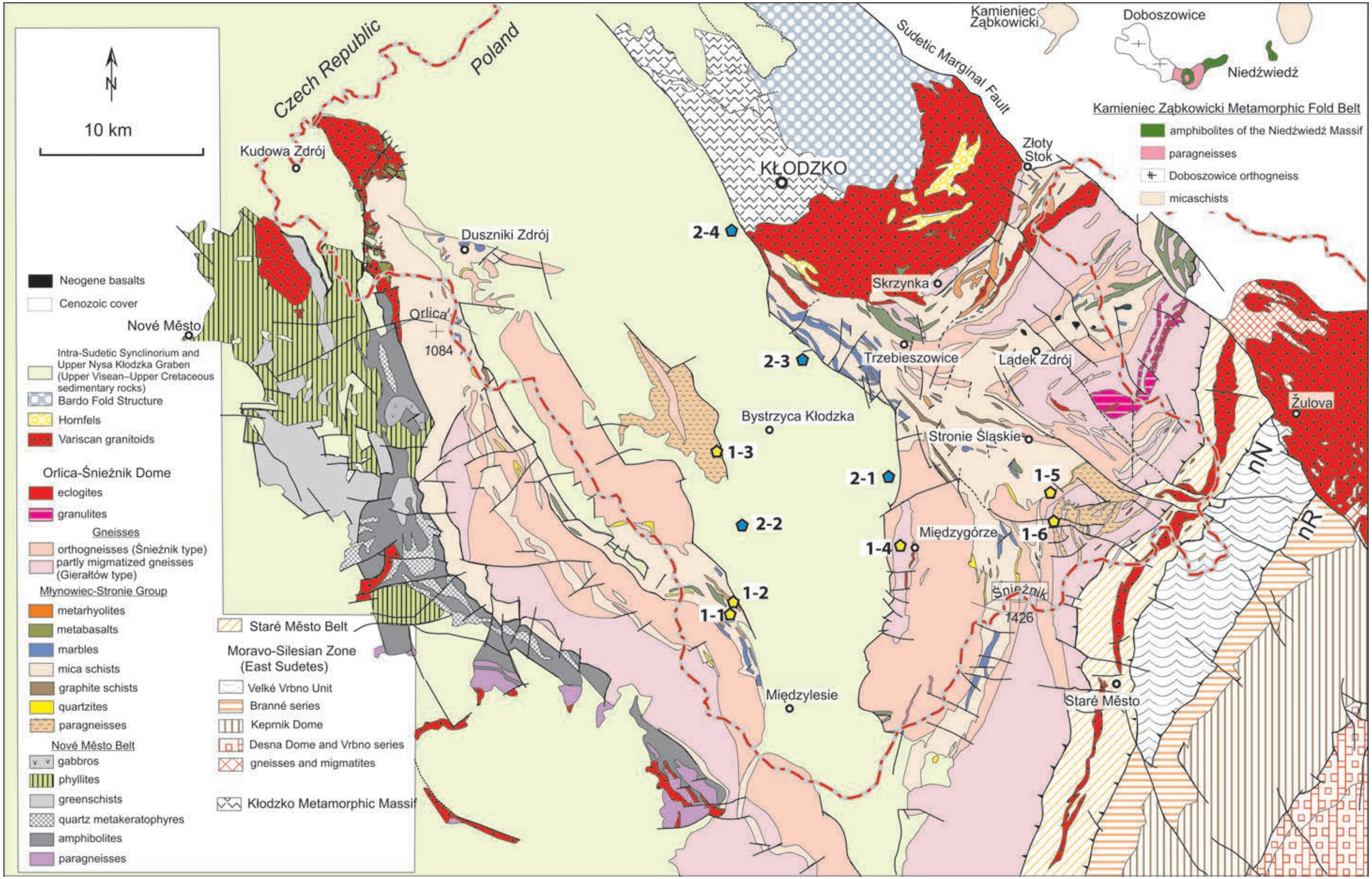

Fig. 1. Map of the Orlica–Śnieżnik Dome and the Upper Nysa Kłodzka Graben with locations of pre-conference (yellow) and post-conference (blue) excursion stops (after Żelaźniewicz, 2006, modified).

WHAT WAS KNOWN IN 2002

Metasedimentary–metavolcanogenic mantle

Lithostratigraphy and geochronolgy

A domal structure of the OSD is expressed by a gneissic core and a schistose, metasedimentary mantle (Fig.1). The latter lithostratigraphically belongs to the ~6000 m thick Młynowiec–Stronie Group represented by two formations assigned to the Late Neoproterozoic(?)–Cambrian on the basis of micropaleontological findings (Gunia, 1974; Gunia & Wierzchołowski, 1979; review in Don *et al.*, 1990). At the base of the group, the Młynowiec Formation occurs, a monotonous unit of greywacke derived paragneisses that outcrop only in the NE part of the dome (Fig. 1). Stratigraphically higher and spread throughout the entire OSD is the Stronie Formation, a varied unit of mainly pelitic rocks, accompanied by bimodal volcanogenic rocks, carbonates and quartzites. Rocks of the entire group were metamorphosed up to staurolite and locally kyanite/sillimanite grade, with metamorphic gradient increasing to the east and southeast (Don *et al.*, 1990).

The Młynowiec Formation is a ~ 2000 m thick succession of two-mica paragneisses with minor mica schists and amphibolites. A protolith of paragneisses were polymict greywacke sandstones to mudstones (Ansilewski 1966; Smulikowski, 1979).

The Stronie Formation is a ~4000 m thick succession of mica schists, marbles, light and graphitic quartzites, massive and schistose acid metavolcanic rocks, schistose and massive amphibolites, and paragneisses. It seemed that quartzites are polygenetic rocks. Some of them presumably represented (1) mature shallow-water deposits as inferred from its composition and contents of accessory minerals (Gunia, 1984; Smulikowski, 1979), (2) mylonitic schists with scarce relic K-feldspar porpyroclasts derived from highly sheared orthogneisses (Żelaźniewicz, 1984; Cymerman, 1997) or (3) schistose silicic metavolcanic rocks characterized by locally significant content (20–30 vol. %) of K-feldspar porphyroclasts (Butkiewicz 1972; Smulikowski, 1979). Variety (2) occurs in proximity to augen orthogneiss bodies. Variety (1) is more abundant close to outcrops of the Młynowiec Formation. A quartzite layer that occurs at the boundary between the two formations is interpreted by some authors as the basal horizon of the Stronie Formation (Vangerow, 1943), which unconformably overlies the Młynowiec Formation (Fischer, 1936, Don & Dowidar, 1990; Don *et al.*, 1990). On the other hand, the Młynowiec–Stronie Group, together with quartzites, can be related to a single and continuous volcano-sedimentary succession (e.g. Wojciechowska, 1993; Smulikowski, 1979). These views required further testing and confirmation.

Crystalline limestones and dolomites (e.g. Butkiewicz, 1968; Witek, 1976) are interbedded with or occur amidst mica schists as compact bodies that may have been former reefs which were built up on submarine (volcanic) highs (Gunia, 1997; Koszela, 1997) or on a platform of the passive continental margin (Karwacki, 1990). Marbles are distributed irregularly through the OSD where they form either lensoid-shaped bodies or elongated interlayers several meters up to 400 meters thick within mica schists and amphibolites of the Stronie Formation (e.g. Kasza, 1964; Don, 1982; Sawicki, 1995). Distinct lithological contacts with adjacent rocks allow to trace tectonic structures on different scales. In the eastern part of the OSD, north- to northwest-plunging, SW-vergent folds were recognized (Kuźniar, 1960; Don, 1964; Oberc, 1964; Karwacki, 1990).

Palaeontological data for marbles, quartzites and paragneisses (Gunia, 1997 and references therein), although controversial, suggested Late Proterozoic–Early Cambrian age of the Stronie Formation and deposition in an ensialic basin that most likely developed on the Cadomian basement. Koszela (1997) indicated the Paleozoic age of marbles of the Stronie Formation in view of the relics of shell fossils preserved in these rocks. Unpublished results of Pb-Pb datings of two zircon samples from acid metavolcanic rocks yielded the age of 521 Ma (Kröner *et al.*, 1997), which pointed to (bimodal) volcanic activity at middle Cambrian times.

Geochemistry of volcanogenic rocks

Metabasites were linked either to a volcanic arc (Wojciechowska, 1986) or to an ensialic rift setting with limited crustal attenuation that never reached true oceanic stage (Floyd *et al.*, 1996, 2000). Nowak & Żelaźniewicz (2002), however, distinguished metabasites of WPB type that pass laterally to the Stronie mica schists with which they were tightly folded and metabasites of MORB-like signature that occur within the schists as more massive and sharply delineated bodies, interpreted as former volcano feeders and lava flows.

Silicic metavolcanogenic rocks, classified as leptites appeared to have been derived from mainly rhyolitic tuffs, tuffites and lava flows that were geochemically similar to orthogneisses (Wojciechowska, 1972, 1989; Wojciechowska *et al.*, 2001; Murtezi, 2002). Therefore they were interpreted as volcanic/subvolcanic edifice of the ~500 Ma granite plutonism that occurred deeper in the crust which was subjected to extension due to back-arc rifting. Tectonometamorphic history legible in schistose metarhyolites concurred with that of the Stronie mica schists (Wojciechowska,1972, 1989; Murtezi, 2002).

