Geologia Sudetica, 2006, 38: 63–80.

Syntectonic Lower Ordovician migmatite and post-tectonic Upper Viséan syenite in the western limb of the Orlica-Śnieżnik Dome, West Sudetes: U-Pb SHRIMP data from zircons

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Key words: Variscan orogen, Bohemian Massif, Gierałtów gneiss, mesosome, Ca-Fe garnet, Śnieżnik gneiss, partial melting, mantled dome.

Abstract In the Orlica-Śnieżnik Dome, the West Sudetes, metagranites of 515–480 Ma age occur as coarse-grained augen gneisses (~ Śnieżnik type) in the middle of the dome, whereas fine-grained, often migmatitic gneisses (~ Gierałtów type) are located more externally. Both the origin and genetic relationships of the gneisses have been disputed for many years. In a quarry near Zdobnice, in the western part of the dome, migmatitic gneisses and a post-tectonic dyke of unfoliated biotite-hornblende high-K syenite occur. The migmatititc gneiss has mesosome with relic minerals, notably Ca-Fe garnet and pseudomorphs after Al_2SiO_5 polymorph (?), indicative of an early granulitic metamorphism at considerably high pressure and temperature. Retrogression at still high temperature of ~720–750°C under the upper amphibolite facies conditions was accompanied by migmatization which among others produced cross-cutting neosome veins of graphic granite. Zircons from the melt derived neosome and from the syenite dyke were analysed with SHRIMP II. The former yielded a concordia age of 485±12 Ma which is taken to constrain the waning stage of the Late Cambrian–Early Ordovician migmatization. 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. Our new data shows that the migmatization in the Orlica-Śnieżnik Dome was concurrent with the intrusion of a granitic precursor of the augen gneisses and does not support the views that the migmatitic gneisses can be a derivative of the ~500 Ma granite. In the Late Cambrian–Early Ordovician, the porphyritic granite intruded in migmatitic country rocks which mantled the granitic core. Both lithologies were later ductilely sheared and deformed under lower conditions of the amphibolite and greenschist facies during the Variscan orogeny. Four zircon grains from the post-tectonic syenite dyke yielded a concordia age of 326±3 Ma, which is interpreted as the time of its intrusion. This constrains the ductile Variscan events in the studied region.

Manuscript received 10 June 2006, accepted 14 October 2006

INTRODUCTION

In the West Sudetes, the NE Bohemian Massif, as in other parts of the Variscan belt in Europe, there are widespread orthogneiss bodies of various dimensions, the granitic protoliths of which intruded between 515 Ma and 480 Ma (van Breemen *et al.*, 1982; Borkowska *et al.*, 1990; Oliver *et al.*, 1993; Kröner *et al.*, 1994; Kröner *et al.*, 2000). The intrusions are usually connected with a phase of crustal extension related to the Cambro-Ordovician breakup of Gondwana. However, the details of the extensional events in that time span are obscured and poorly known. Scarce field evidence (Don, 1989) suggests that granitic S-type magma intruded in metasedimentary rocks whose protoliths were metamorphosed and deformed either before or coevally with the intrusions. The latter option predicts that magmatic and metamorphic processes must have been driven by heat from some common source, and accompanied at least locally by migmatization. This seems to be the case of the Orlica-Śnieżnik Dome in the West Sudetes. We performed U-Pb SHRIMP dating of zircons from a neo- some in the migmatitic gneiss, and from a cross-cutting, unfoliated syenite vein to constrain the age of the migmatization and termination of ductile tectonic events, respectively.

GEOLOGICAL SETTING

In the Orlica-Śnieżnik Dome, the West Sudetes, gneisses of 515–480 Ma age are ubiquitous (Fig. 1). A few variants of two main types of the gneisses, namely of coarse-grained augen gneisses (~ Śnieżnik type) and of fine-grained, often migmatitic gneisses (~ Gierałtów type) have been distinguished for the first time in the eastern part of the dome (Fischer, 1936). In the western part of the dome (Fig.2), these two main types are locally referred to as the Bystrzyca and Orlica gneisses, respectively. Origins of the gneisses have been disputed for many years, however, with attention drawn usually to different data, observations and arguments (e.g., Borkowska *et al.*, 1990; Borkowska & Dörr, 1998; Borkowska & Orłowski, 2000; Turniak *et al.*, 2000; Kröner *et al.*, 2001; Don, 2001; Grześkowiak & Żelaźniewicz, 2002; Lange *et al.*, 2002; see reviews in Don *et al.*, 1990, Żelaźniewicz *et al.*, 2002 and Lange *et al.*, 2005). Some authors argue for different protoliths of different ages, whereas other authors suppose that texturally diverse, but geochemically similar granitic rocks once formed a single granitoid batholith of Early Palaeozoic age that responded differently to deformation and metamorphism in Early Carboniferous times. Yet other workers point to the presence of migmatitic xenoliths within augen gneiss which are similar to the surrounding migmatitic gneisses. They argue that the augen gneisses developed from porphyritic granites which derived from more advanced products of anatectic melting than the migmatitic gneisses themselves, and that all the gneisses were further diversified during the Variscan deformation and metamorphism.

Based on recent isotopic data, although obtained almost exclusively from the augen gneisses, many authors stress the significance of the 515–480 Ma magmatic events in the entire Sudetes (see review in Franke & Żelaźniewicz, 2000). Important details of the events which actually occurred in the ca. 35 m.y. long interval are, however, obscured and remain largely unknown. In the Izera-Karkonosze Block, an S-type granitic magma intruded mica schists of Neoproterozoic protolith age and late to post-orogenic Cadomian granodiorites (Żelaźniewicz *et al.*, 2003; Oberc-Dziedzic *et al.*, 2005). In the Orlica-Śnieżnik Dome, the S-type granitic magma apparently also intruded

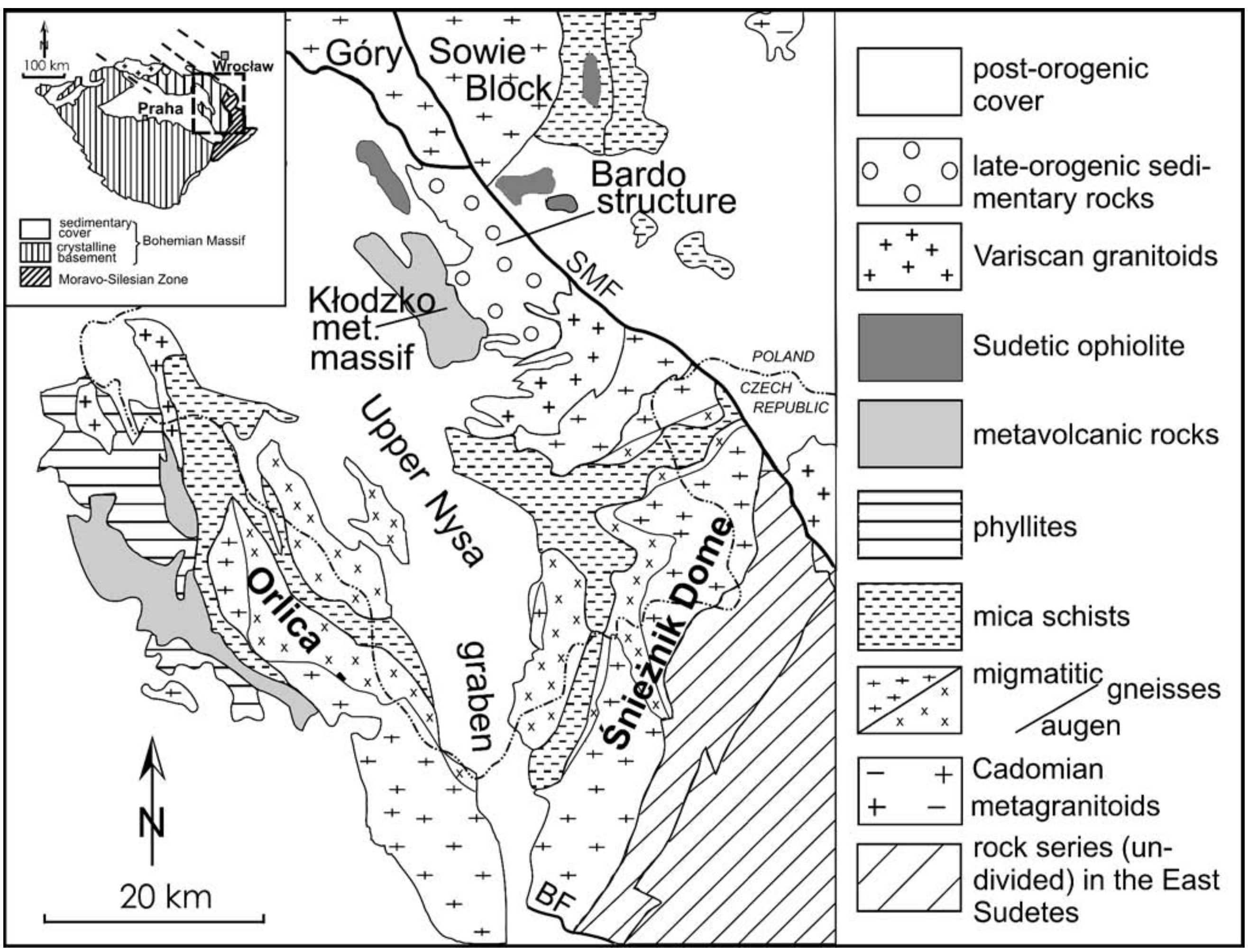


Fig. 1. Geologic sketch of the Orlica–Śnieżnik Dome showing its position in the Sudetes and in the Bohemian Massif (inset). BF – Bušin Fault; SMF – Sudetic Marginal Fault.

