

Quartz c-axis fabrics in constrictively strained orthogneisses: implications for the evolution of the Orlica-Śnieżnik Dome, the Sudetes, Poland

ANDRZEJ ŻELAŻNIEWICZ^{1,2*}, OLGA KROMUSZCZYŃSKA^{1**} AND NATALIA BIEGAŁA²

¹*Institut Nauk Geologicznych PAN, Podwale 75, PL-50-449 Wrocław, Poland.*

*E-mails: *pansudet@pwr.wroc.pl, **olga.kromuszczyńska@twarda.pan.pl*

²*Institut Geologii UAM, Maków Polnych 16, PL-61-606 Poznań, Poland.*

ABSTRACT:

Żelaźniewicz, A., Kromuszczyńska, O. and Biegała, N. 2013. Quartz c-axis fabrics in constrictively strained orthogneisses: implications for the evolution of the Orlica-Śnieżnik Dome, the Sudetes, Poland. *Acta Geologica Polonica*, **63** (4), 697–722, Warszawa.

The Orlica-Śnieżnik Dome (OSD), NE Bohemian Massif, contains in its core several gneiss variants with protoliths dated at ~500 Ma. In the western limb of the OSD, rodding augen gneisses (Spalona gneiss unit) are mainly L>S tectonites with a prominent stretching lineation. The few quartz LPO studies have produced somewhat discrepant results. 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 (450–600°C). Quartz c-axis microfibrils show complex yet reproducible patterns that developed under the joint control of strain geometry and temperature; thus the LPOs are mixed features represented by pseudo-girdle patterns. Domainal differences in quartz microfibrils (ribbons, tails, quartzo-feldspathic aggregate) are common in the Spalona orthogneisses but uncommon in the sheared migmatitic gneisses. In the latter rocks, the constrictive strain was imposed on the originally planar fabric defined by high-temperature migmatitic layering. The constrictive fabric of the Spalona gneisses may have 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.

Key Words: Quartz c-axis; Constriction; Augen orthogneiss; Microfabric; Stretching Lineation; Rodding gneiss; Pseudo-girdle; Bohemian Massif.

INTRODUCTION

The Orlica-Śnieżnik Dome (OSD), one of the tectonostratigraphic units in the West Sudetes, NE Bohemian Massif, contains in its core several gneiss variants with protoliths dated at ~500 Ma. Originally treated

as rocks of different age and origin, the gneisses were later viewed as diverse products of solid-state granulitization due to the so-called feldspathization of mica schists (Smulikowski 1973, 1987; Juroszek 1976), with which they were to share a similar deformational history (Teis-syere 1973). Modern analytical techniques revealed that

the OSD gneisses are broadly geochemically similar in their contents of major, trace and rare earth elements and their characteristic ratios (Lange *et al.* 2002, 2005). Based on such data, the protoliths of the gneisses were reinterpreted as coming from various magma batches which were derived from the same source yet eventually fed a heterogeneous batholith. The F_1 - F_n or D_1 - D_n labeled deformational histories of the OSD rocks proposed in the literature still differ markedly (reviews in Don *et al.* 1990 and in Żelaźniewicz *et al.* 2002; Cymerman 1997; Jatrzębski 2005, 2009; Murtezi 2006; Skrzypek *et al.* 2011; Chopin *et al.* 2012).

Dumicz (1988), Żelaźniewicz (1988, 1991), Grzeškowiak and Żelaźniewicz (2003) and Redlińska-Marczyńska and Żelaźniewicz (2011) observed some significant differences between augen gneisses and other gneiss variants. The augen gneisses have less variable modal compositions, and a simpler deformational history, than other gneissic rocks in the dome (Redlińska-Marczyńska and Żelaźniewicz 2011).

Owing to the simpler deformation history, augen orthogneisses may be particularly useful for studies of textural and microstructural transformations from original porphyritic granite to metagranite. A few analyses of quartz *c*-axis fabrics performed in gneisses of the western limb of the Orlica-Śnieżnik dome, the Góry Bystrzyckie Mts., produced, however, somewhat discrepant LPO patterns. They ranged from pole figures consisting of two girdles around the X axis of the finite strain ellipsoid and subordinate maximum at the Y axis, to patterns interpreted as type I and type II cross girdles (Żelaźniewicz 1988; Přikryl *et al.* 1996; Cymerman 1997; Szczepański 2010). On the other hand, prominent rodding elongation of feldspar and quartz defined a strong stretching lineation in the study gneisses which were apparently deformed only by constriction, as unanimously revealed by the Flinn plots published by Żelaźniewicz (1988, 1991), Přikryl *et al.* (1996) and Cymerman (1997). According to the Lister and Hobbs (1980) model, prolate deformation should bring about a quartz microfabric with two small circle girdles centered on the X axis. Studies of quartz LPOs in rocks deformed in the constrictional regime are, however, infrequent, yet those performed so far generally confirm the model (Sullivan *et al.* 2010). The scarcity of published results on quartz *c*-axis fabrics in constrictorally deformed metagranites unfortunately impedes comparisons with natural examples.

In this paper, we focus mainly on metagranites from the Góry Bystrzyckie Mts., which have a prominent stretching lineation and represent L>S-tectonites, in an attempt to determine how the quartz *c*-axis microfabric matches the mesoscopic fabric in gneisses ranging from

L- to S-tectonites and why the published quartz LPO data on the metagranites are not quite consistent. Reexamination of quartz LPO patterns recorded by these rocks will be integrated with mesoscopic and microscopic structural data.