Metamorphism

Rocks of the Młynowiec–Stronie Group underwent a Barrovian-type metamorphism at the amphibolite-facies conditions. Smulikowski (1979) and Grzechnik (1989) found that staurolite grew in the expense of chloritoid in garnet-bearing mica schists, and this reaction indicates a prograde evolution from low grade (200°C, 3 kbar) to medium-grade (500–550°C, max. 7 kbar). Metabasites were also progressively metamorphosed under amphibolite facies conditions of 550–650°C and 5,5–6,4 kbar (Wojciechowska, 1986). Marbles underwent metamorphism at conditions of ca. 500–530°C (Koszela, 1997), possibly associated with a fluid flow resulting in local transformation of carbonate rocks into calc-silicate rocks (Teisseyre, 1959;

Banaś, 1962). The observed distribution of epidote, Ca-amphibole and Ca-pyroxene suggests a higher metamorphic grade of marbles located in the eastern part of the OSD (Karwacki, 1990). The first who recognized and mapped folded metamorphic isograds in rocks of the western limb of the OSD and the adjacent Nové Město complex were Opletal *et al.* (1980). They found that metamorphic grade increased from the chlorite–biotite to staurolite grade, from the northwest to the southeast and east.

Geothermobarometry applied to rocks of the Młynowiec Formation indicated a higher grade of metamorphism than the adjacent rocks of the Stronie Formation (Józefiak, 1998). The P-T work by Józefiak (1998) on the Młynowiec Formation yielded temperatures of ~590°C and pressures of ~7.5 kbar. In the NE part of the OSD, the metavolcano-sedimentary rocks were locally transformed into hornfelses due to the emplacement of the Kłodzko–Złoty Stok granitoids (e.g. Wierzchołowski, 1976). Structural and metamorphic studies of the Stronie rocks near Javornik (Romanová & Stipska, 2001) revealed that they were buried to a depth corresponding to ~8 kbar (~600 °C) and subsequently nearly isothermally uplifted. The P-T estimations correspond to those determined for mica schists in the Złoty–Stok Skrzynka Shear Zone (Murtezi, 2002). The peak metamorphic conditions experienced by mica schists were calculated at 620°C and 8.7 kbar for st + bi (± grt + chl) assemblage. Then almost isothermal decompression took place at 600°C and 5–4.5 kbar which was inferred from an assemblage grt (rim)-bt-mu-pl-sill-qtz (Murtezi, 2002). It was related to exhumation in the sinistral transpressional regime. The same conditions of metamorphism were inferred for the metarhoylites folded together with the schists. In marbles of the eastern part of the OSD, the peak metamorphic conditions were attained at 570±25°C and 7.7±7 kbar, thus similar to estimations made for mica schists (Jastrzębski, 2002).

Gneissic core

Lithostratigraphy

Gneisses in the OSD, are traditionally subdivided into two types, originally distinguished in the eastern part of the dome, and referred to as the Gierałtów and Śnieżnik gneisses (Fischer 1936; Don *et al.*, 1990; Don 2001a,b). Protoliths and genetic relationships of the two types, their age relations are unclear and debated (Smulikowski, 1979; Borkowska *et al.*, 1990; Don, 1977; Don *et al.*, 1990; Don, 2001a,b; Turniak *et al.*, 2000; Kröner *et al.* 2001). The gneisses range from relatively fine-grained biotite, streaky or homogeneous, often migmatitic gneisses (Gierałtów) to coarse-grained rodding, flaser to mylonitically layered augen orthogneisses (Śnieżnik). Petrographic criteria used for distinguishing between the two types of gneisses happen however to have been in a number of cases ambiguous and misleading (Dumicz, 1989). Clear field evidence that would confirm intrusion of a porphyrytic granite into the already deformed and metamorphosed Stronie Formation rocks (Don, 2001a,b) or into other gneiss variants were not observed. Gneissic and migmatitic enclaves which occur in the augen gneiss indicated that their metamorphism must have been older or coeval with a porphyrytic granite magma emplacement at the latest (Grześkowiak & Żelaźniewicz, 2002). On the other hand, Don (1977, 1982a, 2001a) observed migmatites that developed at the expense of augen gneisses. Such observations suggested that two generations of migmatites can be found in the OSD (Franke & Żelaźniewicz, 2000). This option required further studies along with the unsolved problem of protoliths of the gneisses, their early relationships and geodynamic setting.

Geochemistry

Although by geochemistry the OSD gneisses appeared similar, detailed geochemical and mineralogical studies revealed that their variants in the core of the dome show minor yet systematic differences in element contents and characteristic element ratios (Borkowska *et al.*, 1990; Borkowska & Dörr, 1998). Compositions of rock-forming and accessory minerals were also found to vary systematically. Enclaves in the augen orthogneisses, either chemically different or nearly identical with the host rock, differ in compositions of feldspars, micas and garnets (Grześkowiak & Żelaźniewicz, 2002), and the differences match those recognized by Borkowska (Borkowska *et al.*, 1990; Borkowska & Dörr, 1998; Borkowska & Orłowski, 2001). The chemical affinities and syn-collision to post-collision, S-type, meta-aluminous signatures were explained by inheritance of geochemical features by the c. 500 Ma granitic magma from its parent rocks. However, it remained unsolved whether the ~500 Ma granites (1) formed a single batholith which was later differentiated into the Śnieżnik and Gierałtów variants solely by deformation and high-grade metamorphism up to migmatization during the Variscan collision, or (2) were derived by an extensive anatexis of the lower crust that was earlier/coevally deformed and migmatized, prior to the intense Variscan overprint, eventually which gave rise to polymetamorphism and mutliple deformation observed in the OSD rocks.

Geochronology

Isotopic ages that were determined for gneisses prior to 2002 did not clear any of the above problems. Rb-Sr whole rock data yielded an age of c. 464 Ma for a fine-grained homogenous gneiss (Gierałtów type) and an age of c. 380 Ma for a coarse-grained augen gneiss (Śnieżnik type), with metamorphic overprint at c. 335 Ma (Borkowska *et al.*,1990). However, another set of data yielded a Rb-Sr whole rock isochrone age of c. 487 Ma for other augen gneiss samples (van Breemen *et al.*, 1982). U-Pb conventional and Pb-Pb evaporation datings of single zircon grains did not confirm the reality of such age groups and yielded ages that spanned between ~522 and ~488 Ma (Oliver *et al.*, 1993; Borkowska & Dörr, 1998; Kröner *et al.*, 1997, 2001). U-Pb SHRIMP analyses of two samples from the Międzygórze Antiform also revealed only ca. 500 Ma zircons which had 540–530 Ma cores and 342±6 Ma thin rims (Turniak *et al.* 2000).

According to the Oliver's *et al.* (1993) and Kröner's *et al.* (2001) views, the gneisses were to represent Ordovician magmatic arc which was subsequently built into the Caledonian orogen when East Avalonia collided with Baltica. Turniak *et al.* (2000) proposed that all gneisses were derived from the ~500 Ma granites, which became differentiated during Variscan orogeny at first by mylonitization and then by HT-LP migmatization around 342 Ma. However, mylonitization of the ~500 Ma granites occurred between 340 Ma and 334 Ma as constrained by Rb-Sr and Ar-Ar studies of micas, with later shearing at 337–329 Ma localized but in narrow zones (Steltenpohl *et al.*, 1993; Maluski *et al.*, 1995; Bröcker *et al.*, 1997; Marheine *et al.*, 2002; Lange *et al.*, 2002). The data show that the metagranites must have cooled down in this period to temperatures < 400°C due to fast exhumation. Such conditions rather prevented these rocks from partial melting and migmatization unless decompression contributed effectively to the process.

Metamorphism

Tectonic juxtaposition of rocks in an orogen is generally shown by contrasting P-T paths of neighboring units. In the OSD, precise location of tectonic boundaries between supposedly juxtaposed units is difficult to locate. As mentioned above, P-T estimates, especially in the eastern OSD, show that acid and basic metavolcanic rocks, marbles and mica schists of the Stronie Formation underwent progressive metamorphism at similar conditions climaxing at 560–620°C and 7–9 kbar.

For the Gierałtów-type gneisses, early P–T estimates yielded T=580–670°C and P=4–6 kbar (Smulikowski, 1979), and T=520–555°C and P=4.5–8.5 kbar (Borkowska, 1996). Significantly higher P-T conditions of T= 740° and P = 9.2 kbar were however reported by Szczepański & Anczkiewicz (2000) who also obtained for amphibolite from the Gierałtów gneiss a temperature of 845±130°C and pressure of 9.1±2.5 kbar. Such data would suggest that the Stronie schists have to be separated from the Gierałtów gneisses by a ductile fault(s) yet poorly identified. In migmatitic gneisses at the Międzygórze area, core-to-rim compositions of zoned Ca-rich garnets indicate progressive metamorphism but the high contents of Ca invalidates the usage of grt-bt geothermometry. The Si-geobarometer applied to these migmatites yielded a pressure of 10–11 kbar, while various temperatures estimates gave values between 510 and 550°C (Borkowska, 1996; Grześkowiak & Żelaźniewicz, 2002). The latter, if correct, do not constrain migmatisation rather but re-equilibration that occurred during later metamorphic overprint.

Eclogites and granulites

In the northeastern part of the OSD core, mainly migmatitic gneisses (Gierałtów type) contain lenses of (U)HP eclogites and HP granulites (Smulikowski, 1967; Bakun-Czubarow, 1991; 1992; 1998; Bröcker and Klemd, 1996; Kryza *et al.*, 1996). Sheared and amphibolitized margins of eclogite bodies may have testified to tectonic insertion into the Gierałtów gneisses (Dumicz, 1993; Stawikowski, 2001, 2002; Żelaźniewicz & Bakun-Czubarow, 2002), with which they seemed to share most if not all tectonic history (Dumicz, 1993). Three occurrences of eclogites were known: (I) in the Międzygórze Antiform, (II) in the Śnieżnik Fold, and (III) in the Złote Mts.