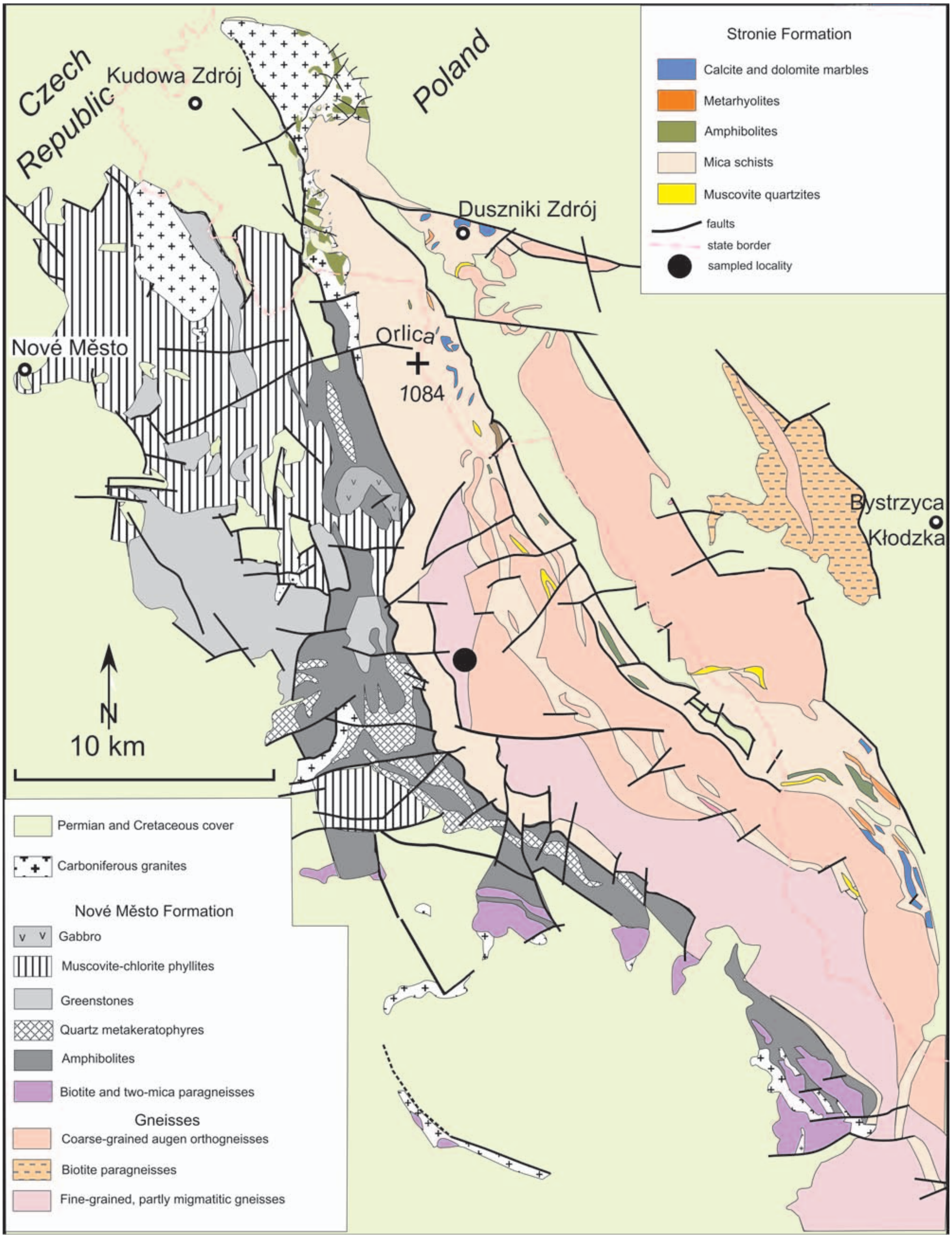


Fig. 2. Geologic sketch map of the western limb of the Orlica-Śnieżnik Dome (after Opletal *et al.* 1980; Sawicki, 1995; Żelaźniewicz, 2006).

a metasedimentary-volcanogenic series, but protoliths of the latter were deposited in Early-Middle Cambrian times at ca. 520–505 Ma as indicated by the Pb-Pb and U-Pb SHRIMP ages of zircons retrieved from acid metavolcanic intercalations in the mica schists across the dome (Kröner *et al.*, 2001; Murtezi, 2004, 2006). These data suggest that sedimentation and acid volcanism apparently started earlier than plutonism, then all the processes were possibly concurrent between 515 Ma and 505 Ma and must have been accompanied by coeval metamorphism because the porphyritic granites intruded metasediments of Cambrian age (Don, 1989).

SAMPLED ROCKS

Gneisses

In the Orlické hory, to the W of the village of Zdobnice, near the road to Kunčice Ves, close to the boundary between the two main types of gneisses (Fig. 2), there is a small abandoned quarry of pinkish gneisses that have been cut by a dyke of unfoliated biotite-hornblende high-K syenite. The rocks are rather poorly exposed, but two varieties of gneisses are megascopically distinguishable: (A) a prevailing fine-grained variety with two micas and irregularly distributed streaks of reddish quartzo-feldspathic leucosomes (Fig. 3, 4), and (B) a coarse-grained flaser variety with a strong foliation defined by reddish feldspathic layers and greyish quartz lenticles (Fig. 5).

The quartzofeldspathic streaks and layers in gneiss A have irregular, sutured and/or diffused boundaries, and their width and spacing differ considerably (Fig. 3, 4a). They may appear as scarce single lenticles set in a groundmass which is relatively richer (Fig. 3a) or poorer (Fig. 3b) in micas and garnet. The lenticles and layers may also increase in number and coalesce into broader bands which entrap micas and groundmass pods (Fig. 3c), or form numerous diffused layers that dominate the groundmass (Fig. 3d) and happen to be folded (Fig. 3e, 4b). Such coalescence combined with flow folding eventually led to the formation of enormously thick feldspathic bands with parallel selvages or pods of other minerals (Fig. 3f), which gave the gneisses their characteristic outlook of stromatic migmatites. The observed stromatic and flow textures suggest segregation and partial melting which allowed the redistribution of the matter in the migmatitic gneisses (compare the gneiss of Figure 3a and the gneiss on Figure 3f).

The migmatitic processes that brought about the stromatic textures (Fig. 4a) were followed by deformation overprint which produced an oblique biotite-muscovite foliation (Fig. 4a) and asymmetric ductile folds in the feldspar-dominated layers to which this foliation was axial planar (Fig. 4b). In tight to isoclinally folded domains, the feldspathic layers were thickened by doubling and became parallel with the new mica foliation. Further deformation was accomplished by zonal shearing which overprinted this foliation. However, parallel to the axial planes of the tight folds, injections of leucogranitic neosome occurred locally (Fig. 4 b). The same neosome also discordantly intruded into the N–S trending irregular openings (Fig. 4c) and remained undeformed, which is an observation of key importance for this study.

The flaser gneiss (type B) appears in two variants in which the coalescing K-feldspar dominated streaks or lenticles are relatively thick (3–5 mm). In one variant, such discontinuous lenticles are set in a polymineral groundmass (the upper portion of the rock on Figure 5a). In the other variant, greyish quartz lenticles appear in the groundmass and alternate with the feldspathic ones (the lower portion of the rock on Figure 5a; Fig. 5b). In cases where the subsequent shearing overprint enhanced the ribbon-like quartzes, the rock may superficially resembles gneiss that derived from a ductilely strained granite. However, no adequately coarse-grained granite protolith is in evidence nearby and the observed zonal concentrations (Fig. 5) of the distributed quartz lenticles seem incompatible with derivation from a homogeneous granite, which rather disproves such a possibility.

In order to control and verify the megascopic observations, a suite of thin sections was made. The microscopic observations (Fig. 6, 7) show that the migmatitic gneisses are composed of microcline, quartz, plagioclase, biotite, muscovite, with relic garnet and pseudomorphs after an unknown mineral (Al_2SiO_5?), mainly composed of white mica and (albitic) plagioclase. These relict minerals are particularly abundant in the streaky gneisses with little leucosome layering (Fig. 3a, b) and in the mesosome portions of migmatitic domains (Fig. 6a, b).

The relict minerals form distinctive arrays parallel with the elongation of feldspar and quartz grains, which likely represents an early (pre-migmatitic) fabric (Fig. 6a, b, 7g). This fabric, although more or less obscured by later recrystallization, can be still recognized in the migmatized gneisses as strongly elongate grains (Fig. 7a–d). The elements of the distinct fabric once possessed by the studied rocks occur along with irregular aggregates of more or less equant quartz and feldspar grains (Fig. 7d) which testify overprint of high-temperature recrystallization interpreted as a record of subsequent anatectic melting.

The microcline (sometimes still perthitic) grains, whether elongate or in such irregular aggregates, were zonally subjected to myrmekitization, locally intensive, which overprinted and largely obliterated the earlier fabric. There is a rather weak correlation between the ductilely deformed planar zones and the abundance of myrmekite (Fig. 7a, e,g), and the presence of unbroken and undeformed myrmekite grains suggests that the process was not extensively controlled by deformation. Marginal, zonal, patchy or wholesale intergrown plagioclase-quartz grains are accompanied by randomly occurring K-feldspar-quartz micrographic intergrowths (Fig. 7a, e) which further testify to volatile assisted partial melting. Such intergrowths are usually ascribed to crystallization from a silicate melt or from a vapour phase (Mehnert, 1971; Fenn, 1986) con-