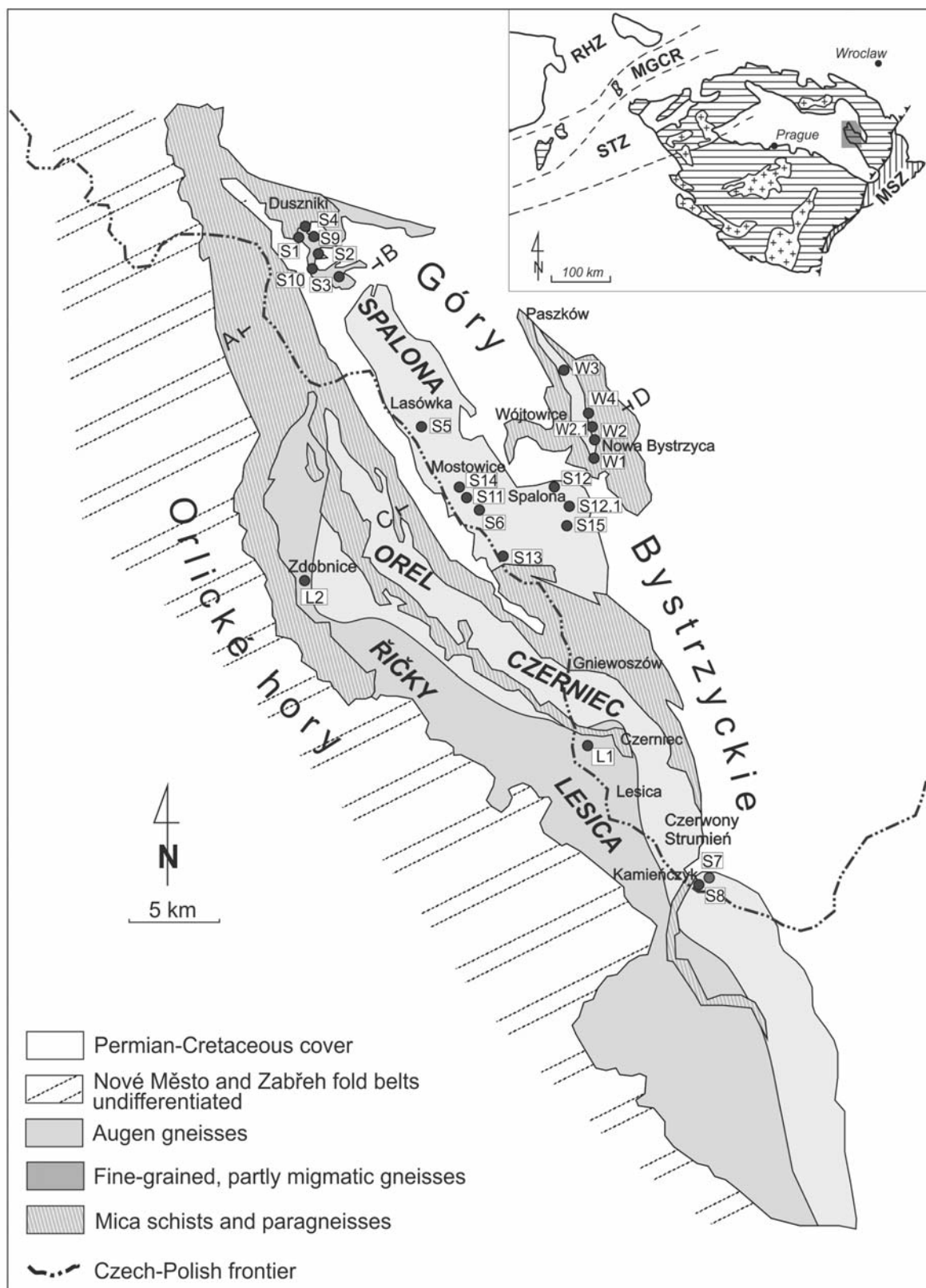
PREVIOUS STUDIES

Żelaźniewicz (1984) recognized that gneisses in the Góry Bystrzyckie Mts. were derived from porphyritic granites and converted mainly to L>S and LS tectonites. Based on the observed mesofabrics and microfabrics in the gneisses, he concluded that the original granites underwent early solid-state coaxial deformation due to the roughly N-S stretching and concurrent W-E contraction at temperatures of the mid-amphibolite facies (Żelaźniewicz 1988, 1991). Under such conditions, dominantly rodding-type gneisses developed, the microfabric of which was characterized by nearly orthorhombic symmetry and small circles around the X axis of the finite strain ellipsoid. In the superposed plane strain regime, foliation developed in the gneisses. This model explained why L>S and LS tectonite types dominate in the Góry Bystrzyckie gneisses.

Cymerman (1997) favored only one deformational episode to have occurred in the OSD and claimed that the augen orthogneisses (Śnieżnik type in local subdivision: for reviews see Don *et al.* 1990 and Redlińska-Marczyńska and Żelaźniewicz 2011) are characterized by a top-to-the NW shearing. However, he emphasized, in accord with Żelaźniewicz (1988, 1991), that almost all gneisses represent L- to LS tectonites. In Cymerman's (1997) opinion, the quartz microfabric of these rocks was generally of type II cross girdle and mainly controlled by a basal <a> slip system under greenschist facies conditions.