Eclogites and plagioclase-omphacite granulites have protoliths derived from (1) MORB-type rocks, (2) calc-alkaline rocks and (3) ferrogabbroic and bimodal volcanic rocks (Bakun-Czubarow, 1998). Primary mafic rocks thus represented different sources and eclogite protoliths must have come from tectonically juxtaposed yet originally different lithotectonic units. Sm-Nd isotopic studies of the eclogites yielded clinopyroxene-whole rock-garnet isochron ages spread between 352±4 and 329±6 Ma, which was interpreted to record time of cooling from the eclogite facies conditions to temperatures preventing omphacite to grow (Brueckner *et al.* 1991). U–Pb zircon ages of 369±1 to 360±6 Ma indicate early stages of HP metamorphism of the mafic granulites, and Sm-Nd Grt-WR ages of 341±10 and 343±11 Ma reflect cooling but at high-pressure conditions of these rocks (Klemd & Bröcker, 1999). Given metamorphism at a depth of c. 120 km, eclogites on their way up arrived at the now exposed crustal levels around 352 Ma and exhumation continued till ~329 Ma. Migmatitic gneisses immediately adjacent to eclogites in Międzygórze yielded a U-Pb lower intercept zircon age of 372±7 Ma and a Rb-Sr thin slab whole rock isochron age of 396±17 Ma (Bröcker *et al.*, 1997) hinting to tectonothermal events in mid-Devonian times.

In the OSD, the eclogites that occur within the Gierałtów gneisses reached the peak P–T conditions at T = 660–780°C and P = 30 kbar, which was followed first by decompression to P =10(–12) kbar and then by isothermal retrogression to the amphibolite facies assemblage at 9–5 kbar and c. 600°C (Bakun-Czubarow, 1991; 1992; 1998; Bröcker & Klemd 1996; Klemd & Bröcker, 1999). However the eclogites that occur within quartzofeldspathic granulites (III – Złote Mts occurrence) underwent metamorphism at the peak conditions set between ca. 21 to 28 kbar and 800 to 1000°C (Bakun-Czubarow, 1992, 1998; Klemd & Bröcker, 1999), in consistence with those estimated for the granulites (Kryza *et al.* 1996). Bakun-Czubarow (1998) found that the latter eclogites temporarily resided in the granulites, thus at least two groups of eclogites might be envisaged in the OSD, which presumably belonged to different lithotectonic units or lithospheric segments with different geotectonic histories.

The eclogite boudins enclosed in the Gierałtów migmatitic gneisses at Międzygórze underwent metamorphism first at 770°C and 33 kbar, then at 750–680°C and 20–15 kbar, and still further at 650°C and 11 kbar (Bakun-Czubarow 1998; Żelaźniewicz & Bakun-Czubarow, 2002). The adjacent gneisses reached the peak between 650–700°C and 9 kbar. Such data suggested a stepwise exhumation of the (U)HP rocks from a depth of c. 120 km via 65–55 km to a depth of 30–25 km where eclogites became retrograded to amphibolites under conditions similar to those responsible for metamorphism of the Gierałtów gneisses. Whether other rocks of the OSD also underwent HP history, or HP rocks were separated from the others by ductile shear zones remained unsolved.

Deformation history

In the OSD, a complex outcrop pattern of adjacent gneisses and mica schists were traditionally interpreted as large-scale fold structures (Bederke, 1943; Don, 1964; Dumicz, 1964, 1979; Oberc; 1968) within which smaller folds were identifiable (Kasza, 1964; Teisseyre, 1973, 1975; Don, 1991) with axes striking in the N–S to W–E direction (Cloos, 1922; Don, 1964; Teisseyre, 1956; Wojciechowska 1975; Żelaźniewicz, 1976, 1978). In contrast, Cymerman (1997) claimed the presence of over twenty, internally complicated, northward transported thrust sheets as a huge nappe pile.

Although multiphase tectonic evolution was almost unanimously considered by most authors, yet the consecutive sets of structures reported by them from various parts of the OSD differed in details. In metasedimentary rocks, F_1 folds, accompanied by an intersection lineation and axial planar shearing, appeared on micro- or mesoscale as intrafolial features, or folded inclusions in plagioclase and garnet blasts, etc. (Teisseyre, 1973; Wojciechowska, 1972; Żelaźniewicz, 1976; Szczepański, 2001; Romanová & Štipska, 2001), and they were also recognized in outcrop pattern (Don, 1976; Don & Gotowała, 1980). Most of recognizable large-scale and small-scale folds in the OSD belonged to F_2 set that overprinted F_1 structures.

It was inferred from the observed structural relationships that an early W–E subhorizontal shortening of D_1 episode generally gave pace to subvertical shortening during D_2 episode (Dumicz 1979). S_2 foliation in the Stronie rocks, defined by progressive mineral assemblages, varied from spaced crenulation cleavage to dense schistosity in high strain zones. In mica schists, such zones might be overlooked, unless located along the lines of abrupt changes in the orientation of F_2 & L_2 structures (e.g. Żelaźniewicz, 1978), or in the vicinity of rheologically more rigid bodies composed of marbles and metavolcanic rocks (Jastrzębski, 2002; Murtezi, 2002). Passive rotations of earlier linear features in the reactivated foliations (S_1 and S_2) due to N–S to NE–SW transport are often observed. The earliest D_1 shearing remained however unconstrained.

Some field evidence suggested that in the time span between D_1 and D_2 event intruded the porphyritic Śnieżnik granite that locally seemed to truncate the S_1 planes (Don *et al.*, 1990; Don, 2001a). This observation, however, in view of granite intrusion age of ~500 Ma, would push the D_1 episode to the Cambrian–Ordovician. Such option could not be excluded but then what was assigned to D_1 features had to be revised as a heterogeneous set of structures. On the other hand, the augen Śnieżnik gneisses evidently recorded shorter and simpler structural evolution than mica schists. Only one set of a mylonitic foliation developed in the former porphyritic granite, parallel to the subhorizontal S_2 foliation in the surroundings. The metagranite ranged from predominantly rodded (L- and L>S tectonite) to layered and laminated (S-tectonite) variants (Żelaźniewicz, 1988).

In the NE part of the dome, subsequent deformation, labelled F_3 (Teisseyre, 1973; Wojciechowska, 1972, 1975; Don 1982a,b, 2001a,b), brought about the NW–SE transversal belt of the Stronie Formation, the Krowiarki belt. The NW-trending folds F_3 were accompanied in gneisses by biotite lineation which overprinted the earlier stretching lineation and was taken as a record of migmatization that reworked mylonitic orthogneisses (Don, 1982a, 2001a,b). However, the Stronie Formation rocks in the Krowiarki belt were not migmatized and the record of migmatization compatible with and assignable to the biotite lineation was poor in gneisses. F_3 folds that overprinted the mylonitic fabric in augen ortho-g neisses can be locally observed the northeastern part of the OSD but with rather weak axial planar recrystalli- zation incompatible with migmatization. Similar transversal folds were also observed in the northwestern part of the OSD, though labelled F_4 because of their position in the local structural sequence, with F_3 being parallel to the F_2 axes but refolding the S_2 axial planar foliation (Żelaźniewicz, 1976).

Ubiquitous brittle overprints brought about a rich realm of kink folds (F_5 and F_6 the Góry Orlickie Mts., Żelaźniewicz, 1976, 1977) connected with the conjugate sets of kink planes, of which the NW-striking system is older than the NE-trending one. NE–SW shortening responsible for the older system brought the OSD rocks into a large-scale antiform in the western part of the OSD and a synform in the eastern part. Summing up, the structural evolution of the northern OSD might be subdivided into three stages. In the first stage, foldings about roughly N–S oriented axes occurred being accompanied by the E-vergent and W-vergent shearing. In the second stage transversal folds were formed in association with the N-vergent shearing along the S_2 foliation planes under retrograde metamorphic conditions. In the third stage, semi-brittle structures developed in response to the NE–SW and then NW–SE shortening.

An overall architecture of the OSD remained unclear. Pauk (1977) interpreted it in terms of two large-scale easterly vergent nappe structures. Cross sections for the Międzygórze–Śnieżnik or Kletno areas showed a complex generally upright fanned structure with W and E-vergent folds and thrusts, the important details of which varied greatly (Teisseyre, 1973; Don, 1982b). Anticlinoria and synclinoria were controversially identified in the NE part of the dome (Oberc, 1972). Regional tectonics of the OSD was controlled by the collision of the Bohemian Massif terranes and the Brunovistulian Terrane (Schulmann & Gayer, 2000). The suture between these terranes was earlier identified by Fajst (1976) as a structural Cadomian unconformity, referred to as the Orlica unconformity, that was to separate the core units of the Orlica–Śnieżnik Dome (gneisses and Młynowiec–Stronie rocks) from its Proterozoic envelope observed in the Staré Město, Zabřeh, and Nové Město fold belts.