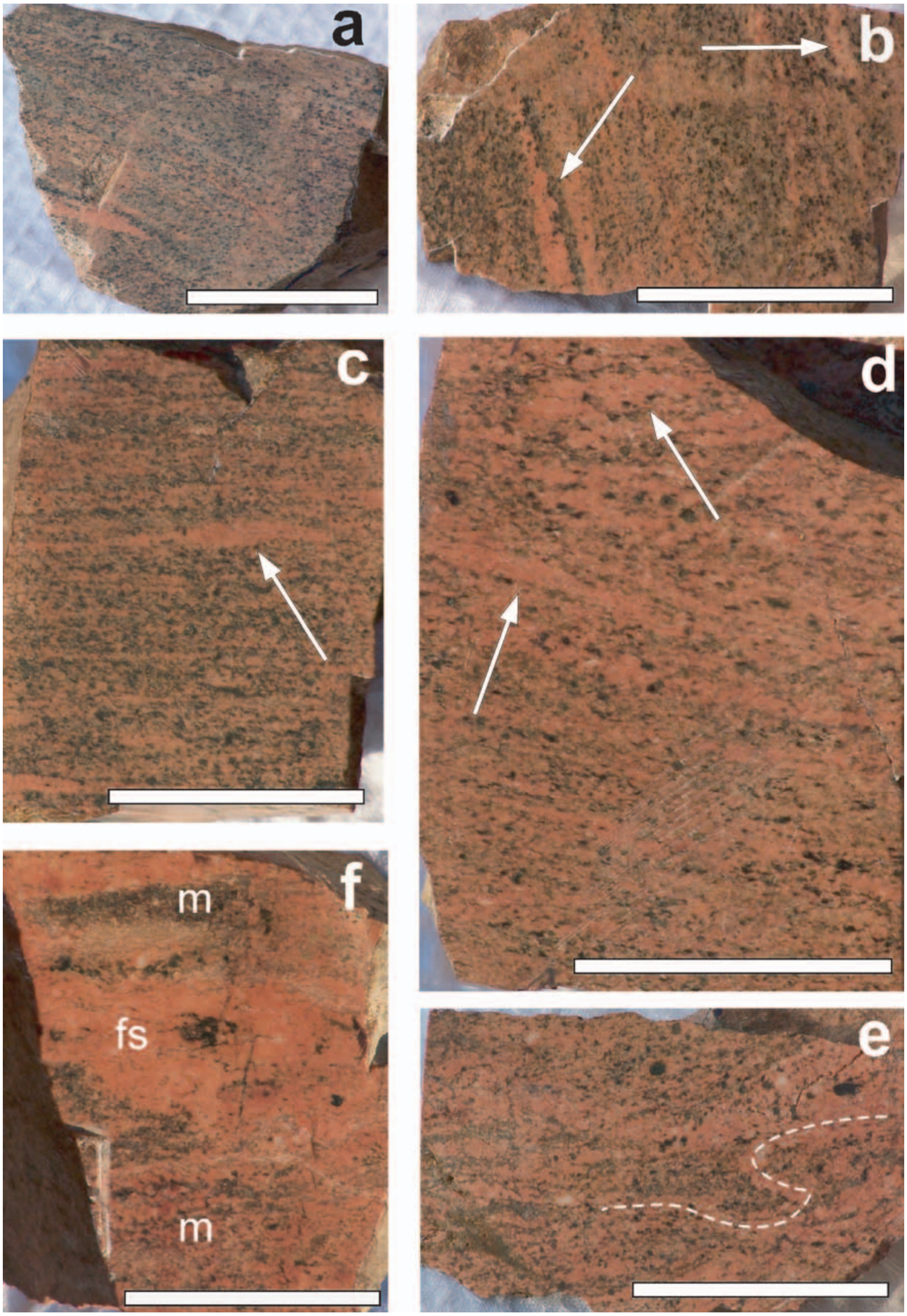


Fig. 3. Migmatitic gneisses of Zdobnice. **a** – fine-grained streaky gneiss with scarce leucosome layers; **b** – streaky gneiss grading to stromatic migmatite due to growing number of leucosome segregations with irregular boundaries (arrows); **c** – stromatic migmatite, note diffused boundaries of leucosome layers (arrows); **d** – stromatic migmatite with dominant leucosome layers; **e** – diffused S-shape flow folds in migmatitic layering (white dashes); **f** – stromatic migmatite with mesosome (m) layers and pods alternating with thick feldspar (fs) layers. Scale bars are 3 cm long.

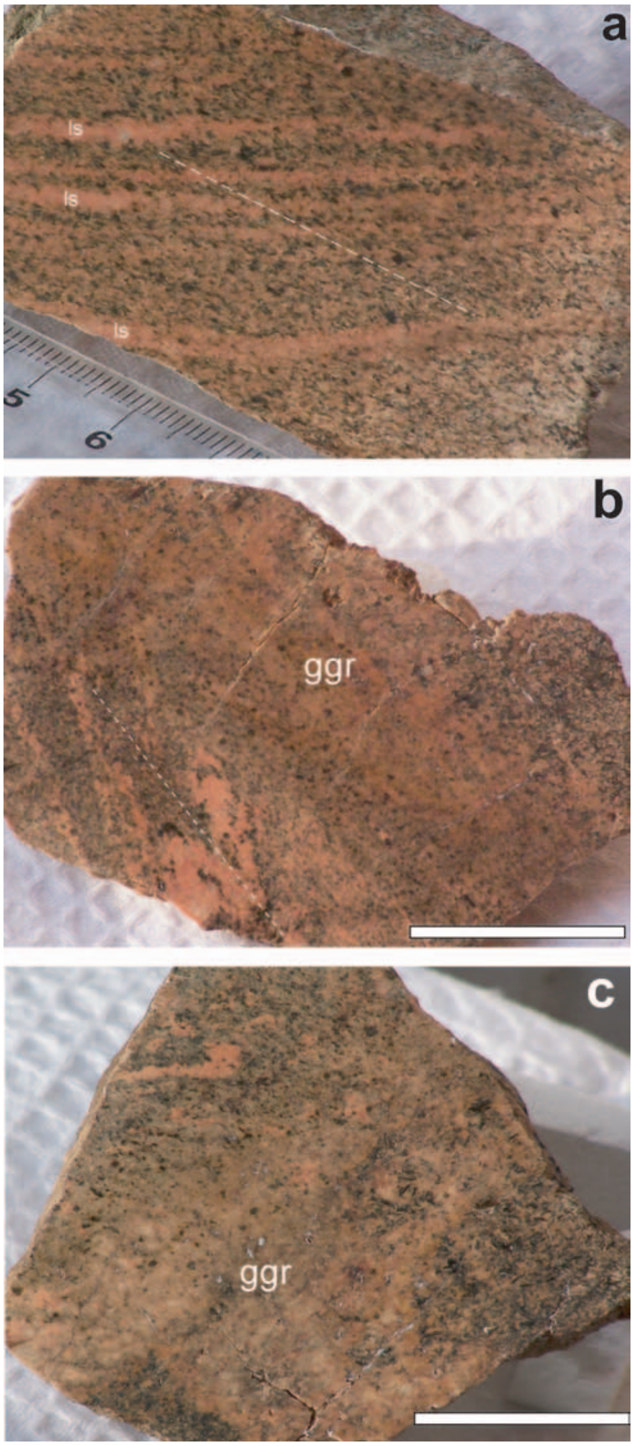


Fig. 4. Deformed migmatitic gneisses. **a** – leucosome (ls) layering overprinted by mica foliation (dashed line); **b** – folded stromatic migmatite with the axial planar injection of granitic neosome (ggr); **c** – intrusive vein of graphic granite (ggr) intersecting earlier foliation and leucosome layering. Scale bars in b and c are 3 cm long.

trolled by pressure (Černý, 1971; Lentz & Fowler, 1992), although metasomatic replacement may also contribute (Seclaman & Constantinescu, 1972).

In the mesosome layers, multiple coronitic garnet (Fig. 7h) and polymineral pseudomorphs after unknown mineral (Fig. 7f, h) occur. They retain their former shapes

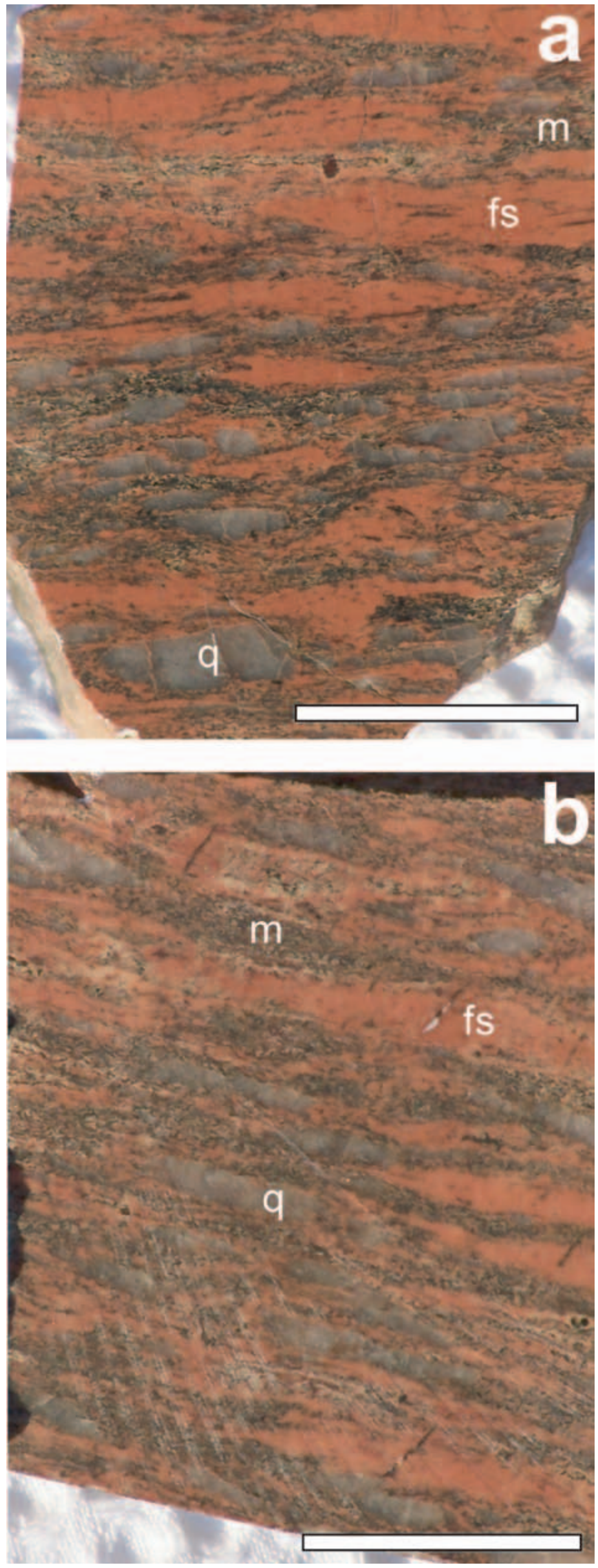


Fig. 5. Flaser gneiss. **a** – lower part: zonal distribution of quartz lenticles, upper part: mesosome (m) bands with abundant relict garnet and mica-feldspar pseudomorphs, note obscured isoclinal folds; **b** – polymineral K-feldspar-plagioclase ± quartz leucosome (fs), mesosome (m) and short quartz lenticles (q). Scale bars are 3 cm long.