Szczepański (2010) assumed that the granitic protolith of the orthogneisses intruded during the first deformational episode (D1) in the Orlica-Śnieżnik dome, whereas shearing responsible for the observed quartz microfabrics, both in the gneisses and schists, operated during the final stage of ductile deformation (D3). It was assumed in the Szczepański scheme that the quartz *c*-axis patterns in all quartz-bearing rocks of the OSD, irrespective of their origin and diversified multiple deformational history, resulted from the last episode of pervasive dynamic recrystallization, which was capable of erasing all pre-existing LPOs at the end of the Variscan collision in the region. For measurements of quartz *c*-axis orientation, Szczepański (2010) used the method of approximate image analysis proposed by Stoeckhert and Duyster (1999); that, however, may be

QUARTZ C-AXIS FABRICS IN CONSTRICTIONALLY STRAINED ORTHOGNEISSES



Text-fig. 1. Geological sketch of the western limb of the Orlica-Snieżnik Dome, with location of sampling sites. Modified after Dumicz (1964), Opletal *et al.* (1980) and Don *et al.* (2003). Inset: Map location (shaded box) within the wider context of the Bohemian Massif (horizontal rulings). Abbreviations are as follows: MGCR (Mid-German Crystalline Rise); MSZ (Moravo-Silesian Zone, vertical ruling); RHZ (Rhenohercynian Zone); STZ (Saxothuringian Zone, horizontal dashed ruling); Variscan granitoids (crosses)

unreliable in rocks with complex recrystallization histories. Based on quartz LPO data, he concluded that gneisses in the central part of the Góry Bystrzyckie Mts. were deformed under the greenschist facies by coaxial plane strain conditions, locally accompanied by non-coaxial simple shear with activation of (c) $\langle a \rangle$, $\{r,z\} \langle a \rangle$ and $\{m\} \langle a \rangle$ slip systems.

In gneisses of the Orlicke horý Mts. further west (Text-fig. 1), Příkryl *et al.* (1996) found microstructural evidence for two deformation episodes. An early, high temperature stretching in the E-W direction was assigned to pre-Variscan events. A subsequent Variscan overprint took place at lower temperature and non-coaxial compression in the N-S direction, which almost completely obliterated the earlier fabric.

METHODOLOGY USED AND BASIC TENETS OF QUARTZ MICROFABRIC ANALYSIS

Methods

In the western limb of the Orlica-Śnieżnik dome (Text-fig. 1), twenty-one samples of augen orthogneisses and two samples of sheared migmatitic gneisses were collected, ranging from L- to S-tectonites. An additional sample was taken from a quartz-sericite schist (L < S tectonite) occurring at the contact between the augen orthogneiss (L > S tectonite) and mica schist of the Stronie-Młynowiec Group at the southern part of Duszniki Zdrój. Thin sections for microstructural studies were cut perpendicular to the foliation and parallel to the stretching lineation (the XZ plane of the finite strain ellipsoid).

A classic technique of the measurement of the quartz c-axis orientation was employed, using the 3-axis universal stage according to the procedure described by Turner and Wise (1960) and Passchier and Trouw (1998). The data were processed and presented using Stereo32 v. 1.0.2 software (Röller and Trepmann 2010). All LPO fabric plots are presented on the lower hemisphere equal area Schmidt projection. For microfabric analyses Żelażniewicz (1988, 1991), Příkryl *et al.* (1996), Cymerman (1997) and Szczepański (2010) used monomineral quartz ribbons in the study gneisses. In this study the quartz LPOs patterns c-axis orientations were measured for: (1) quartz ribbons, (2) quartzo-feldspathic aggregates, (3) pressure shadows at K-feldspar porphyroclasts. Synoptic diagrams were then constructed.

In six selected samples, quartz c-axis orientations were measured (in the XZ plane) for each of the three distinguished domains independently, to check whether their microfabrics are similar or different and to what extent they differ.

In order to test the validity of the obtained fabric pattern, sampling was repeated in three gneiss outcrops and quartz c-axis orientations were studied independently by two of us (OK and NB) in separate thin sections, with no distinction being made between the structural positions (domains 1–3) of the measured grains in the sample.

Quartz microfabric controls

Comprehensive studies of natural quartz fabrics (Marjoribanks 1976; Schmid and Casey 1986; Law *et al.* 1990; Passchier and Trouw 1998) and numerical modelling (Etchecopar 1977; Lister and Hobbs 1980; Etchecopar and Vasseur 1987), which commenced about 40 years ago, have demonstrated that quartz c-axis fabrics produce characteristic patterns on LPO diagrams. Such fabrics depend on: (1) deformation paths controlled by strain regime and symmetry and (2) dislocation glide systems controlled by temperature.

Temperature

The activation of various possible slip systems in quartz during deformation depends on the temperature of the process (review in Passchier and Trouw 1998). On microfabric diagrams, the $\langle c \rangle$ axis poles/maxima can be localized according to temperature conditions: (1) at the outer rim of the diagram owing to the activation of the basal $\langle a \rangle$ slip system, (2) half way between the perimeter and the center of the diagram, indicating operation of the rhomb $\{r,z\} \langle a \rangle$ slip system, (3) in the Y position on the diagram pointing to prism $\langle a \rangle$ slip system activity, and (4) at the periphery of the diagram but relatively close the X position, which indicates prism $\langle c \rangle$ slip. Position (1) is expected at the relatively low temperatures of the greenschist facies, position (2) at higher greenschist facies, position (3) at low-to-medium amphibolite facies, whereas position (4) is due to the high temperatures characteristic of the medium-high amphibolite or granulite facies. At a given temperature, coeval activation of some of these slip systems may take place.