WHAT HAS BEEN LEARNED IN THE 2002–2014 PERIOD

Metasedimentary–metavolcanogenic mantle

Lithostratigraphy

In the featured period, metasedimentary rocks of the OSD focused much more attention than ever. Based on the field observations and detailed mapping, a lithostratigraphic column for the Młynowiec–Stronie Group was proposed by Don *et al.* (2003) largely reconfirming an earlier scheme (Don *et al.*, 1990). In general, the Młynowiec Formation composed mainly of paragneisses is followed upward by the Stronie Formation with dominant mica schists that include light and dark quartzites in its bottom part, marbles in the middle and bimodal volcanogenic rocks in the middle and upper parts (Fig. 2). Indeed, mafic volcanism was concurrent with carbonate sedimentation because in the field the two lithologies overlapped, presumably on submarine highs (Koszela, 1997). Both mafic (Stop 1.1) and felsic (Stop 1.2) volcanogenic rocks also overlapped, which testifies to bimodality of magmatism with lava flows and remarkable pyroclastic accumulations (Wojciechowska, 1993; Murtezi, 2006), though hyabyssal felsic intrusions into other rocks of the Stronie Formation may have occurred too (Mazur *et al.*, 2013).

What is a boundary between the two formations of the group, an old lithostratigraphic problem in the region remains still debatable. Based on the zircon data and the overlapping U-Pb ages, Jastrzębski *et al.* (2010) suggested a concordant sedimentary contact. However, Don *et al.* (1990, 2008) argued for discordant contact and interpreted light quartzites at the base of the Stronie Formation (Stop 1.5) as a basal horizon of a new sedimentary succession younger than the Młynowiec Formation Mazur *et al.* (2012, 2013) and Szczepański & Ilnicki (2014) assumed that the quartzite horizon referred to as the Goszów quartzite is a relic of the third, youngest succession in the region, was later tectonically inserted between the two others. In this interpretation, there are three distinct metasedimentary successions in the region: (1) the Młynowiec paragneisses, (2) the Stronie formation, and (3) the Goszów quartzites, which were to represent a Neoproterozoic back-arc basin, Cambrian incipient rift and Orodovician post-rift succession, respectively. It was based on differences in the maximum sedimentation ages assumed for those basins and in the chemistry of rocks which pointed to active continental margin setting in case of Młynowiec and Stronie and to passive margin in case of Goszów (Szczepański & Ilnicki, 2014). Having considered similarities in both geochemistry and detrital zircon ages, Szczepański & Ilnicki (2014) assumed that the Wyszki paragneisses that crop out in the western part of the OSD might be equivalent to the Młynowiec paragneisses which so far were reported only from the eastern part and that the Goszów quartzite might have equivalents in the western limb of the OSD (Stop 1.3).

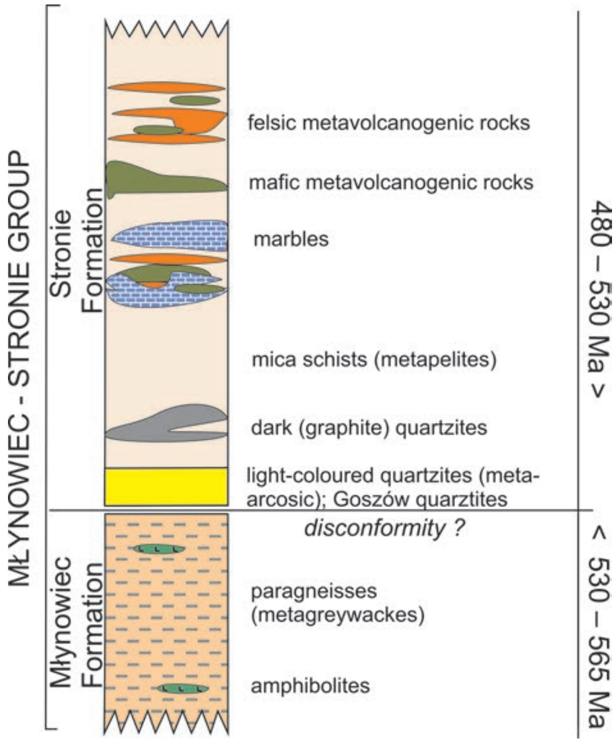

Fig. 2. Lithostratigraphic column of the Młynowiec–Stronie Group (after Don *et al.*, 2003; Jastrzębski *et al.*, 2010; modified). The Młynowiec Formation (MF) is composed of medium-grade metamorphosed greywackes with very scarce amphibolite intercalations. The Stronie Formation (SF) is composed of metapelites mica schists and subordinate paragneisses with light and infrequently occurring graphitic quartzites in its lower part, marbles in its middle part, and alternating basic and acid metavolcanic rocks in its upper part, with the former giving upwards the pace to the latter. Based on the zircon spectra, the minimum age of the MF and the maximum age of the SF overlaps at ~530 Ma. It is uncertain whether the boundary between the two formations is conformable, unconformable, or disconformable. A discrete, ~15 m thick horizon of light-coloured, K-feldspar-bearing quartzites (Fig. 1) that occurs at the interface of the formations has been interpreted as a basal member of the SF separated by an unconformity from the underlying MF (Don *et al.*, 1990, 2003) or as an independent lithostratigraphic unit referred to as the Goszów quartzites (GQ), actually younger than the MF and SF (Mazur *et al.*, 2012). The observed position of the GQ is explained by tectonic insertion. See text for further details.

Geochemistry of volcanogenic rocks

The field and geochemical studies indicate that felsic metavolcanic rocks formed more or less massive bodies and well foliated quartzofeldspathic schists parallel with the surrounding mica schists. They are accompanied by biotite bearing leptites interpreted as metatuffites with a variable share of sedimentary material (Murtezi, 2005, 2006). Such observation is important as it informs that acid volcanism went on concurrently with pelitic sedimentation. This likely occurred in an extensional basin over a subduction zone (Murtezi, 2006). On the other hand, Mazur *et al.* (2013) supposed that the felsic metavolcanites were subvolcanic intrusions into earlier deposited pelitic rocks of the Stronie Formation. Although such setting cannot be excluded, no cross-cut relationships were observed to support the view.

In 2002–2014, metabasites were extensively studied in both limbs of the OSD. Nowak & Żelaźniewicz (2006) identified 4 groups: within plate tholeiites (WPT), MORB-like tholeiites, alkali basalts and low-Ti tholeiites. Alkali basalts of WPB type (Nb/Y > 1.5, Ti/V > 50, Zr/Y > 4, Zr/Nb < 5) occur as laminated biotite amhibolites which pass laterally into mica schists or calcareous schists next to marble bodies assigned to Cambrian (Gunia, 1997). These amphibolites likely originate from tuffites merged with clastic rocks and represent pyroclastic products of volcanic eruptions. Such observations were used to suggest the same age for WPB volcanism in a continental rift setting. Similar association of acid volcanism with pelitic sedimentation allowed to infer a bimodal rift related magmatism/volcanism in the Cambrian during deposition of the Stronie Formation.

MORB-like metatholeiites (Nb/Y < 0.7, Ti/V < 50, Zr/Nb > 20, Zr/Y <3.5 Ti/Y <327) appear as are widely separated bodies of different size. They have fine-grained gabbroic or diabasic protoliths interpreted as hypabyssal lava bodies or dykes feeding individual volcanoes during more advanced rifting at a plate margin setting (Nowak & Żelaźniewicz, 2006).

Felsic metavolcanic rocks (leptites) either associated with metabasites or occurring as intercalations in mica schists are characterized negative anomalies of Eu, Ti, Sr as well as low Ba, Hf, Zr, Ta and Nb contents. High ratio of Th/Nb, LREE/HREE and high content of REE suggest that the protolith of leptites was derived from highly differentiated products of melting of the continental lithosphere rather than from magmas derived from garnet-rich oceanic lithosphere. Geochemical characteristics of leptites indicate that their origin was controlled by both intracontinental rift and active continental margin. Strong geochemical similarities between leptites and metagranites in the OSD which are commonly linked with the extension of the Cadomian crust suggest that all these felsic rocks developed in a ensialic rift (~515–480 Ma), possibly owing to a back-arc extension at a poorly defined magmatic arc. The arc may have developed via transformation of the earlier Cadomian arc of an Andean type into a complex arc of western Pacific type (Murtezi, 2005, 2006).

In the western OSD, based on immobile trace element and Nd isotope features Ilnicki *et al.* (2013) also distinguished 4 groups of metabasic rocks: dominant E-MORB- or mildly enriched N-MORB-like metatholeiites, depleted metatholeiites and scarce OIB-like alkaline metabasalts. They also observed field evidence that the emplacement of the tholeiites must have been coeval with the sedimentation of the Stronie Formation, yet neither age nor relationships between these four groups were determined by them. Tholeiitic magmas may have been derived from MORB-type mantle (DMM) while OIB-like alkaline melts reflect an enriched mantle (EM)-type astenospheric source. Based on contrasting geochemical signatures and Nd isotope features, the investigated metabasalts were ascribed to back-arc basin and within-plate tectonic environments. Consequently, Ilnicki *et al.* (2013) came out with a model of magmatism related to cessation of the supra-subduction zone activity, presumably induced by ridge-trench collision, followed by the development of a transform plate boundary and opening of a slab window. Contrasting BAB- and within-plate-like affinities of the OSD metabasites, and petrogenetic constraints from the contemporaneous ca. 530 Ma Stronie formation rift basin (Mazur *et al.* 2012, 2013; Szczepański, 2010; Szczepański & Ilnicki, 2014), connected the appearance of the OSD mafic volcanics with the cessation of the supra-subduction zone activity (Ilnicki *et al.*, 2013).