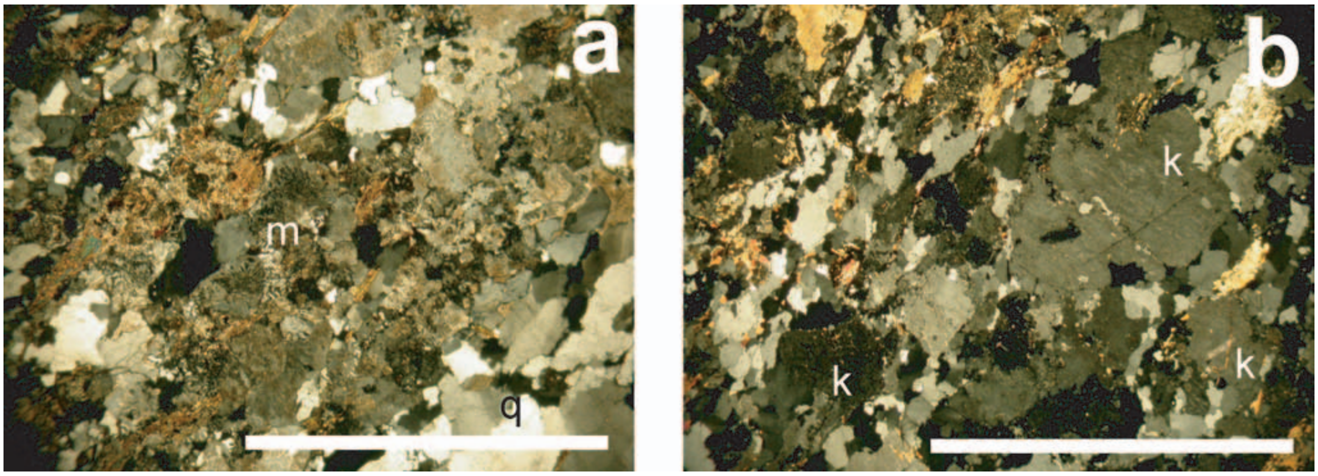


Fig. 6. Microphotographs of undeformed graphic granite in the neosome vein. Similar micrographic intergrowths develop in the myrmekitized K-feldspar aggregates in migmatites. Scale bars are 2 mm long.

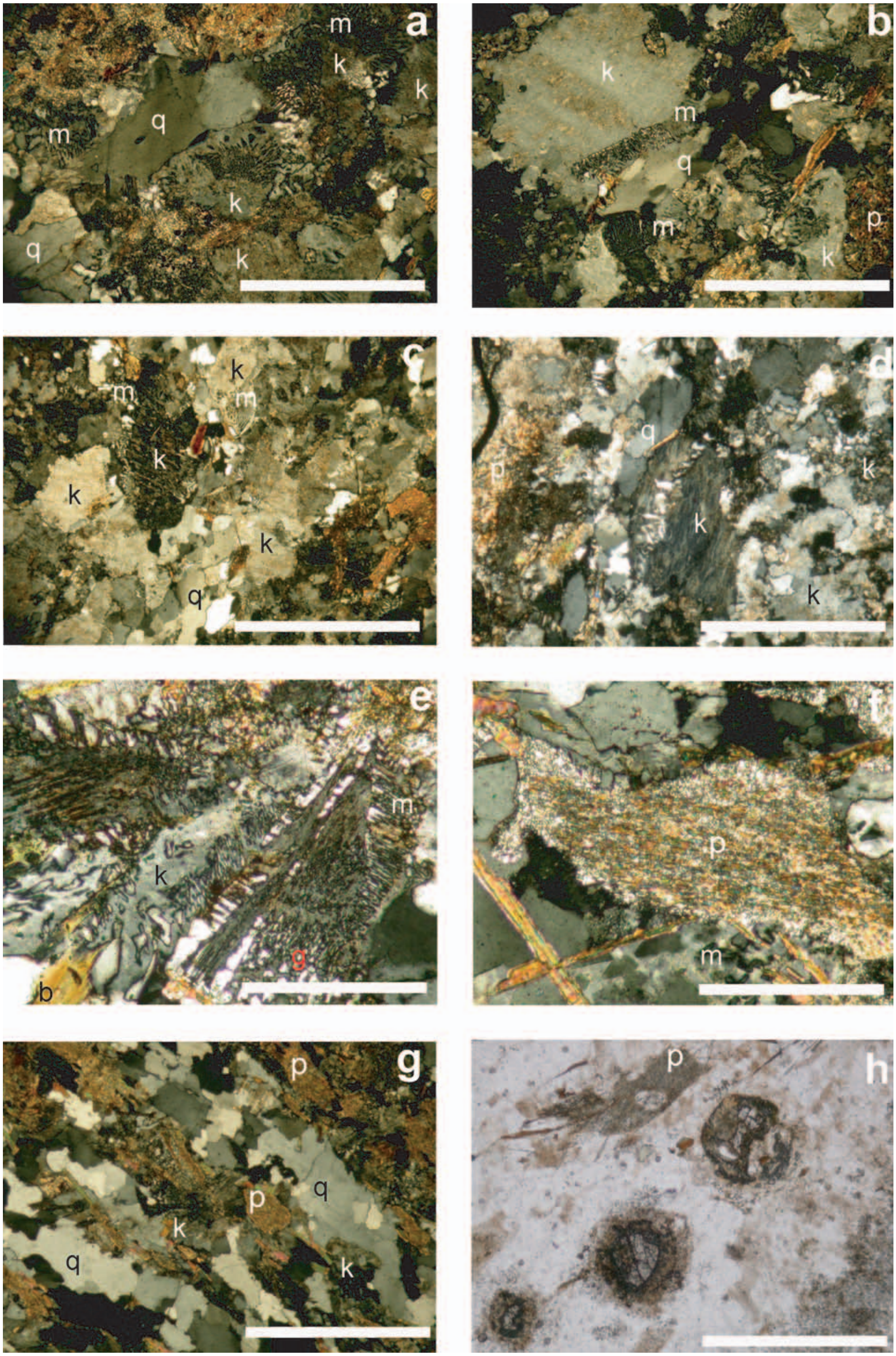
against their felsic neighbours, suggesting a complex metamorphic history of the stromatic migmatites. The garnet cores are rich in Ca (up to 30%) and Fe, and are surrounded by zones (where fully developed) of fine-grained white micas (compositio- nally close to muscovite) and then in turn by Fe-rich garnet rims, with biotite neoblasts in the outermost halos (Fig. 7h). Garnet with such unusual Ca-Fe composition was already reported from the migmatitic and augen gneisses of the Międzygórze area, and interpreted as relicts of the HP stage the original rock underwent earlier in its history (Borkowska *et al.*, 1990; Bröcker & Klemd, 1996; Stawi- kowski, 2006). An aggregate of muscovite (Si content of 3.25–3.4) and albite form pseudomorphs after an unidentified mineral (Al_2SiO_5 polymorph?). The Si content in the matrix muscovite is around 3.0–3.1. The pseudomorphs are adorned by the directionally oriented biotite flakes which overprinted the white mica-feldspar assemblage.

Besides adorning the pseudomorphs, biotite occurs in the matrix and also adjacent to the retrograde garnet. Irrespective of their position, the biotite grains have similar composition (Mg# 0.15–0.35), which suggests that they recrystallized in the conditions allowing for the retrogression of garnet, formation of pseudomoprhs, and development of myrmekite and micrographic intergrowths. To estimate temperature of these processes, garnet-biotite geothermometry was applied to almandine rims of garnets and adhering biotites. Using various calibrations (Bhattacharya *et al.*, 1992; Ganguly & Saxena, 1984; Perchuk & Lavrent'eva, 1983), and assuming pressure of 7 kbar, a temperature within the range of 722–752°C were obtained for these pairs, which is consistent with petrographic evidence for recrystallization of the studied rocks under the amphibolite facies conditions. The quartz microstructure in such layers (Fig. 7g) also points to high-temperature recrystallization. At such temperatures, partial melting assisted by concurrent operation of volatiles could cause migmatization and profound modification of mineralogy of these rocks which likely originated as granulites.

Although further details of this complex story are beyond the scope of this paper, the evidence shown above seems convincing enough to claim that the polimineral K-feldspar-plagioclase-quartz layers in the stromatic migmatite (Fig. 3, 4) and in the flaser gneisses (Fig. 5) are products of migmatization and irrespective of the superficial similarities of the latter they do not represent plastically deformed K-feldspar phenocrysts subjected to dynamic recrystallization and grain size reduction as occurred in the genuine augen orthogneisses that occupy the core of the Orlica-Śnieżnik Dome (Fig. 1, 2).

The observed injections of leucogranitic neosome are composed of a graphic granite with characteristic intergrowths of K-feldspar and quartz (Fig. 4b,c, 8a,b). Rocks of this type are usually taken as evidence of the presence of a magmatic melt from which alkali feldspar and quartz crystallized simultaneously (Fenn, 1986) at volatile-saturated conditions (Lentz & Fowler, 1992), although crystallization from a vapour phase (Simpson, 1962) is also feasible. The graphic leucogranite injections utilized the axial planar zones in synmigmatitic folds (Fig. 4a) and were roughly controlled by N–S oriented openings, thus were normal to the observed E–W folds. Accordingly, the syntectonic migmatization controlled by the E–W extension was accompanied or immediately followed by the intrusions of leucocratic facies of a granitic magma.

Summing up, the mineralogy of the studied rocks still retains evidence of having passed through a granulitic high-pressure stage (Fig. 7h), followed by deformation and fluid-assisted retrograde amphibolite facies metamorphism. The latter allowed for the decompression triggered partial melting and formation of the leucosome layering that later underwent deformation/folding, which in turn preceded the granite neosome intrusions. As mentioned in the Introduction, the problem of the origins and relationships of the gneissic lithologies in the Orlica-Śnieżnik Dome has yet to be resolved satisfactorily, despite over 80 years of research (see Don *et al.*, 1990, 2003; Żelaźniewicz *et al.*, 2002; Lange *et al.*, 2005). The data collected in the Zdobnice quarry shows that the migmatitic gneisses exposed there (Fig. 3–7) differ substantially from the augen orthogneisses, thus it supports the view of two originally different types of gneisses in the Orlica-Śnieżnik Dome.


a
m k k m q k q k
b
k m q m p k
c
k m m k k k q
d
q p k k k
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g
p q p k q k
h
p

Fig. 7. Microphotographs of migmatitic gneisses. **a** – myrmekitized aggregate of K-feldspar with single elongate quartz grains; **b** – perthitic microcline grain with myrmekite rim separated by single quartz from myrmekitized aggregate of finer grained microcline developed by earlier recrystallization; **c** – marginally myrmekitized elongate K-feldspar grains which formed early fabric together with elongate quartz grains showing evidence of high-temperature recrystallization (triple point boundaries, prismatic subgrains parallel to the foliation), note that the quartz aggregate is slightly oblique to the subvertically arranged feldspars; **d** – from left to right: white mica-feldspar pseudomorph, highly elongate quartz aggregate, perthitic microcline dissected by myrmekite blebs, aggregate of quartz and feldspar recrystallized from partial melt, all grains define the subvertical foliation; **e** – undeformed myrmekite developing concurrently with biotite and micrographic intergrowths; **f** – white mica-albite pseudomorphs, they are adorned by the directionally oriented biotite flakes which overprinted the white mica-feldspar assemblage; **g** – quartz aggregates of grains with lobate boundaries indicative of grain boundary migration recrystallization and prismatic subgrain boundaries parallel to the foliation trace, all pointing to high temperature differentiation and recrystallization; **h** – mesosome: an array of multiply retrograde garnet and parallel arranged mica-feldspar pseudomorph (upper left), parallel polars. Abbreviations: biotite (b), K-feldspar (k), micrographic intergrowths (g), myrmekite (m), pseudomorphs (p), quartz (q). Scale bars are 1.5 mm long.