Strain symmetry, intensity and regime

For tectonites developed by coaxial plane strain ($k = 1$), a symmetric cross-girdle pattern of c-axes is usually predicted. A similar pattern may also develop in a simple shear regime ($k = 1$) of low strained tectonites; however, progressively increasing shear strain may then change the pattern through asymmetric cross-girdle fabrics to single-girdle fabrics (e.g. Etchecopar and Vasseur 1987; Jessell and Lister 1990). In tectonites that de-

QUARTZ C-AXIS FABRICS IN CONSTRICTIONALLY STRAINED ORTHOGNEISSES

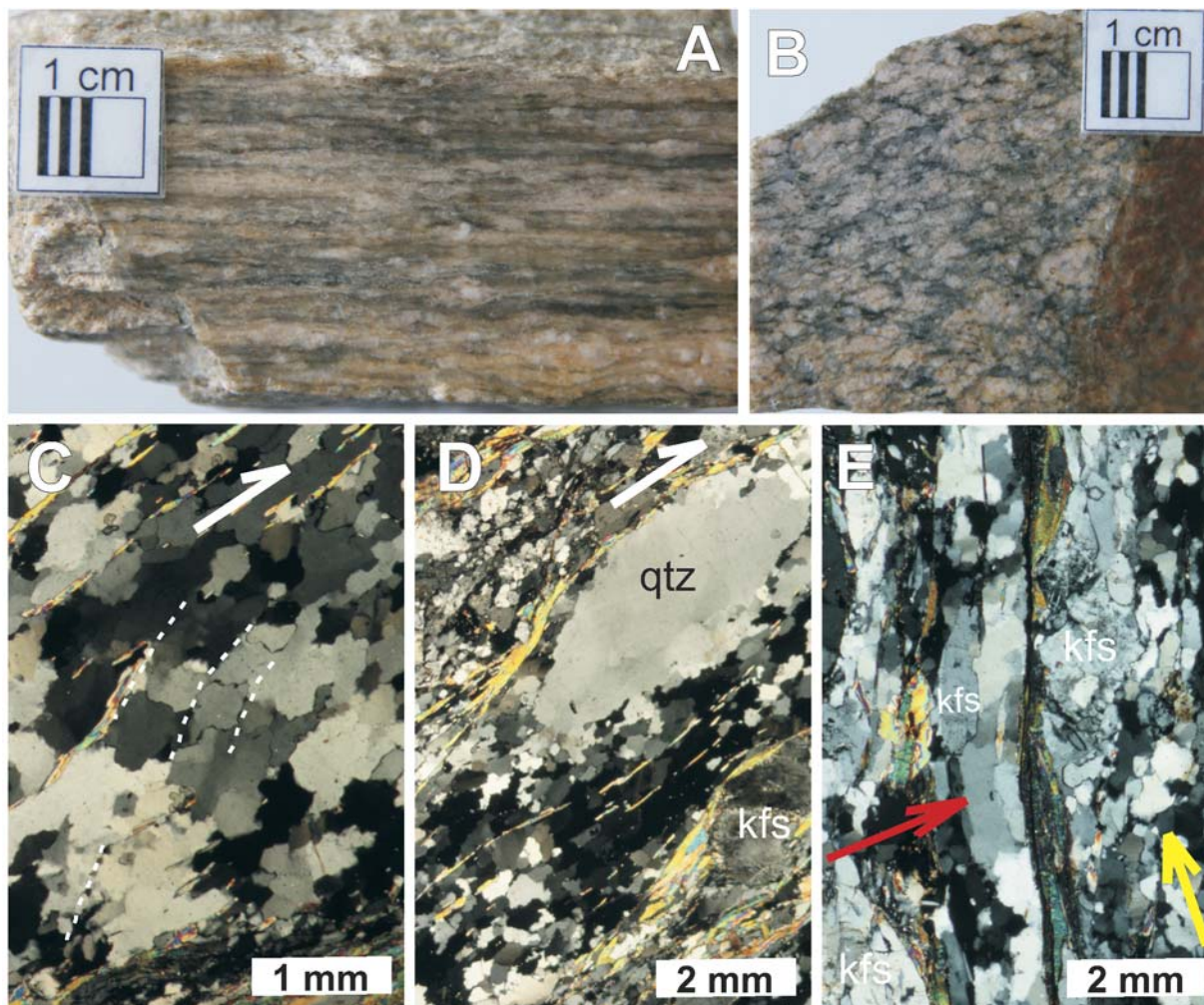
velop by uniaxial/coaxial flattening strain ($k = 0$), a small-circle girdle distribution of c-axes around the pole (Z) to the foliation is expected, whereas coaxial extensional strain ($k = \infty$) should result in a small-circle distribution centered about the stretching lineation (X). For tectonites deformed either in a flattening or constrictional field ($1 > k > 0$ or $\infty > k > 1$), patterns transitional between cross-girdle and small circle distribution are expected, as predicted from the Flinn diagram (Lister and Hobbs 1980).