Geochronology

From the Młynowiec greywacke a number of detrital zircons were retrieved and two samples were studied with U-Pb SHRIMP analyses. One sample yielded Palaeao- and Mesoproterozoic age clusters around 2.34 Ga and between 2.02 Ga and 1.79 Ga, 1,17 Ga and three Neoproterozoic age clusters: 660–640 Ma, 618–590 Ma and 578–531 Ma (Jastrzębski *et al.*, 2010). The other sample yielded the youngest zircons dated at 563±6 Ma, which was interpreted as the maximum deposition age of the Młynowiec Formation (Mazur *et al.*, 2012).

In the western OSD, paragneisses from Wyszki yielded Archaean (2.8–2.7 Ga), Palaeoproterozoic (2.2–1.9 Ga) and Neoproterozoic age clusters of 803–566 Ma, thus similar to the Młynowiec greywackes as reported earlier by Mazur *et al.* (2012). Mazur *et al.* (2013) supposed that the Wyszki paragneisses actually represent a part of the Młynowiec Formation They may be tentatively correlated, however, boundaries of these rock units remain unknown, which impedes the lithostratigraphic correlation.

U-Pb SHRIMP analyses of zircons from the Młynowiec paragneisses and Stronie mica schists performed by Jastrzębski *et al.* (2010) showed that the youngest detrital grains were formed at the source at ~540–530 Ma. Although the onset of basin accumulation cannot be well constrained with this type of data, it is pretty obvious that the minimum age of both formations cannot be older than 530 Ma. Still the same source areas were being eroded and shed clasts as shown by similar age clusters of older zircons in the two formations and similar geochemistry of metasediments. The zircons of the 560–530 Ma cluster are identical with intrusion age of the Lausitz granodiorites further west and other granitoids in the Cadomian basement of the Sudetes and Fore-Sudetic block in the Saxothuringian Zone (Żelaźniewicz *et al.*, 2004).

In quartzites of the Stronie Formation, two youngest zircon groups cluster around 540–530 Ma and 500–480 Ma. A newly identified age cluster of 500–480 Ma zircons in the Stronie Formation suggest that new source became available in the Late Cambrian. However many of these zircons do not show signs of roundness expectable in detrital grains but still retain shapes characteristic of magmatic grains. This is because they did not undergo long transport but fell down to the sea from the air as ash-fall coming from pyroclastic products of felsic volcanism ubiquitous in the depositional history of the Stronie Formation (Jastrzębski *et al.*, 2010). The cluster of 500–480 Ma is consistent with granitic plutonism accompanied by migmatization that occurred in the region between 515 Ma and 480 Ma (van Breemen *et al.*, 1982; Kröner *et al.*, 2000; Żelaźniewicz *et al.*, 2006). This event has been commonly recognized and interpreted either as an intracontinental rift related A-type magmatism (Pin *et al.*, 2007) or a back-arc rift behind a poorly identified arc at Gondwana margin (Murtezi, 2006; Jastrzębski *et al.*, 2010; Ilnicki *et al.*, 2013). The detrital zircon concentrate from metasediment sample of the Stronie formation delivered by Mazur *et al.*, (2012) revealed Jastrzębski's *et al.* (2010) conclusion that maximum sedimentation age for these rocks is not older than ~530 Ma.

Metarhyolites from the Stronie Formation were utilized to date acid volcanism in the Orlica–Śnieżnik Dome. U-Pb SHRIMP zircon ages obtained for acid metavolcanic rocks yielded ages of 507±4 Ma, 506±4, 496±6 Ma (Murtezi, 2005) and 501±3 (Mazur *et al.*, 2013). The ages were taken to record time of crystallization of these rocks. Some zircons, interpreted as inherited xenocrysts, revealed ages of ca. 520 and 560 Ma and ca. 1,3 to 2,1 Ga (Murtezi, 2005).

For metasedimentary rocks, microprobe monazite geochronology provided mainly Early Carboniferous metamorphic ages ranging from 352±5 Ma down to 334±5 to (Gordon *et al.*, 2005), which is in line with the Sm-Nd garnet–WR isochron age of 346.5± Ma obtained for garnet from the Stronie mica schist and interpreted as timing of the progression of Barrovian metamorphism (Jastrzębski, 2009). Later exhumation is documented by 340–330 Ma ^{40}Ar–^{39}Ar cooling ages on muscovite and biotite (Schneider *et al.*, 2006). Ar-Ar plateau ages for biotite and muscovite of ca. ~334, ~339, ~338, and ~314 Ma (Schneider *et al.*, 2006) and ~349 and ~336 Ma (Chopin *et al.*, 2012a) testify to rather slow rate of Early Carboniferous cooling of the OSD mica schists between ~350 and ~315 Ma.

Metamorphism

The recent P-T reconstructions of the Młynowiec–Stronie Group have been based on meso- and microstructural observations combined with conventional geothermobarometry or pseudosection analyses. Conventional geothermobarometry indicated the prograde evolution of the mica schists and adjacent marbles of Stronie Formation both in the western and eastern limb of the OSD to amphibolite facies metamorphism (Mazur *et al.*, 2005; Murtezi, 2006; Jastrzębski, 2005, 2009). The pseudosection analyses gave more detailed insight into the P-T path(s) of the metapelites of the Stronie Formation (Murtezi, 2006; Szczepański, 2010; Skrzypek *et al.*, 2011a, 2011b; Štípská *et al.*, 2012). In the eastern limb of the OSD, a modelled garnet zoning and changing mineral assemblages indicates a prograde evolution from ~3.4–4.5 kbar in the earliest recognized metamorphic fabrics progressing towards 6.5–7.5 kbar and 560–620°C and followed by pressure and temperature decrease (Murtezi 2005, 2006; Skrzypek *et al.* 2011a, 2011b; Štípská, 2012). Murtezi (2006) indicates in addition a subsequent heating episode that locally took place at depths corresponding to ca. 3 kbar. Such P-T history is in contrast with recent findings of blueschist facies metamorphism in the western limb of the OSD (Faryad & Kachlik, 2013). The latter data would imply that that at least part of metasedimentary rocks in the OSD underwent metamorphic conditions of ~20–21 kbar at 500–550°C (Faryad & Kachlik, 2013) followed and obliterated by the Barrovian progressive P-T evolution described above. Such HP conditions may have prevailed during D1 event in the region, which is so far rather poorly identified with unclear timing.

In the OSD, the different metamorphic grades of the Barrovian metamorphism have been mapped. The peak mineral assemblages was related to a single tectonometamorphic episode (Jastrzębski, 2009) or to three successive tectonometamorphic stages (Chopin *et al.*, 2012a). The map of isograds presented by these authors indicate the presence of kyanite and sillimanite (in mica schists) and diopside and tremolite (in marbles) mainly in the eastern part of the OSD. According to Jastrzębski (2005, 2009), the Barrovian metamorphic isograds dip outwards at moderate angles due to (re)folding during the late folding event.

In the western OSD, Szczepański (2010) also studied garnets and phengites in the Stronie mica schists utilizing various geothermobarometers and found that the schists were metamorphosed under different P-T conditions ranging from 500°C/9 kbar to 630°C/5 kbar, with the temperature increasing southwards from the center of the dome. Based on isopleth geothermobarometry coupled with garnet fractionation model utilized for 3 samples, he was able to distinguish three P-T paths with the peak pressures different by 4 kbar. The differences were used to infer the presence of 3 nappe units in the western OSD although their boundaries have remained unrecognized. However, Szczepański (2010) was able to identify biotite, garnet and staurolite isograds, with metamorphic grade increasing to the SW, outwards from the central part of the Bystrzyckie Mts. The isograds were formed concurrently with the youngest napping during the P-T drop that was followed by a brittle-ductile event.

Gneissic core

Lithology/lithostratigraphy

In 2002–2012, once again was approached the problem of how and when gneisses in the OSD and their protoliths were formed. Several studies showed that geochemical characteristics of the Gierałtów gneisses and Śnieżnik gneisses, are similar, which suggests that they were genetically affine. In general, such similarities may be interpreted in at least two different ways. (1) Gneiss protoliths may have come from a single magma source and granites, after emplacement, get diversified via subsequent deformation and metamorphism. (2) Gneiss protoliths may have represented diversified products that evolved via anatexis from a crustal source with memory of earlier/concurrent processes.

In the field, the Gierałtów and Śnieżnik gneisses, distinguished some 80 years ago (Fischer, 1936), differ however so widely that the differences require more rigorous analysis of their structural and metamorphic features. Such analysis has not been provided by most authors who favor the first option (Turniak *et al.*, 2000; Kröner *et al.*, 2001; Lange *et al.*, 2002, 2005), with one exception (Chopin *et al.*, 2012a).

Chopin *et al.* (2012a) ommited the problem of how to distinguish the Śnieżnik from Gierałtów gneisses and took them all as orthogneisses which were then classified into three types (I–III) according to the strain intensity. Such classification can hardly be applied in the field because it is not suited for an instant use to distinguish between apparently similar rocks. Moreover, judging from the published photographs and descriptions of the samples they studied but in one outcrop, these authors apparently mixed augen orthogneisses of the Śnieżnik type with the streaky Gierałtów gneisses considered as a more strained variety of the former. Type I and type III were found to be deformed at drastically different depths equivalent to 11 kbar and to 20 kbar, respectively. Around 30 km long vertical separation seems, however, unrealistic if transitions from type I to type III occur in one outcrop. Besides, the REE diagram published by Chopin *et al.* (2012a) also shows that the individual element contents in type III is several times less than in type I.