In the quarry, the foliation planes in the migmatitic gneisses dip at moderate angles to the west or northwest (280/50, 320/40, 240/80). The E–W folds in the feldspathic streaks/layers have two senses of asymmetry suggestive of the presence of bigger mesoscopic folds, which, although obscured, may account for the observed differences in the foliation attitude. Three lineations are in evidence. One is an intersection lineation (Fig. 4a) parallel to the ~E–W oriented axes of tight to isoclinal synmigmatic folds (Fig. 4b), with the minerals of their hinge zones often turned into feldspathic porphyroblasts (not to be misidentified as porphyrocrysts). Another is a mineral lineation represented by a preferred orientation of biotite and/or muscovite, arrays of relict garnet and mica-feldspar pseudomorphs. It plunges very shallowly to the WNW or N–S. This lineation overprinted the high-temperature synmigmatic folds and because it is formed by the same minerals we expect that it was synmigmatitic too. The third lineation is a mineral stretching lineation (the youngest of the three) which overprinted the other two in the form of stretched feldspars and particularly quartz segregations. It strikes almost subhorizontally in mainly N–S or NE directions and was brought about by the superimposed shearing in the thrust or strike-slip regime (recent attitude of the foliation) at lower temperatures (lower amphibolite to greenschist facies).

The two younger lineations are broadly co-linear and thus may happen to be misidentified as a single stretching feature with varying plunge orientation: to NNW, N, NE, or also S-ward. The recognition of the high-temperature, E–W oriented lineation which was overprinted by the lower temperature N–S oriented lineation is generally consistent with the observations of Přikryl *et al.* (1996) performed in the Orlické hory gneisses of the western Orlica-Śnieżnik Dome. They found the E–W lineation in the migmatitic gneisses that underwent partial anataxis in pre-Variscan times, whereas the N–S lineation was to represent a younger, Variscan overprint in the migmatites and a dominant linear feature in the augen gneisses.

The N–S directed shearing enhanced the planar fabric in the flaser gneisses by a concentration of the ductile deformation into weak quartz segregations that turned into ribbons and into more micaceous foliae. Once this deformation superposed the fabric in the migmatitic gneisses, the latter underwent considerable strain increment and may have acquired outlook of a sheared granite (Fig. 5). Then they megascopically resemble mylonitic augen orthogneisses, except that the augens, if present, were de-

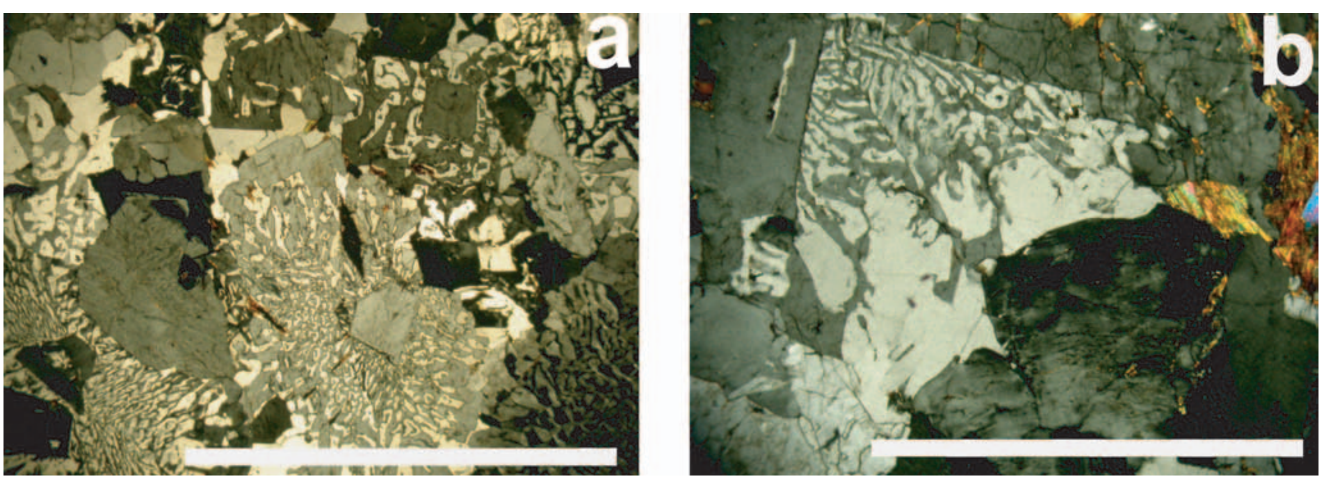

Fig. 8. Zonal occurrence of myrmekites. **a** – myrmektized K-feldspars (m) in mesosome neighboured by high-temperature recrystallized quartz (q); **b** – not myrmekitized K-feldspars (k) in slightly migmatized (scarce leucosome) streaky gneiss of type A (see Fig. 3a), such rock contains Ca-Fe garnet and pseudomorphs after Al_2SiO_5(?) and forms mesosome in the migmatitic domains. Scale bars are 2 mm long.

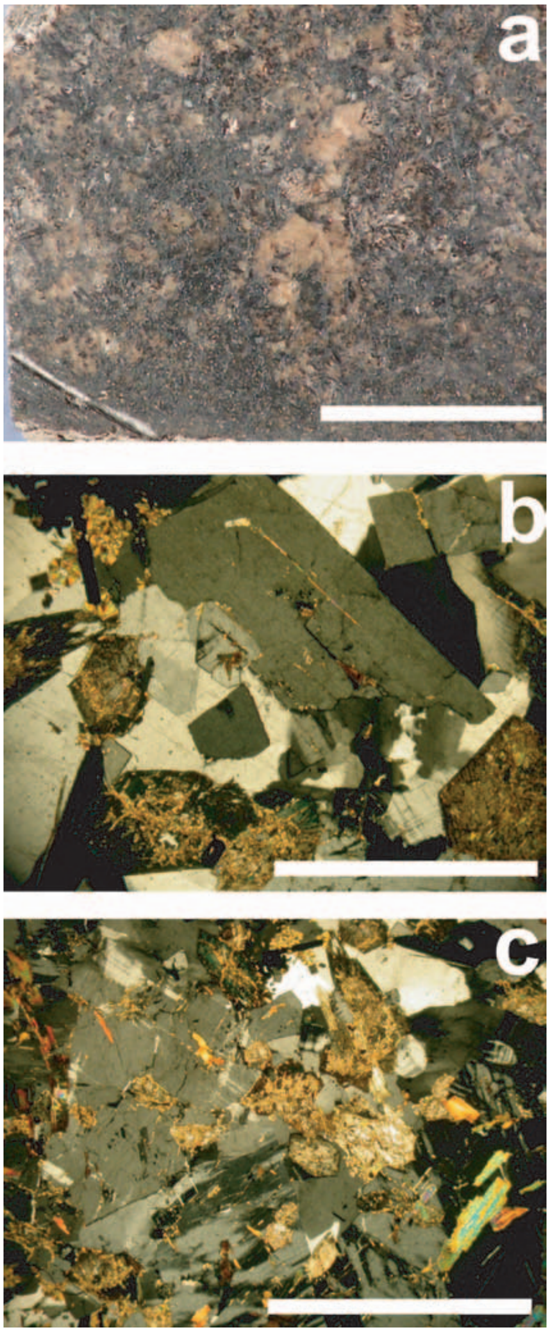

Fig. 9. High-K post-tectonic syenite. **a** – polished section of the rock sample, scale bar is 3 cm long; **b** – euhedral crystals of K-feldspar and hornblende; **c** – poikilitic K-feldspar with smaller hornblende and biotite crystals. Scale bars in b and c are 2 mm long.

rived from the porphyroblasts of which a part often grew in the fold hinge regions (Fig. 4b).

Syenite

The syenite is a dark medium-grained, unfoliated rock composed of K-feldspar, hornblende and biotite (Fig. 9 a, b, c). Both its texture and field relationships confirm its post-tectonic position. In the quarry, the syenite vein is seen to have intruded along a fracture which dips shallowly SE-wards and cross-cuts the folded foliation of the sheared migmatitic gneisses.

Geochemistry

Geochemically (Table 1), the gneisses are equivalent to high-K (alkali) granite which do not differ from other gneisses, quartzofeldspathic granulites and acid metavolcanites (leptites) in the Orlica-Śnieżnik Dome (Murtezi, 2004, 2006), which are high-K, peraluminous rocks with relatively low Sr, Ba, Ca and Mg but high Rb contents typifying granites of S-type. The vein rock classifies as metaluminous syenite or quartz monzonite (TAS or R1-R2 diagrams, respectively) that has significantly higher contents of trace and REE elements and much different REE pattern when compared to the migmatitic gneiss (Table 1).

ZIRCON SAMPLES

Zircons were retrieved from the granitic neosome domain in the migmatitic gneiss (sample Migm) and from the syenite vein (sample Syen). They differ significantly. Most zircons of sample Migm are euhedral, short prismatic (120–150 μm long), with a low aspect ratio of 1:2 to 1:3, and oscillatory zoning characteristic of igneous rocks (Fig. 10). Their internal structures differ. One group of grains shows simple and uniform zonation pattern (grains 4, 7, 6, 9, 11, 12) so that they might crystallized possibly during one event. The zircons of the second group are complex, with differently structured cores and rims (grains 1, 2, 3, 8,10) pointing to at least two growth episodes. The minor third group is represented by zircons anhedral, often rounded, zoned or not (grain 13), which are likely detrital. Zircons of any of these groups may have been rimmed by usually thin, black (U-rich) outgrowths (grains 1, 2, 3).

The zircons of sample Syen are slightly bigger (160–200 μm long), with an aspect ratio not less than 1:3. Viewed in the transmitted and reflected light, the grains are euhedral. In the CL images, however, they are all dark and spotty (Fig. 11) owing to very high U-content (Table 2), which may render them difficult to use for U-Pb analyses. The more or less greyish spots in most cases do not reflect the structure of the grains rather, but some unidentified processes (hydrothermal fluid influence?).