Another group of microfabric controls comes from the intensity of strain in a given regime. At low strain, $\langle c \rangle$ axis poles distribute widely irrespective of temperature. In the plane strain/general shear regime, with progressively increasing strain, the type I cross girdle, which consists of two small circle girdles and a connecting gir-

dle, changes to a single girdle. The opening angle of the small circle girdles depends on the temperature – the larger angle, the higher temperature (Kruhl 1998).

Prism $\langle a \rangle$ slips reflect a rather high intensity strain, whereas basal $\langle a \rangle$ slips are more characteristic of low strain (Heilbronner and Tullis 2006). In natural examples, the strong Y-maxima or single girdle CPOs are connected with high ductile shear strains under amphibolite facies conditions, whilst cross-girdle patterns are ascribed rather to lower strains at lower temperature conditions (Toy *et al.* 2008).

In shear zones, the kinematic/geometric elements of the shear zone (shear sense, shear plane attitude) control the non-coaxial distribution of quartz $\langle c \rangle$ axes that may form a girdle which is at right angles to the shear plane, and thus inclined to the foliation (Lister and Price 1978;



Text-fig. 2. Augen orthogneiss from the Spalona gneiss body, sample S2 from Duszniki Zdrój. A – section parallel to the stretching lineation and normal to the foliation; B – section normal to the stretching lineation; C – quartz ribbon recrystallized by the grain boundary migration mechanism with faint oblique foliation (white dashes) indicating kinematics (white arrow), D – core-and-mantle structure of quartz (qtz) contributing to the ribbon by grain boundary rotation recrystallization, kinematics (white arrow) shown by the quartz grain and by sigma type asymmetric K-feldspar (kfs) porphyroclast; E – quartz ribbon (red arrow) with ~rectangular grains, white mica felt at the interface with polymineral layer (yellow arrow) with elongate K-feldspar (kfs)

Burg and Laurent 1978; Brunel 1980; Simpson 1980). Quartz LPOs change across the ductile fault zone. Small circle girdles normal or parallel to the foliation are taken to represent coaxial strain with a marked direction of extension or shortening, respectively. Symmetric pseudo-two girdles may develop due to two distinct intracrystalline slip systems.

In constriction, a type II cross-girdle is expected to develop. Rhomb slip may dominate over prism slip in such a regime (Bouchez 1978; Schmid and Casey 1986). In uniaxial constriction, increasing strain results in narrowing the small circle girdles. The same is true of the uniaxial flattening regime. However, most natural cases depart from uniaxial conditions as they developed in the triaxial field.

Although non-coaxial strains result in girdles inclined to the foliation plane (XY) and the direction of tilting of the girdle toward the foliation is taken as the sense of shearing, hence a kinematic indicator, caution must be exerted as such a fabric may be distorted by the presence of other mineral grains, or by an unsuitable orientation of quartz grains for activation of a particular slip system. Coaxial strains yield *c*-axis fabrics of orthorhombic symmetry. Non-coaxial strains yield monoclinic (single-girdle) and triclinic (localized area) *c*-axis fabrics.

In type II S-C mylonites (Lister 1977) which have undergone a large shear strain, *c*-axis fabrics form girdles that are only slightly inclined to the C-surfaces. In general, if the observed quartz *c*-axis preferred orientations occur at a low angle to the stretching lineation then prism *c*-slip may be inferred, and if *c*-axes are oriented at high angle to the stretching lineation and at a low angle to the foliation, then prism *a*-slip may be interpreted (Schmid *et al.* 1981; Mainprice *et al.* 1986). In contrast, in low strain zones deformation by crystalline plasticity may not be sufficient to induce a new quartz *c*-axis preferred orientation. Then LPOs reflect the original orientation of grains within the quartz lenses or seams.

In gneisses with a multistage deformational history, where the grain shape preferred orientation differs from that of the mylonitic foliation, two fabric elements may be produced during two different events or may develop during progressive simple shear. Fabric skeletons help to identify the type of microfabric observed. Using contour diagrams, they are defined by linking maxima, although such skeletons may be difficult to discern unequivocally in low strain tectonites.

CHARACTERISTICS OF GNEISSES

In the Góry Bystrzyckie Mts., augen orthogneisses are a dominant lithology, forming a compact body

(Spalona unit of Dumicz 1964) surrounded in map view by mica schists and partly hidden under an Upper Cretaceous sandstone cover (Text-fig. 1). Contacts with the mica schists are only fragmentarily exposed at the northwestern and southwestern parts of the body, near Duszniki and Rudawa-Poręba, respectively. A nearly 3 km wide belt of metasediments narrowing southwards (Gniewosów-Kamieńczyk unit of Dumicz (1964) continues NW-wards into the Neratov-Kunštát synclinorium (Opletal *et al.* 1980) on the Czech side and separates the Spalona body from the Czerniec gneiss unit (Dumicz 1964) equivalent to the Orel anticlinorium in Czech territory which actually forms a large part of the Orlické hory Mts. in the Czech Republic (Text-fig. 1). Another narrow mica schist belt, named průh Zakletého or the Zakletý synclinorium in the Czech literature (Pauk 1977; Opletal *et al.* 1980) or the Niemojów-Czerwony Strumień unit in the Polish literature (Dumicz 1964), separates the Czerniec gneiss body from the Lesica gneiss body (Dumicz 1964) which in turn is equivalent to the Řičky anticlinorium in Czech territory. The third, smallest gneiss outcrop in Poland occurs as a N-S elongate, ~0.5 km wide belt, referred to as the Wójtowice unit (Dumicz 1964), set in mica schists and paragneisses to the NW of Bystrzyca Kłodzka (Text-fig. 1).