On the other hand, studying carefully the relationships between various types of gneisses in the Międzygórze Antiform, Redlińska-Marczyńska (2011) and Redlińska-Marczyńska & Żelaźniewicz (2011) came to a conclusion that the distinction between the two main type of gneisses, Gierałtów and Śnieżnik, made some 80 years ago (Fischer, 1936), is fully justified. Redlińska-Marczyńska (2011) and Redlińska-Marczyńska & Żelaźniewicz (2011) observed profound structural differences between these gneisses which reflected diverge protolith evolution. One type was evidently derived from rather coarse grained porphyrytic granite that during subsequent deformation was changed commonly to augen orthogneisses and locally to quartz/feldspar laminated mylonites, generally with a single set of mylonitic foliation developed under amphibolite facies conditions. Such rocks were assigned to the Śnieżnik Augen Gneiss Formation much in consistence with the original Fischer's definition, except for time of intrusion (Redlińska-Marczyńska, 2011). Their characteristic feature is the mylonitically imparted foliation with prominent rodding lineation which were involved in the Antiform into two sets of folds prior to semi-brittle kinking. According to such criteria that are easily legible in the field, the Śnieżnik gneisses can be relatively easily distinguished from all others, consequently assigned to the Gierałtów Gneiss Formation which is however more complex. Additional criteria provided by Redlińska-Marczyńska & Żelaźniewicz (2011) for the distinction between the two types in the field are as follows:

the Śnieżnik augen gneiss/metagranite	the Gierałtów gneisses
migmatitic xenoliths and their derivates (restites, schlieren), felsic microgranular enclaves,	no migmatitic and other gneissic enclaves
no (U)HP rock enclaves	HP granulite and (U)HP enclaves and their retrograde derivates (amphibolites)
no signs of migmatization	common evidence of migmatization
intrusive contacts to Gierałtów gneisses	

The Gierałtów gneiss type embraced banded gneisses, layered-streaky gneisses, porphyroblastic gneisses and migmatites that all possess two sets of metamorphic foliations, records of shearing and shear-induced banding consistent with the earlier foliation, and records of metablastesis and migmatization related to the second foliation set. All these features were subsequently overprinted by the shearing that caused mylonitization observed in the Śnieżnik metagranite, which made the fabric of the Gierałtów gneisses even more complex and thus easily misinterpreted.

Besides the presence of enclaves and xenoliths, of particular importance are rare but real, discordant contacts between the augen gneisses and other rocks: primary interface of the porphyritic granite that intersects the foliation in the surrounding gneisses (Redlińska-Marczyńska & Żelaźniewicz, 2011). Such contacts have low preservation potential being exposed to the superposed shearing and resultant rotation toward parallelism with the shear zones.

Modal composition and geochemistry

Other features that justify the distinction between gneisses are determined by the observed differences in composition of the rock-forming minerals (over 13 000 analytical spots) and modal composition of these rocks. Such differences invariably point to the two formations of gneisses. One formation (comprises migmatites, layered-streaky gneisses and porphyroblastic gneisses, thus is equivalent to the Gierałtów gneisses (GGF). The other formation consists of augen gneisses, thus is equivalent to the Śnieżnik gneisses (ŚGF). In GGF rocks, feldspars, micas and garnets are significantly more diversified compositionally than the feldspars, micas and garnets in the augen gneisses (Redlińska-Marczyńska & Żelaźniewicz, 2011). The heterogeneities in GGF rocks (plagioclase $An_{0\text{-}36}$, biotites either poor or enriched in Al^{VI} = 0.26–1.07) have been likely inherited from their sedimentary-volcanogenic protoliths that underwent multiple metamorphic transformations up to partial melting and migmatite formation. In ŚGF, nearly equal modes of feldspars and quartz, relatively little scatter of composition of feldspars (plagioclase $An_{6\text{–}23}$) and a rather stable amount of Al (0.3–08 Al^{VI}) in the biotites are all indicative of significantly less heterogeneous, hence more evolved nature of the augen gneisses. In view of (1) overall similarities in chemistry of GGF and ŚGF rocks, (2) similarities in U-Pb age spectra of zircons, (3) the presence of enclaves/domains of group I type rocks in the augen gneisses but never opposite and (4) distinctly simpler and shorter deformational history of the ŚGF, Redlińska-Marczyńska & Żelaźniewicz (2011) interpreted the evidence of more advance homogenization observed in the augen gneisses as a record of the anatectic origin of their granitic precursor (Śnieżnik granite) which came from the same or similar sedimentary-volcanogenic protoliths as the group II gneisses and migmatites. The Śnieżnik granite is simply a more evolved product of extensive migmatization and crustal melting that occurred at ~515–480 Ma, which is confirmed by similar age spectra of zircons retrieved from all types of gneisses. In the OSD, the isotopic evidence of migmatization at this time span were found both in the western limb (Żelaźniewicz *et al.*, 2006) and it could be suggested in the eastern limb (Stop 1.6) in line with the earlier expressed view of Přikryl *et al.*, 1996) based on the structural ground. The above observations of Redlińska-Marczyńska & Żelaźniewicz (2011) are also consistent with the analytical data of Chopin *et al.* (2012a), though not with the interpretation proposed by them. Their type I augen gneisses equivalent to the evolved GGF rocks of Redlińska-Marczyńska & Żelaźniewicz (2011) appear chemically least diversified and 2–3 times and richer in REE than the their type III which is equivalent to a not anatectically overwhelmed streaky gneiss of ŚGF rocks of the latter authors. Such data are in line with the view that the augen gneiss protolith was more evolved than the others. It is presumably the very reason that Chopin *et al.* (2012a) could not find evidence of melting in their type III gneisses – they simply never been melted. They also observed a wide range of mineral composition in type III gneisses, which inhibits precise estimations of P–T conditions. In general, rock-forming minerals in the Śnieżnik gneisses are less diverse compositionally than in the Gierałtów gneisses in which significantly wider ranges of mineral compositions are observed.

Metamorphism

Only few studies in the last 12 years dealt with P-T conditions under which gneisses were formed. Grześkowiak (2006) and Redlińska-Marczyńska (2011) utilized phengite barometry and for the assumed temperature range of 400–800°C she reported pressures: 11–16 kbar for the migmatitic Gierałtów gneisses and xenoliths (mesocratic enclaves) in the augen gneisses, 8–14 kbar for the porphyroblastic Gierałtów gneisses, and 6–14 kbar for the Śnieżnik gneisses. Unusually Ca-rich garnets are characteristic of both the Gierałtów and Śnieżnik gneisses (e.g. Stawikowski, 2006). This feature may have been related to high-grade metamorphism and/or to the bulk composition of the protolith. On the other hand, the garnets in the two types of gneisses differ in Fe and Mn contents invariably indicating lower temperature conditions of metamorphism in the Śnieżnik gneisses (Redlińska-Marczyńska & Żelaźniewicz, 2011).

Although neglecting the subdivision into the Gierałtów and Śnieżnik gneisses, Chopin *et al.* (2012a) recognized similar relationships between their three type of gneisses: <15 kbar and < 700°C in case of the augen gneisses (~Śnieżnik gneiss) and >15 kbar (19–20 kbar) and >700°C in case of the mylonitic gneisses (~Gierałtów gneiss). These results however do not fit easily the P-T estimations and the isograd pattern recognized in rocks of the Młynowiec–Stronie Group (Jastrzębski, 2005, 2009; Szczepański, 2010) with which the gneisses were intricately folded (Fig. 1). The orthogneisses and the metapelites must have been separated by ~30 km vertical distance during early metamorphism. However, there is no evidence of subvertical or dip-slip stretching lineation in the gneisses or in mylonites, which would be necessary to prove the vertical transport. In the field, only subhorizontal elongation in the N–S direction can be observed. This issue also needs further studies.

Geochronology

A geochemical analyses, U-Pb zircon dating and series (12 samples) of Rb-Sr, WR-Ms and WR-Bt datings were performed by Lange *et al.* (2005b). εNd_{500} ranging between –3.3 and –5.7 suggest derivation of both the Śnieznik and Gierałtów gneisses protoliths from pre-existing continental crust. Two-stage TDM model ages showed ages of 1.4 and 1.6 Ga. The Rb–Sr whole-rock ages indicate the ca 320–340 Ma cooling whereas SIMS U–Pb analyses provide ages of 527–472 Ma and 364–341 Ma, which were interpreted to reflect the timing of gneiss protolith formation and Variscan high-temperature metamorphism, respectively (Lange *et al*. 2005b).

According to Gordon *et al.* (2005), the OSD represents the UHP crustal unit. The microprobe monazite dating performed on gneisses samples gneisses yielded ages of 372±8 Ma interpreted as timing of the UHP metamorphism of the Śnieżnik gneisses and 343±7 and 333±4 Ma interpreted as timing of their exhumation to mid-crustal depths. Schneider *et al.* (2006) provided ten Ar–Ar plateau Ms and Bt ages obtained from the OSD gneisses, which are taken to coherently represent cooling between 341.6±1.1 Ma and Ma 334.9±0.4 Ma. These ages are consistent with the Ar–Ar total gas age of 336 Ma and Rb–Sr Bt-WR ages of ~337–321 Ma obtained for the orthogneisses by Bröcker *et al.* (2009).

In the western OSD, migmatitic gneisses (~ Gierałtów type), with mesosome containing with relic Ca-Fe garnet and pseudomorphs after an unidentified mineral, possibly Al_2SiO_5 polymorph, yielded a concordia age of 485±12 Ma which was taken to constrain the waning stage of the Late Cambrian–Early Ordovician migmatization (Żelaźniewicz *et al.*, 2006). Migmatitic gneisses may have represented a metasedimentary-metaigneous Neoproterozoic crust that underwent multistage metamorphism, granulite facies inclusive, and then yielded to extensive partial melting between 515 Ma and 480 Ma. The migmatitic gneisses were cut by a post-tectonic syenite dyke dated at 326±3 Ma, interpreted as an intrusion age (Żelaźniewicz *et al.*, 2006).