ISOTOPIC STUDIES

Previous data

The rocks in the western part of the Orlica-Śnieżnik Dome have been the subject of fewer isotopic studies than those of the eastern part, but the results are broadly similar. Several isotopic age numbers were obtained for augen orthogneisses outcropped in the Góry Bystrzyckie Mts. (Poland) and in the Orlické hory Mts. (Czech territory). A selection of 7 samples yielded the Sm-Nd ages of 503–510

Ma (Hegner & Kröner, 2000). The zircons from the same rocks samples were also subjected to Pb-Pb and/or U-Pb analyses the results of which entirely confirmed the earlier timing (Kröner *et al.*, 2001). Combined with the distinctly negative $\varepsilon_{Nd(t)}$ values between –3 to – 6 and various zircon xenocrysts ages, this data was interpreted as evidence of extensive melting of the Precambrian crust which gave rise to the granitic precursors of the Orlica-Śnieżnik Dome gneisses. From the Zdobnice quarry, Kröner *et al.* (2001) reported the dating of a ca. 10 m wide unfoliated amphibole-biotite microgranite dyke, the zircons from which yielded the Pb-Pb age of 491.7 ± 1.0 Ma. Since the dyke rock has been classified by us as a medium-grained syenite (Fig. 9 a,b,c; Table 1) and not as a microgranite, and the host has been recognized as a deformed, ductilely sheared migmatitic gneiss (Fig. 3, 4) and not just a simply solid-state foliated metagranite as are the regular augen gneisses in the Orlica-Śnieżnik Dome, we decided to apply U-Pb SHRIMP analyses to zircons from both the host and the dyke rocks.

Methods

After a standard heavy liquid and magnetic separation procedure, zircons were handpicked under a microscope, mounted in epoxy and polished. Transmitted and reflected light photomicrographs and CL images were made in order to select grains and choose sites for analyses omitting cracks and inclusions. The Sensitive High-Resolution Ion Microprobe (SHRIMP II) at the Center of Isotopic Research (CIR) of the All-Russian Geological Research Institute (VSEGEI), St. Petersburg, was used to perform in situ U-Pb analyses by applying a secondary electron multiplier in a peak-jumping mode following the procedure described in Williams (1998) or Larionov *et al.* (2004). A primary beam of molecular oxygen was employed to bombard the zircon in order to sputter secondary ions. The elliptical analytical spots were c. 27 × 20 μm, and the corresponding ion current was c. 4 nA. The sputtered secondary ions were extracted at 10 kV. The 80-μm wide slit of the secondary ion source, in combination with a 100-μm multiplier slit, allowed a mass-resolution of $M/\Delta M \geq 5000$ (1% valley), so that all the possible isobaric interferences were resolved. One-minute rastering over a rectangular area of c. 60 × 50 μm was employed before each analysis in order to remove the gold coating and possible surface contamination with common Pb.

The following ion species were measured in sequence: $^{196}(Zr_2O)$-^{204}Pb-background (c. 204 AMU)-^{206}Pb-^{207}Pb-^{208}Pb-^{238}U-^{248}ThO-^{254}UO, with an integration time ranging from 2 to 20 seconds. Four cycles for each spot analyzed were acquired. Every fifth measurement was carried out on the zircon Pb/U standard TEMORA (Black *et al.*, 2003) with an accepted $^{206}Pb/^{238}U$ age of 416.75 ± 0.24 Ma. The 91500 zircon with a U concentration of 81.2 ppm and a $^{206}Pb/^{238}U$ age of 1062 ± Ma (Wiedenbeck *et al.*, 1995) was applied as a "U-concentration" standard. The collected results were then processed with the SQUID v. 1.12 (Ludwig, 2005a) and ISOPLOT/Ex 3.22 (Ludwig, 2005b) software, using the decay constants of Steiger & Jäger (1977). The common lead correction was done using measured ^{204}Pb according to the model of Stacey & Kramers (1975).

Table 1

Chemical analyses of migmatitic gneiss and syenite

		Migmatite	Syenite
SiO_2	%	73.85	60.14
Al_2O_3	%	12.82	10.55
Fe_2O_3	%	2.03	4.65
MgO	%	0.25	5.77
CaO	%	0.37	3.12
Na_2O	%	2.41	0.99
K_2O	%	6.24	9.63
P_2O_5	%	0.17	1.56
LOI	%	1.17	1.54
Total	%	99.49	99.67
Sc	ppm	4	10
Be	ppm	3	22
V	ppm	5	54
Cr	ppm	< 20	120
Co	ppm	134	41
Ni	ppm	40	110
Cu	ppm	< 10	< 10
Zn	ppm	< 30	80
Ga	ppm	15	19
Ge	ppm	1.3	2.2
As	ppm	< 5	20
Rb	ppm	259	623
Sr	ppm	31	623
Y	ppm	56.7	36.5
Zr	ppm	95	794
Nb	ppm	8.6	43.5
Mo	ppm	< 2	< 2
Ag	ppm	< 0.5	0.8
In	ppm	< 0.1	0.2
Sn	ppm	< 1	8
Sb	ppm	7.3	7.4
Cs	ppm	7.1	22.9
Ba	ppm	166	1980
La	ppm	16.6	91.6
Ce	ppm	37	239
Pr	ppm	4.69	38
Nd	ppm	19.9	172
Sm	ppm	4.98	35.6
Eu	ppm	0.236	4.95
Gd	ppm	5.26	19.4
Tb	ppm	1.25	1.84
Dy	ppm	8.87	7.64
Ho	ppm	1.84	1.18
Er	ppm	5.69	3.06
Tm	ppm	0.865	0.397
Yb	ppm	5.3	2.21
Lu	ppm	0.696	0.276
Hf	ppm	3.4	20.2
Ta	ppm	0.73	2.9
W	ppm	819	279
Tl	ppm	1.42	4
Pb	ppm	20	19
Bi	ppm	< 0.1	0.8
Th	ppm	11.5	130
U	ppm	2.95	28.4

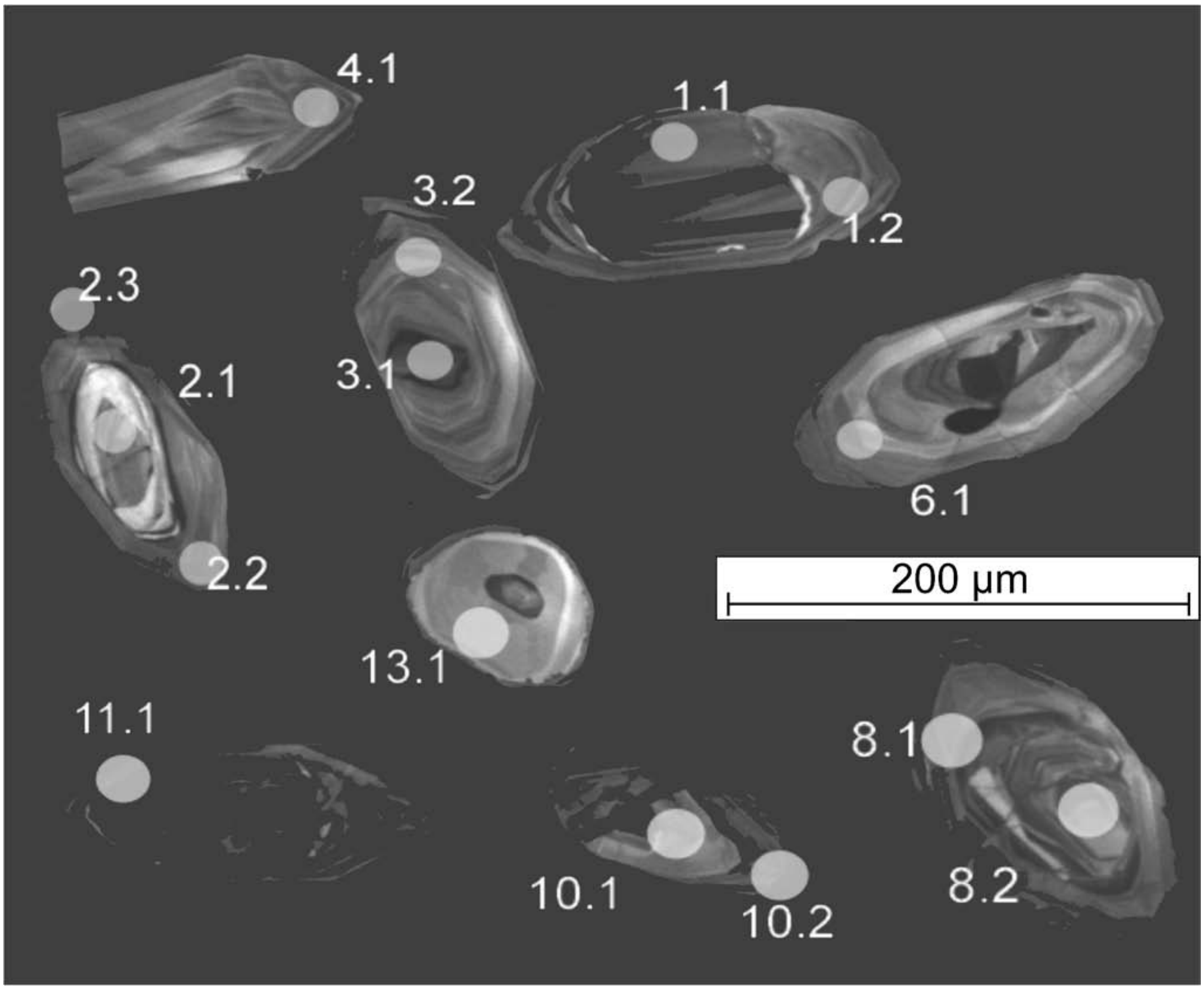

Fig. 10. CL images of the analysed zircons from the granite neosome veins, sample Migm.

Results

Table 2 contains the results of the U-Pb SHRIMP analyses which have been plotted on Concordia diagrams (Fig. 12, 13). For sample Migm (Fig. 12B), 12 grains out of 21 yielded a concordia age of 484.8 ± 12 Ma (6 analyses out of 21 yielded gave slightly more precise age of 482 ± 7 Ma) which is interpreted as the time of synkinematic intrusion/injection of the graphic granite neosome in the migmatitic gneisses. Three groups of zircons which have been distinguished by their CL images also show some differences in U-Pb systematics. The group of simply zoned grains (grains 3, 4, 6,11), which apparently crystallized from a melt yielded $^{206}Pb/^{238}U$ ages between ~500 Ma and 470 Ma (despite some lead loss). In the group of grains with the cores structured differently than simply oscillatory rims, the cores (grains 2, 8, 10) have $^{206}Pb/^{238}U$ ages spread between ~ 2426 Ma and 620 Ma. The latter represents inheritance similar to the age (~620 Ma) of the clearly detrital grains (grain 13). In this group of zircons, the rims are persistently younger than 500 Ma. Such rims along with the first group of zircons are all attributed to a late Cambrian–early Ordovician event of deformation and migmatization. In grain 2, the thin black outgrowth (No. 2.3), extremely rich in Pb, U and Th, and yielded a meaningless age of ~160 Ma. However, the presence of such outgrowths (grains 2, 3) draws attention to an unconstrained metamorphic event which was likely associated with fluid movement evidently younger than the ~500–480 Ma migmatization.