From a petrographic point of view, gneisses in the Góry Bystrzyckie Mts. represent several types. These are: (1) two-mica, coarse-grained augen gneisses with pinkish K-feldspar, (2) medium-grained, grey-yellowish muscovite gneiss with white to cream-coloured K-feldspar rods and augen, (3) medium-grained, reddish muscovite gneiss with pink to red K-feldspar rods and augen, (4) medium-to-coarse grained reddish/pinkish layered gneiss with but scarce augen, (5) medium- to coarse-grained, biotite, flaser to layered gneiss, with lenseoid quartz and quartzo-feldspathic aggregates, and locally pinkish or yellowish K-feldspar augen.

Some spatial distribution of these gneiss types can be observed throughout the region. In the Spalona body, there are mainly gneisses of types (1) to (3), in the Czerniec-Orel unit types (3) and (2) occur, type (4) dominates in the Lesica-Řičky unit, whereas the Wójtowice body is composed mainly of type (5). From the structural point of view, the gneisses differ in having either poorly, moderately or strongly developed foliation planes, usually with a better- or less-pronounced stretching lineation. For this study, gneisses ranging from L- to S-tectonites were selected to cover all the mesofabric variants observed in the field. The L- and L>>S tectonites characterized by a top-to-the S kinematics mainly appear in the N-S oriented belt stretching from Duszniki via Lasówka and Mostowice to Rudawa (Text-fig. 1).

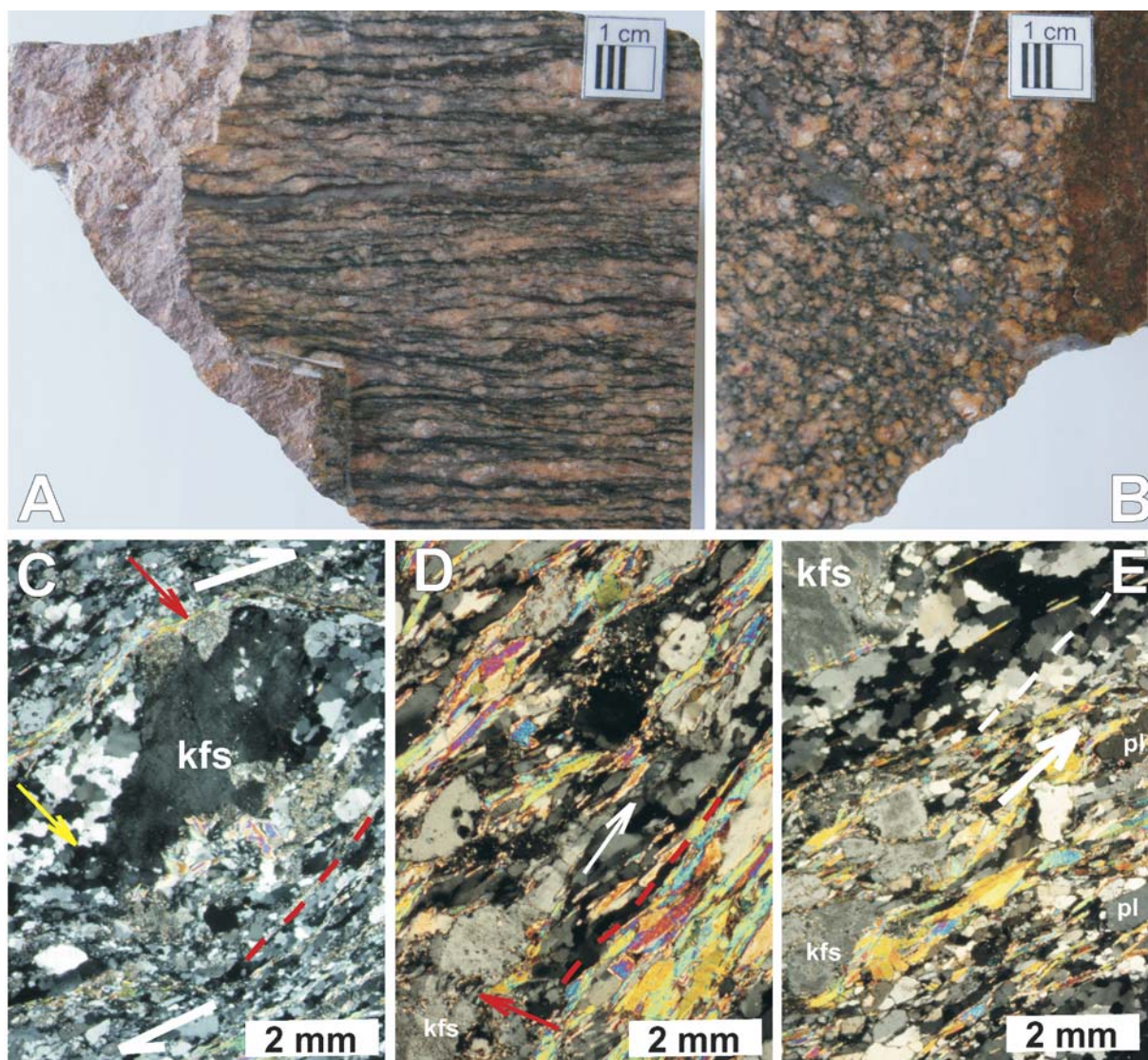
Spalona gneiss body

The Spalona gneisses are mainly L to L>S tectonites of petrographic type 2 and 3 and have a common outlook of rodding gneisses. Typical examples are shown on Text-figs 2, 3, 4.