SIMS U–Pb analyses of zircons from gneisses performed by Lange *et al.* (2005b) confirmed the reality of two groups of $^{206}Pb/^{238}U$ ages: 527–472 Ma and 364–341 Ma. The Rb-Sr ages of micas around c. 340–320 Ma constrained the time when the orthogneisses were cooled moving upwards in the crust. The zircon ages were interpreted as records of protolith formation and Variscan high-temperature metamorphism, however many aspects of the P-T-t-D path remained unclear inviting further studies in order to look through the Variscan overprint.

SHRIMP U–Pb zircon dating of leucosomes and leucocratic veins developed in the orthogneisses and granulites revealed analogous two age populations (i.e. 490–450 and 345–330 Ma) (Bröcker *et al.*, 2009). However, these authors interpret these ages as corresponding to protolith ages of the magmatic precursors and timing of late Variscan anatexis. The zircon evaporation method used for zircons coming from a granitic patch developed in a migmatitic orthogeiss provided Pb-Pb mean age of 366.3±1.1 Ma (Štípská *et al.*, 2004).

Eclogites and granulites

A common conviction that precise dating may be critical for successful resolution of the above events, further attempts were made to get more detailed data. In the eastern OSD, HP granulites and eclogites which form lensoid bodies within migmatitic gneisses were repeatedly studied isotopically. The U-Pb SHRIMP zircon dating yielded a mean age of 342 ± 5 Ma, whereas zircon evaporation dating provided Pb-Pb age of 341.4 ± 0.7 Ma, both interpreted as timing of the peak metamorphism of the felsic granulites from the Červený Důl (Štípská *et al.*, 2004).

Štipska *et al.* (2004) questioned estimations of UHP conditions (Bakun-Czubarow, 1991, 1992, 1998) and claimed that granulites cropping out near Gierałtów did not undergo pressures higher than 18 kbar at temperatures of ca. 800–900°C.

Lange *et al.* (2005a) performed Sm–Nd and U-Pb (ID-TIMS and SHRIMP) analyses that yielded ages clustered around c. 350–340 Ma and around c. 370–360 Ma, which confirmed earlier reported results. However, they found that zircons were liable to resetting during high grade metamorphism and pointed to difficulties in interpreting U–Pb zircon data of HT rocks. Possible isotopic rejuvenation effects may produce erroneous conclusions especially if the mechanism and the time of Pb-loss has not been determined. Indeed, Lange *et al.* (2005a) obtained the U–Pb zircon age of a 393 Ma for a single, concordant zircon crystal from felsic granulites from the Červený Důl area.

Anczkiewicz *et al.* (2007) obtained the Lu-Hf age of 387.6±5 Ma for the garnet from felsic granulite of Stary Gierałtów and Sm-Nd age of 381±7 Ma for the garnet from adjacent metapelite (migmatitic Gierałtów gneiss) interpreted as a record of a prograde UHP metamorphic path. Garnets from mafic granulites yielded U-Pb and Sm-Nd ages of c. 344 Ma during event that occurred on a retrograde path for HP rocks in the OSD. This age is similar to the above mentioned Sm-Nd garnet age reported for the Stronie Formation mica schists by Jastrzębski (2009). Such data hint to rather prolonged metamorphic evolution of metasedimentary rocks in the OSD. The monazite age of 315±4 Ma was interpreted as a record of last heating episode in the OSD rocks (Gordon *et al.*, 2005), which apparently extended its metamorphism for over 50 Ma long time span.

Bröcker *et al.* (2009) went on with the ^{40}Ar-^{39}Ar, Rb-Sr, Sm-Nd, and U-Pb studies of granulites but with the methods used they did not find unambiguous confirmation of pre-350 Ma eclogite metamorphism, which left the debate open. The ^{40}Ar-^{39}Ar phengite dating peformed on the OSD eclogites yielded ages of ~348 Ma Ma and two older ages of 453 and 388 Ma, the latter interpreted in terms of contamination of the dated samples by extraneous Ar. Perhaps memory of earlier event(s) in HP rocks may only be legible with Lu-Hf method or some new methodology is necessary.

Bröcker *et al.* (2010) concluding their study on U-Pb zircon geochronology in eclogites found that the protolith ages of these rocks cannot be resolved either, probably because of multi-stage Pb-loss and that the geological significance of the ~340 Ma age group is controversial. An apparent protolith age of eclogites estimated at 506 ± 6 Ma and granulites estimated at 509 ± 9 Ma and 477 ± 7 Ma suggest the same age of magmatic precursors of both (U)HP rocks and the orthogneisses (Bröcker *et al.*, 2010).

Chemical dating of monazite by electron and proton microprobes performed on felsic granulites from Stary Gierałtów yielded an isochron age of 347±13 Ma that was interpreted as timing of the amphibolite-facies metamorphism which followed earlier high-pressure event (Kusiak *et al.*, 2009).

Summing up, the 2002–2014 period brought remarkable hints for records of HP events in granulites and eclogites by ~40–50 Ma earlier than the peak of the prograde metamorphism in metapelites of the Młynowiec–Stronie Group which occurred around 345–340 Ma.

Sequence of deformations

Papers that in 2002–2014 dealt with geochronological analyses or reconstructions of the P-T conditions did not discuss structural details or referred vaguely to a sequence of multiple tectonic events. However, there is little consensus between various authors about the identity of the successive deformational (D) events and little attempt is made to correlate their observations with those made by the others.

No attempt was made to date specifically any of individual episodes recognized in the deformational history of the OSD rocks. The results obtained determined relatively short time slot for eclogite facies metamorphism, subsequent migmatization, shearing, exhumation and uplift. Similar age numbers for different isotopic systems in minerals with different blocking temperature apparently reflected fast cooling. However, timing of onsets of those processes remained unclear and unconstrained. Mechanism for exhumation was not clear either, especially that no record of a large-scale low-angle fault was found, and evidence for massive denudation and extensive accumulation in a foreland basin was poor.

For the Młynowiec–Stronie Group, Jastrzębski (2006, 2009) and Murtezi (2006) argued that the onset of the Variscan orogenic deformation was accomplished by E–W sub-horizontal shortening (D_1 stage) related to the collision of the West Sudetes terranes and the Brunovistulian terrane. Upright folding on the N–S trending axes resulted in burial and thickening of the lithosphere. As a consequence of subsequent, near-coaxial gravity-controlled vertical shortening (D_2), the S_1 subvertical foliation was deformed in tight recumbent folds F_2. The flattening strain was associated with the progression to amphibolite-facies conditions. D_2 event led to development of the subhorizontal S_2 axial planar schistosity. During subsequent retrogression the S2 planes were reactivated owing to a top-to-the-N shear (D_3 stage) due to the mutual interaction of the OSD with the adjacent terranes the shear deformations were localized within marginal parts of these units. Finally, as a result of the NE–SW and the NW–SE oriented regional shortening (D_4 stage and D_5 stage, respectively), both the structural surfaces and metamorphic isograds were regionally folded with W(NW)-ward plunges under semi-brittle conditions.

According to the results of structural studies in mica schists, orthogneisses and eclogites performed by Štípská *et al.* (2004; 2012), an early shallow-dipping fabric (D_1) was folded by upright folds and overprinted by a heterogeneously developed subvertical foliation (D_2). During a subsequent tectonic event, late recumbent folds associated with a weak shallow dipping axial-plane cleavage (D_3) developed locally. The pseudosection modeling coupled with microstructural observations indicated that the eclogite and metasedimentary rocks were metamorphosed during the D_1 deformation at different crustal levels corresponding to the lower and middle crust, respectively. Due to development of large-scale folds, eclogites were exhumed to mid-crustal levels from depths corresponding to 22–19 kbar but metasedimentary rocks were buried at the same time. During the D_2 folding, the eclogites experienced only exhumation, whereas the metapelites underwent first a burial increment to ~7.5 kbar and ~630°C. This was followed by the exhumation of both the HP and MP rocks (Štípská *et al.*, 2012). The subvertical planar fabric was taken as a record of the early vertical extrusion of the granulite body in Gierałtów area, whereas the later subhorizontal fabrics developed during the lateral spreading of the granulite body (Štipska *et al.*, 2004).

In the western OSD, the Góry Bystrzckie Mts, Szczepański (2010) came to the conclusion that D_1 event produced S_1 foliation parallel to S_0 sedimentary bedding. D_2 event was accomplished by napping and folding and accompanied by progressive metamorphism (M_2). Three main tectonic units, bearing records of contrasting metamorphic paths, have been identified in the western OSD (from base to top): the Poręba, Młoty and Niemojów Units (Szczepański, 2010; Szczepański & Ilnicki, 2014; Fig. 7). Upper part of each tectonic unit consists of orthogneiss, whereas the lower portion is composed of the supracrustal succession. Locally, the highest pressures were obtained for the Młoty Unit, the lowest pressures for the structurally lowest Poręba Unit. In the eastern OSD, Szczepański & Ilnicki (2014) assumed that in places, the youngest Goszów quartzites were tectonically inserted between the Stronie and the Młynowiec Formations whereas, elsewhere, both the Stronie Formation together with the Goszów quartzites were separated from the Młynowiec Formation by orthogneiss bodies. D_3 event was possibly associated with the dextral strike-slip shearing along the contact of the Teplá–Barrandian and Moldanubian terranes at 340 Ma.