It is suggested that the Late Cambrian–Early Ordovician migmatization was accomplished by partial melting of fragments of Neoproterozoic crust. The distinctive graphic texture observed in the dated granitic neosome is consistent with derivation from a granitic melt. An age of the reworked crust is however poorly constrained. One detrital grain of ~ 620 Ma ages allows to infer the presence of a metasedimentary component whose protolith was derived from a crystalline source area of that age.

In sample Syen (Fig. 11), all zircons that appear spotty dark in CL are very rich in U and Th, with Th/U ratios ranging from 0.17 to 0.76 (such features render them similar to the black metamorphic outgrowths on the zircons from sample Migm). Despite the very high U contents and some lead loss, there is a pronounced cluster of zircons that provides consistent results. 4 analyses yielded a concordia age of 326±3 Ma (Fig. 13), which is interpreted as the time of intrusion of the post-tectonic syenite vein. This constrains the ductile deformations during the Variscan orogeny in the studied region.

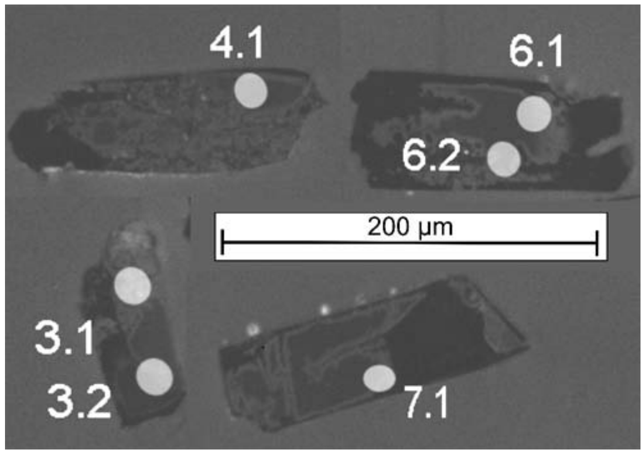

Fig. 11. CL images of the analysed zircons from the syenite vein, sample Syen.

DISCUSSION AND CONCLUSIONS

During mapping in the Orlické hory Mts. which form the western limb of the Orlica-Śnieżnik Dome, Opletal *et al.* (1980) distinguished finer grained gneisses of migmatitic habit located more externally and coarser grained augen gneisses located more centrally in the dome (Fig. 1, 2). The latter were compared with the Śnieżnik type gneisses and the former with the Gierałtów type gneisses discerned in the eastern limb of the Orlica-Śnieżnik Dome (see review in Don *et al.*, 1990, 2003; Żelaźniewicz *et al.*, 2003; Lange *et al.*, 2005). Having emphasized the textural differences, Opletal *et al.* (1980) did not draw any genetic distinction between the two types. Přikryl *et al.* (1996) worked with these rocks in the Orlické hory and found that the migmatitic gneisses differ from the augen orthogneisses because of their longer metamorphic and deformational history. These authors suggested that although both types were derived from ~500 Ma granitoids, the migmatitic gneisses with characteristically high-temperature deformational textures developed via anatectic melting already in Early Palaeozoic times. Kröner *et al.* (2001) dated several samples of basement gneisses in the Orlica-Śnieżnik Dome and assumed such model viable.

The Zdobnice quarry is the very locality from which Kröner *et al.* (2001) reported the presence of the ~492 Ma microgranite vein that intruded the already foliated orthogneiss. Seemingly similar augen gneiss occurring ca. 2 kilometres further N in the Zdobnice Valley was dated by these authors (Pb-Pb zircon) at 503 Ma. Such a relationship was interpreted as evidence of a gneiss-forming event between ca. 503 Ma and 492 Ma. It was also taken to imply that the early deformational/metamorphic event affected the ca. 500 Ma granite throughout the entire West Sudetes in early Palaeozoic times. The event was to have occurred in an Andean-type magmatic arc setting located at the active margin of Eastern Avalonia.

However, our studies conducted in the Zdobnice quarry show that the post-tectonic dyke is a high-K syenite and not a microgranite, which better conforms to the earlier assignments (Opletal *et al.*, 1980). It is obvious from the field relationships that the syenite vein intruded along a fracture in the solid rock after the ductile deformation of the host migmatitic gneiss had ceased. Thus, our data fits recent distinctions of post-collisional, high-K magmatic rocks that intruded late in the Variscan orogeny at 332–325 Ma (e.g. Hegner *et al.*, 1998). The intrusion age of 326±3 Ma obtained by us is consistent with the above interval. Our result does not contradict the observed evolution and relationships of local geologic features and plausibly constrains the ductile orogenic deformation in the Variscan cycle. The data, however, strikingly contrast with a Pb-Pb zircon age of 492 Ma reported for the same rock by Kröner *et al.* (2001), which is not easy to explain unless assuming that they happened to analyse zircon xenocrysts that were intercepted from the host migmatitic gneiss.

Despite the questionable timing of the syenite intrusion, the suggestion of Kröner's *et al.* (2001) about Early Palaeozoic metamorphism and deformation of the Zdobnice gneisses is still valid. It has been confirmed by our studies of the syntectonic granitic neosome which occurred as irregularly cross-cutting and axial-planar injections in the folded migmatitic layers (Fig. 4). The zircons from these unfoliated granite veins proved that the neosome was formed at ca. 484–482 Ma as a late or post-deformational feature in the migmatite series, and may define the upper age limit of the Early Palaeozoic tectonic event.

The disputable question is what sort of event it was and what the protolith of the migmatitic gneisses was. We have shown that the folded, ductilely sheared migmatitic gneisses (Fig. 3, 4, 5) from Zdobnice are not a simply solid-state foliated metagranite (in contrary to the regular augen gneisses in the centre of the Orlica-Śnieżnik Dome, Żelaźniewicz, 1984, 1988, 1991). Such gneisses may have represented a metasedimentary-metaigneous crust that underwent multistage metamorphism, granulite facies inclusive, and then yielded to partial melting between 515 Ma and 480 Ma. The latter processes led to the formation and subsequent emplacement of the S-type porphyritic granite magma in the core of the dome. Alternatively, the migmatitic gneisses may be regarded as a derivative of the ~500 Ma granite which would have undergone high temperature deformation and coeval migmatization immediately after its emplacement.

Our observations seem to speak in favour of the first option because this better explains:

– why the porphyritic granite body was located centrally with respect to the wide migmatitic peripheries, as

U-Pb isotopic results of zircon analyses

Table 2

Spot	% $^{206}Pb_c$	ppm U	ppm Th	$^{232}Th/^{238}U$	$^{206}Pb^*$ ppm	$^{206}Pb/^{238}U$ Age		$^{207}Pb/^{206}Pb$ Age		% Dis-cor-dant	$^{207}Pb^*/^{206}Pb^*$	±%	$^{207}Pb^*/^{235}U$	±%	$^{206}Pb^*/^{238}U$	±%	err corr
Migm.1.1	0.26	324	42	0.14	24.9	551	±16	457	± 75	-21	0.0561	3.4	0.691	4.5	0.0892	3.0	.669
Migm.1.2	0.05	316	17	0.06	20.8	476	±14	550	± 48	13	0.0585	2.2	0.619	3.8	0.0767	3.0	.808
Migm. 2.1	0.14	170	69	0.42	51.6	1,953	±51	2,513	± 44	22	0.1655	2.6	8.07	4.0	0.354	3.1	.763
Migm.2.2	0.15	372	27	0.07	23.4	455	±13	560	± 39	19	0.0588	1.8	0.593	3.5	0.0732	3.0	.863
Migm.2.3	21.06	1977	515	0.27	53.4	158.2	± 6.4	1,586	±410	90	0.098	22	0.336	22	0.0248	4.1	.185
Migm.3.1	0.13	661	82	0.13	47.8	521	±16	449	± 45	-16	0.0559	2.0	0.649	3.7	0.0842	3.1	.837
Migm.3.2	--	215	58	0.28	14.7	495	±15	599	± 64	17	0.0599	2.9	0.659	4.2	0.0798	3.1	.720
Migm.4.1	--	344	65	0.19	22.2	468	±14	577	± 83	19	0.0593	3.8	0.615	4.9	0.0753	3.0	.622
Migm.5.1	0.45	301	39	0.13	20.5	489	±14	424	±120	-15	0.0553	5.4	0.601	6.2	0.0789	3.1	.492
Migm.6.1	--	149	90	0.63	10.4	503	±15	618	± 76	19	0.0604	3.5	0.676	4.7	0.0811	3.1	.657
Migm.7.1	--	514	7	0.01	38.3	537	±15	559	± 28	4	0.05879	1.3	0.704	3.3	0.0869	3.0	.918
Migm.7.2	1.09	511	387	0.78	39.1	545	±16	493	±110	-11	0.0570	5.0	0.693	5.8	0.0882	3.0	.518
Migm.8.1	0.43	270	28	0.11	17.1	457	±13	617	± 69	26	0.0604	3.2	0.611	4.4	0.0734	3.0	.688
Migm.8.2	--	259	179	0.71	102	2,426	±63	2,805.5	± 7.2	14	0.19748	0.44	12.44	3.1	0.457	3.1	.990
Migm.9.1	0.27	250	80	0.33	16.7	482	±14	373	± 75	-29	0.0540	3.3	0.579	4.5	0.0777	3.1	.674
Migm.9.2	0.10	307	78	0.26	20.0	472	±14	495	± 77	5	0.0571	3.5	0.598	4.6	0.0759	3.0	.653
Migm.10.1	0.11	204	11	0.06	17.7	621	±18	964	± 33	36	0.0712	1.6	0.993	3.5	0.1011	3.1	.882
Migm.10.2	1.59	750	92	0.13	38.6	369	±11	540	± 80	32	0.0583	3.7	0.474	4.7	0.0590	3.0	.636
Migm.11.1	0.02	603	68	0.12	41.7	500	±14	541	± 26	8	0.05830	1.2	0.648	3.2	0.0806	3.0	.927
Migm.12.1	0.06	359	47	0.13	24.8	498	±14	411	± 49	-21	0.0550	2.2	0.608	3.7	0.0803	3.0	.806
Migm.13.1	0.42	54	109	2.08	4.75	622	±20	663	±130	6	0.0617	5.9	0.861	6.8	0.1012	3.3	.485
Syen.1.1	0.00	4168	1203	0.30	187	328.3	±2.7	325	± 12	-1	0.05291	0.52	0.3812	0.98	0.05225	0.83	.849
Syen.2.1	0.43	5360	2125	0.41	222	302.5	±1.6	419	± 61	38	0.0552	2.7	0.365	2.8	0.04804	0.55	.199
Syen.3.1	1.13	5514	3281	0.61	179	236.2	±1.3	439	± 70	86	0.0557	3.1	0.2864	3.2	0.03732	0.56	.175
Syen.3.2	0.00	10889	6445	0.61	480	322.3	±1.6	323.7	± 8.6	0	0.05288	0.38	0.3738	0.64	0.05127	0.52	.811
Syen.4.1	0.00	5599	2595	0.48	253	330.1	±1.7	341	± 10	3	0.0533	0.44	0.3861	0.68	0.05254	0.52	.761
Syen.5.1	0.27	12526	1778	0.15	815	469.4	±2.9	391	± 12	-17	0.05449	0.53	0.5674	0.84	0.0755 3	0.65	.774
Syen.6.1	0.00	6405	1037	0.17	284	324.6	±1.7	324.9	± 9.5	0	0.05291	0.42	0.3768	0.68	0.05165	0.53	.784
Syen.6.2	0.16	6458	975	0.16	265	299.8	±1.6	325	± 15	8	0.05291	0.67	0.3473	0.86	0.0476	0.53	.622
Syen.7.1	0.02	6259	2197	0.36	267	311.9	±1.6	320	± 11	3	0.05279	0.5	0.3608	0.73	0.04958	0.53	.730
Syen.8.1	0.61	8136	1471	0.19	280	251.9	±1.3	344	± 24	37	0.05335	1.1	0.2932	1.2	0.03985	0.54	.446
Syen.9.1	1.00	8046	2461	0.32	294	266.2	±3.5	464	±170	74	0.0563	7.8	0.327	7.9	0.04216	1.3	.168
Syen.10.1	0.21	5551	4076	0.76	223	293.6	±1.5	336	± 18	14	0.05317	0.79	0.3415	0.96	0.04659	0.54	.563