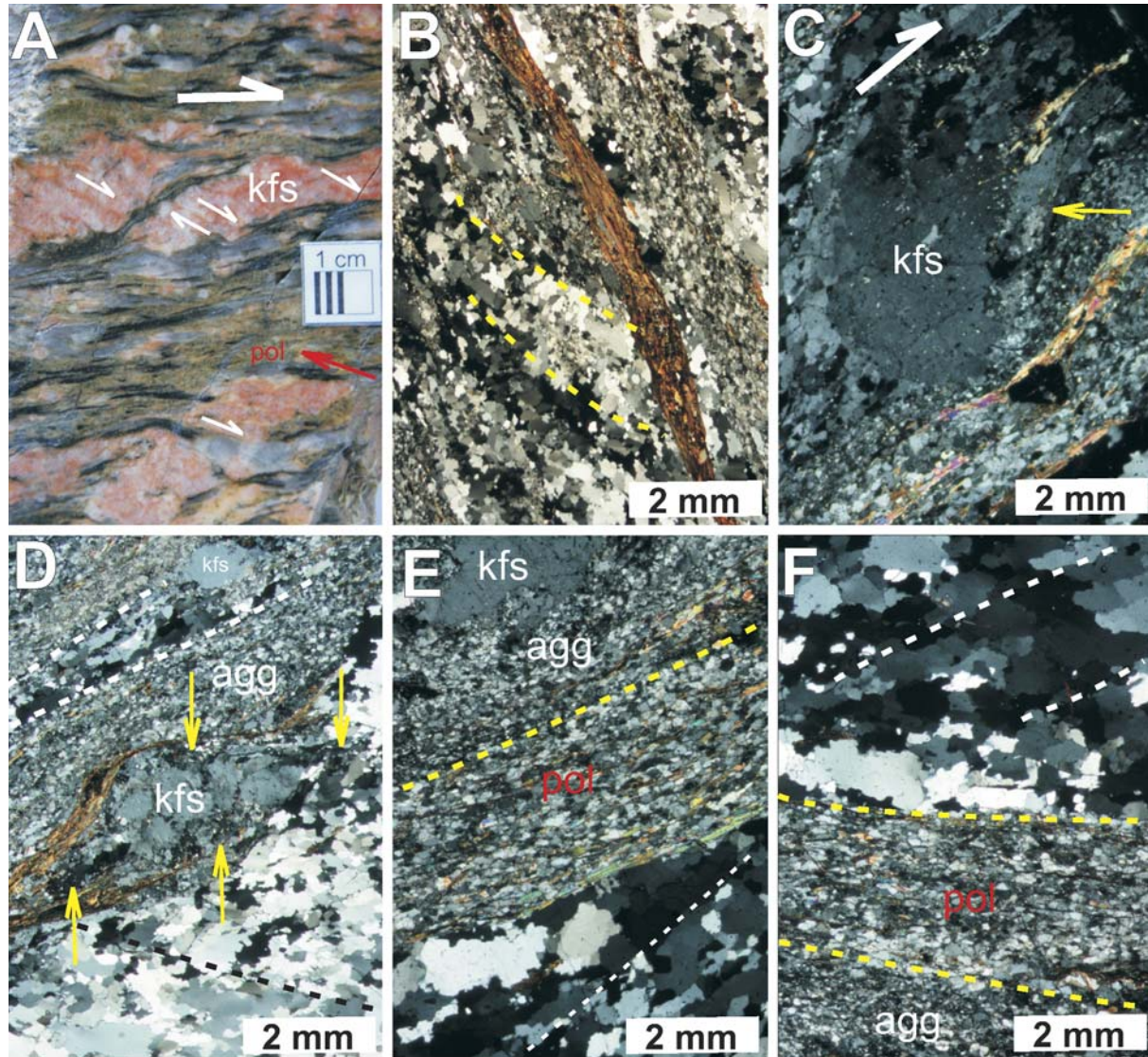
In samples from Dolina Strażyska, south of Duszniki Zdrój (Text-fig. 1), one may observe in sections parallel to the stretching lineation (the XZ plane of the strain ellipsoid): (1) thin, ribbon-like or lensoid layers of greyish quartz with occasional quartz porphyroclasts (2) lenticular, yellowish to pinkish feldspathic layers deco-

rated with beads of small, mainly sigma-type K-feldspar porphyroclasts, (3) darker micaceous layers and (4) thin, multiminerallenticles containing fine-grained plagioclase, quartz and micas (Text-fig. 2A, C–E). Some K-feldspar porphyroclasts are distinctly asymmetric (Text-figs 2A, D, 3A, C, 4A, C).