In gneisses of the Międzygórze Antiform, Redlińska-Marczyńska (2011) and Redlińska-Marczyńska & Żelaźniewicz (2011) observed that the early folds developed in compositional banding mimetically followed by metamorphic foliation S_1, parallel or slightly oblique to S_0 in the fold limbs. F1 folds had originally roughly the W–E to NW–SE axial directions which now vary greatly due to subsequent foldings and internal rotations. D_1 structures observed in the banded gneisses, layered-streaky gneisses, migmatites and porphyroblastic gneisses (all GGF), apparently with N- to NE vergence, were refolded on roughly N–S axes by F_2 folds having tight to open asymmetric geometry and accompanied by formation of the axial planar foliation (S_2) developed in a top-to-the W kinematic regime. In the Międzygórze Antiform, the D_2 event also included zonally intense shearing which additionally gave rise to small-scale shear folds F_2. The most prominent feature of the D_2 event was a high temperature metamorphic episode which terminated with migmatization and metablastesis that continued late- to post-kinematically (with respect to D_2). In the hinge areas of F_2 folds, the new porphyroblasts grew and random recrystallization led to obliteration of earlier fabrics, which imparted a granitic appearance to the rock. This process also swapped felsic blast or leucocratic segregations (leucosome) nucleated earlier in the hinge zones of F_1 folds. Structural control exerted by F_2 folds on leucosome extracted in situ (nests) and/or injected (phlebites) also point to migmatization occurring syn-to post-kinematically with respect to the D_2 event. In subsequent stage (D_3) an overprint of the stretching lineation (L_3) and reactivation of the S_1–S_2 surfaces by shearing (S_1 –S_2›S_3) with roughly top-to-the N (locally top-to-the-S and to-the-NW) kinematics took place. At least in the Międzygórze Antiform, the Śnieżnik granite was at the very stage strongly sheared, mylonitized and turn to the Śnieżnik rodding augen gneisses conspicuous mylonitic foliation/banding and stretching lineation. The rejuvenation of S_2 planes resulted in the transformation of earlier porphyroblasts into porphyroclasts (both delta and sigma types), which is particularly common in the porphyroblastic gneisses. The next (D_4) event refolded earlier structures on the N–S trending axes which coincided with the earlier stretching lineation L_3 and produced E-vergent folds (z-type F_4) with flat-lying longer limbs, steep to overturned short limbs with weak to none axial plane growth.

Referring to the whole OSD, most studies overlooked that a significant part of orthogneisses is characterized by a constrictional fabric of L and L>S tectonites. Such fabric may have passed unnoticed in metasedimentary rocks with original planar fabric, which does not mean however that these rocks were not affected by this type of strain. In the western limb of the OSD, augen gneisses are mainly L>S tectonites with a prominent stretching lineation. Recent reexamination of these rocks revealed that texture formation was a protracted, multistage process that involved strain partitioning with changing strain rate and kinematics in a general shear regime at temperatures of the amphibolite facies (Żelaźniewicz *et al.*, 2013). Quartz c-axis microfabrics in the augen gneisses show complex yet reproducible patterns but differ from those developed in the sheared migmatitic gneisses, in which the constrictional strain was imposed on the originally planar fabric defined by high-temperature migmatitic layering. The constrictional fabric of the augen gneisses probably developed in the hinge zones of kilometer-scale folds, where the elongation occurred parallel to the fold axes. Other occurrences of rodding gneisses throughout the Orlica–Śnieżnik Dome are thought to occupy similar structural positions, which would point to the significance of large-scale folds in the tectonic structure of the dome.

Concluding their study, Żelaźniewicz *et al.* (2013) proposed that the rodding augen gneisses in the Góry Bystrzyckie Mts. developed in partly or wholly detached bodies which were located in the hinge zones of antiformal folds and bounded by ductile faults. However, such view is in conflict with the model of Szczepański (2010) and Szczepański & Ilnicki (2014) who interpreted the metagranites as slab planar bodies intimately refolded with metasediments and repeatedly appearing in the structural section due to napping and tectonic repetitions. On the other hand, both views are inconsistent with the model of Chopin *et al.* (2012b) who assumed that the augen orthogneiss was buried to a depth of ~40 km along a few kilometer thick shear zone at the base of the accretionary prism and its more deformed variants were depressed to a depth of ~70 km. According to this model, the least deformed gneisses should outcrop in the western part of the OSD, which is obviously not the case.

Chopin *et al.* (2012a) assume for the whole OSD: D_1 – subhorizontal fabric due to N–S orogenic flow, D_2 – subvertical fabric due to W–E shortening, D_3 – again subhorizontal fabric due to ductile thinning and unroofing. Skrzypek *et al.* (2011) and Štipská *et al.* (2004) also recognized S_1 in all rocks of the OSD as a weak flat-lying schistosity without a distinct metamorphic differentiation, which in orthogneiss was to be commonly refolded by rootless isoclinal folds. The S_1 foliation was then transposed into a NE–SW subvertical S_2 foliation distinguished as quartz and mica-rich layers in metapelites and quartz-feldspar ribbons alternating with biotite layers in orthogneisses. Such scenario requires however that quartz-feldspar and biotite layers in orthogneisses had already been or were, at the latest, developed concurrently with the isoclinal folds F_1, which would imply strong shear fabric S_1 in the metagranites quite incompatible with the weak schistosity in the metapelites. Moreover, Skrzypek *et al.* (2011) interpreted the D_3 event as due to E–W shortening and not vertical unroofing.

Palaeogeographical and geotectonic models

It is commonly assumed that the Orlica–Śnieżnik Dome developed during the Variscan orogeny but key tectonometamorphic events during which the OSD was evolving have been explained by various geodynamic scenarios. These are: (1) collision of the Moldanubian Terrane with the Góry Sowie Block as a part of the Central Sudetic Terrane (Cymerman *et al.*, 1997), (2) collision of the Moldanubian Terrane with the Tepla–Barrandian (Bohemian) Terrane (Mazur *et al.*, 2005; Szczepański, 2010), (3) collision of the Moldanubian Terrane with the Brunovistulian Terrane in the lower plate (Schulmann & Gayer, 2000); (4) collision of the Moldanubian or Saxothuringian terranes with the Brunovistulian Terrane in the lower plate (Štipská *et al.*, 2004, Murtezi, 2006; Pressler *et al.*, 2007, Jastrzębski, 2009), (5) collision of the Saxothuringian and Tepla–Barrandian terranes with the Brunovistulian Terrane backstop (Chopin *et al.*, 2012; Mazur *et al.*, 2012; Szczepański & Ilnicki, 2014). Clearly, still more work is needed to this point.

In terms of palaeogeographical models that date back to Gondwana break-up in Early Palaeozoic times, the OSD is commonly seen as a fragment being once part of Gondwana. Based on the detrital zircon age spectra in the Młynowiec–Stronie Group, the West Africa derivation is suggested (Jastrzębski *et al.*, 2010; Mazur *et al.*, 2012). However, most epsilon Nd_{500} values for the OSD gneisses were in the range between –3.3 and –5.7 pointed to derivation of their protoliths from pre-existing continental crust with two-stage T_{DM} model ages mostly in a range of 1.6–1.4 Ga, which indicated rather Avalonian connection (Lange *et al.*, 2005). The issue of the provenance of the OSD ancestors also needs further studies.

The above uncertainities make unclear details of a back-arc rifting process at the Gondwana margin in Early Palaeozoic times, which is commonly assumed as the principal reason of eventual separation of future terranes from the mainland (Murtezi, 2006; Jastrzębski *et al.*, 2010; Ilnicki *et al.*, 2013). Early Palaeozoic acid and basic magmatism recorded in the Orlica–Śnieżnik complex is usually taken as an evidence of that rifting.

This event has been commonly recognized and interpreted either as an intracontinental rift related A-type magmatism (Pin *et al.*, 2007) or a back-arc rift behind a poorly identified arc at Gondwana margin (Murtezi, 2006; Jastrzębski *et al.*, 2010; Ilnicki *et al.*, 2013). According to Pin *et al.*, (2007), the 500-Ma igneous event that produced felsic magmas was unrelated to any active subduction or to any prior collisional orogeny, reflected continental break-up. Ilnicki *et al.* (2013) suggested that the generation of protoliths to metabasites of the western part of the OSD recorded processes related to final stages of the Cadomian orogeny and incipient Early Palaeozoic rifting of Gondwana that heralded the opening of the Rheic Ocean.

Szczepański & Ilnicki (2014) proposed that the evolution of a volcano-sedimentary sequence in the OSD involves three main stages: (1) the pre ~540 Ma evolution of an active continental margin and related back-arc basin ceased with the collision and accretion of the magmatic arc to the Gondwana margin; (2) Early Cambrian rift to drift transition (540–500 Ma) and development of a depositional basin characterized by basic volcanic activity and filled with detritus derived from remnants of the magmatic arc; (3) Peri-Gondwana breakup leading to the formation of shallow-water passive margin depositional basins filled with quartz-rich detritus resembling Early Ordovician Armorican Quartzites known from other parts of the Variscan Belt.

The above short review shows that the significant progress was made during last 12 years in broadening our knowledge on evolution of rocks which eventually formed the Variscan basement of the Orlica–Śnieżnik Dome and its Upper Cretaceous cover. As it often happens, new data has created some new problems and some old problems are still unresolved. We hope that the review will help to identify what we have learned up to now, what is still poorly known, controversial or misinterpreted and thus remains debatable, and what is unknown and needs to be studied better or in greater detail in the future. Certainly some more work is to be done and further research is ahead of us. Let us meet in the dome after next 12 years.

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