Errors are 1-sigma; Pbc and Pb* indicate the common and radiogenic portions, respectively. Common Pb corrected using measured 204Pb
Error in Standard calibration was 1.30.

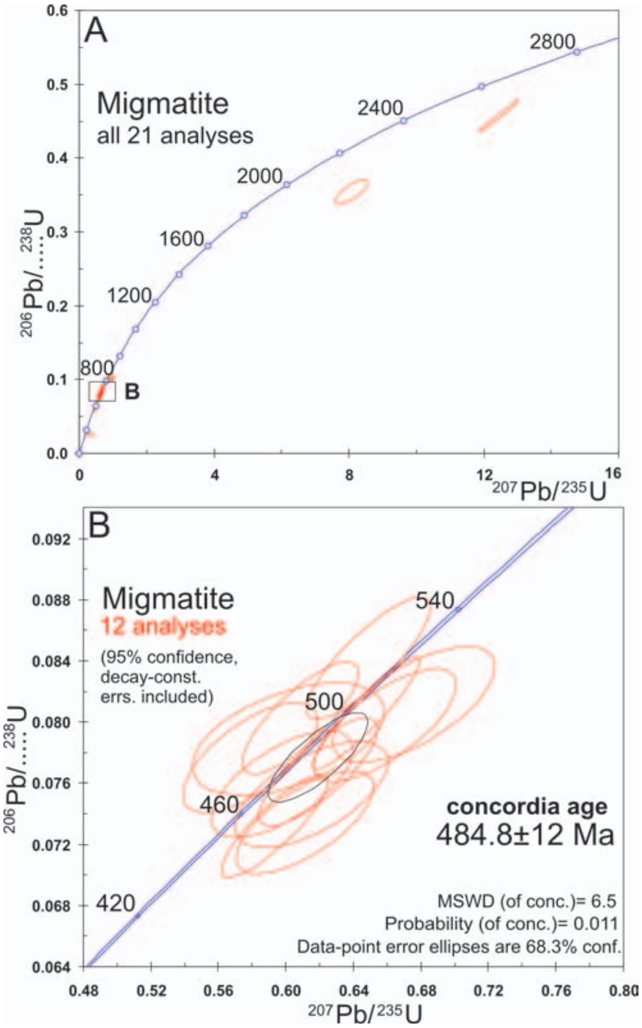

Fig. 12. U-Pb concordia diagram plotting analyses of zircons from migmatitic neosome. **A** – all analyses; **B** – 12 nearly concordant analyses (red ellipses), pooling age of 484.8 ± 12 Ma (black ellipse). Further explanation in the text.

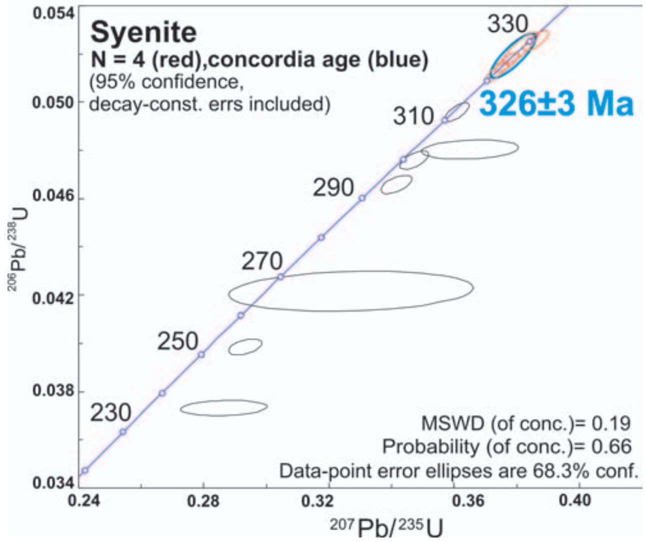

Fig. 13. U-Pb concordia plot for syenite. Explanation in the text.

seen in the outcrop pattern (Fig. 1, 2; Opletal *et al.*, 1980; Don *et al.*, 2003), which resembles mantled gneiss domes[1],

– why numerous enclaves of migmatitic rocks were enclosed in the porphyritic metagranite (Grześkowiak & Żelaźniewicz, 2002),

– why the migmatitic gneisses contain multistage retrograde minerals which testify complex metamorphic history of these rocks,

– why the migmatitic gneisses contain evidence of HT/HP deformation and polyphase structural evolution from high-grade conditions down to those of the greenschist facies (cf. Żelaźniewicz, 1991; Přikryl *et al.*, 1996),

– why the augen gneisses that developed from the porphyritic metagranite display close geochemical similarities to the migmatitic gneisses and also contain relic (not wholly assimilated) assemblages including Ca-rich garnet with sphene and rutile,

– why feldspars and micas from the metagranite are compositionally distinctly less heterogeneous as compared to those from the migmatitic gneisses (Grześkowiak, 2003, 2004),

– why the migmatitic gneisses demonstrably underwent much more complex and longer deformation/metamorphic history than that experienced by the augen gneisses,

– why there are structural differences between the observed gneiss variants,

– and why not all deformational structures observed in the migmatitic gneisses can be assigned to the Variscan orogeny.

In the migmatitic gneiss of Zdobnice, the garnet grains possessing complex coronas and unusual Ca-Fe cores are similar to garnets identified in the migmatitic gneisses of the Międzygórze area. The presence of such garnets along with relic rutile was interpreted as a possible indication of a HP episode that the parent rock had once experienced (Borkowska *et al.*,1900; Klemd & Bröcker, 1996; Grześkowiak, 2004; Stawikowski, 2005, 2006). Likewise, the observed garnet and white mica-albite pseudomorphs suggest that the precursors of the Zdobnice migmatitic gneisses likely underwent HP/HT metamorphism. Thereafter, they were exhumed to shallower crustal depth at which an extensive (decompression) partial melting eventually gave rise to the porphyritic granite intrusions at 515–480 Ma in the centre of the migmatite mantled dome domain (Fig. 1). The exumation and relevant deformation occurred, however, not in a magmatic arc settting but probably during rifting and crustal thinning associated with mantle

1 Such domes were reported from other parts of the Saxothuringian Terrane. For instance, the Catherine mantled gneiss dome in the central Erzgebirge was produced by diapiric intrusion of Cambro-Ordovician muscovite-biotite porphyritic granite (Mlčoch & Schulmann, 1992).

upwelling that allowed for widespread migmatization which terminated around 484–482 Ma. We suggest that the migmatitic rocks represent severely reworked fragments of the lower crust once subducted to considerably greater depths in pre-515 Ma times.

Unfortunately, the age of the exhumed lower crust could not be constrained with the material analysed. In sample Migm, there some zircons that are older or have cores older than the Cambrian. These are represented by single discordant analyses which cluster around 540–560 Ma and 620 Ma. The former group of ages is well known from the Cadomian basement in the Sudetes (Żelaźniewicz *et al.*, 2004), the latter group has been found in gneisses in the Zdobnice Valley (Kröner *et al.*, 2001) near the studied quarry and in the Izera-Karkonosze Block further NW, where it represents the dominant zircons in the schistose metavolcanite belt entrapped as the country rock/roof pendant in the ~500 Ma Izera metagranite (Żelaźniewicz *et al.*, 2003). Such data suggest that the crust that was severely reworked during the 515–480 Ma event had actually been formed between 620 Ma and 540 Ma in the course of the Cadomian orogeny. We speculate that the relicts of HP/HT mineralogy in the migmatitic gneisses were originally developed in granulites connected with this orogeny. Likewise, these rocks possess composite fabrics which originated at that time and should not be interpreted as an exclusively Variscan feature.

The 515–480 Ma event is compatible with a geo-d ynamic setting which assumes rifting during ~E–W extension, crustal attenuation toward an oceanic stage and mantle upwelling which provided increased heat flow to melt the crust. This a scenario not only explains the strong similarities in geochemistry observed between the two main gneiss types in the Orlica-Śnieżnik Dome, but also the similarities to acid metavolcanic rocks included in the metasedimentary Stronie formation at 520–500 Ma.

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