In the L>S Duszniki-Rudawa belt only the outermost gneisses (sample S9) at the NW-dipping contact with mylonitic quartz-sericite schists and mica schists have kinematic indicators that point to a top-to-the-NW shearing corroborated there by traces albeit faint of S-C' type structures. All other gneiss samples in the Duszniki-



Text-fig. 3. Augen orthogneiss with perfect rodding structure from the Spalona gneiss body, sample S6 from Mostowice. A – section parallel to the stretching lineation and normal to the ghost foliation, note: (1) thin, ribbon-like or lensoid layers of greyish quartz, (2) lenticular, pinkish feldspathic layers decorated with sigma-type beads of small, mainly K-feldspar porphyroclasts, (3) dark micaceous layers and (4) thin, multiminerallenticles containing fine-grained plagioclase, quartz and micas; B – section normal to the stretching lineation (rods); C – K-feldspar (kfs) corroded by myrmekite (red arrow) and recrystallized to form the tail (yellow arrow), kinematics shown by white arrows, red dashes mark oblique mica shred orientation; D – broken and plastically elongated K-feldspar (kfs), white arrow shows the direction of elongation at $\sim 15^\circ$ to the mica foliation traces, T-fracture at $\sim 75^\circ$ to the foliation traces; E – K-feldspar (kfs) and plagioclase (pl) arranged parallel to mica flakes (white arrow). Note that the foliation apparently well developed in this section is actually poor in the section normal to the lineation (see B) and mineral constituents are round in form



Text-fig. 4. Augen orthogneiss from the Spalona gneiss body, sample S12 from a quarry 600 m N of the Jagodna tourist hostel. A – section parallel to the stretching lineation and normal to the foliation, pinkish K-feldspar (kfs) is extended and thinned due to displacement along C' structures (white thin arrows) consistent with overall kinematics (thick white arrow), K-feldspathic layers alternate with quartz ribbons (bluish grey) and polymineral layers (pol, red arrow); B – oblique fabric (yellow dashes) in quartzo-feldspathic aggregate, note biotite band in the middle that localizes strain and separates ribbon quartz from quartzo-feldspathic aggregate; C – asymmetric K-feldspar (kfs) porphyroclast with lighter mantle (yellow arrow) due to subgrain rotation/grain boundary migration recrystallization; note tails composed of the recrystallized material; D – deformation induced compositional alteration: quartz ribbon with relic S-C structure (black dashes), elongated K-feldspar (kfs) is fragmented and replaced by quartzo-feldspathic aggregate which also contributes to the tails (yellow arrows), quartzo-feldspathic aggregate (agg), and polymineral bands (pol); E – K-feldspar (kfs) replaced by quartzo-feldspathic aggregate (agg) that passes (yellow dashes) to polymineralic bands in which grains are nearly twice larger and more elongated; note the sharp boundary with quartz ribbon with weak secondary fabric (white dashes); F – mylonitically induced layering, for explanation see 4E

Rudawa belt have rather poorly developed foliation¹ (Text-fig. 2B, 3B), yet indicate a top-to-the-S/SSE kinematics during shearing (Text-figs 1, 5).

The quartz-sericite schists at the northernmost tip the Spalona body represent a L<S tectonite (Text-fig. 6). It

forms a ~30 m thick horizon of strongly sheared rocks that separates the gneiss body from the structurally overlying mica schist and which, owing to the presence of sporadic, relic K-feldspar porphyroclasts, was interpreted as an ultramylonite that developed at the contact

¹ While using terms such as foliation, lamination, layering throughout the text, we usually refer, unless otherwise stated, to the picture observed in sections parallel to the stretching lineation and the X axis in the XZ plane of the finite strain ellipsoid. Foliation is a planar feature, thus it is considered poor, even when its traces are very obvious in one direction but weak in the other. In L>S gneisses, in sections perpendicular to the stretching lineation (the ~YZ plane), felsic mineral grains are roughly equant to faintly flattened and form indistinct, ghost-like foliation, better identifiable only by micas.

zone between the two rheologically contrasting lithologies (Żelaźniewicz 1984, 1988) due to strain incompatibility. In contrast to the L>S gneisses, the quartz-sericite schist possesses the perfect schistosity overprinted by weak secondary foliation at an angle of 40°, which adds an intersection component to the otherwise prominent mineral lineation. Characteristic of this rock are occasional bluish quartz blasts (Text-fig. 6), likely due to tiny rutile inclusions (Juroszek 1972). The contact zone is characterized by an abrupt passage from the L>S to L<S tectonite in the gneisses to the S-tectonite in the quartz-sericite and mica schists. The change from NW-trending to NE-trending foliation strikes occurs there, owing to the presence of a kilometer-scale fold (Żelaźniewicz 1978).

Under the microscope, gneisses of the Duszniki-Rudawa belt reveal in the XZ sections the presence of quartz layers, 1–2 mm thick, composed of differently elongated grains with aspect ratios of 1:1 to 1:4. The quartz grains were partly deformed by crystal plasticity, mainly by grain boundary migration recrystallization (Text-figs 2C–E, 3D–E, 4D–F). In the case of large quartz grains, bulging and sub-grain rotation evidently assisted the process of grain-size reduction which resulted in core-mantle structures (Text-fig. 2D). In thin laminae/layers, quartz grains may be nearly rectangular (Text-fig. 2E) with grain boundaries controlled by mica flakes parallel to the foliation (Text-fig. 2C). Such quartz-mica boundaries are stable. In thicker ribbons, quartz tends to develop new grains or subgrains with boundaries oblique to the main foliation, which defines a secondary foliation kinematically consistent with the overall shear sense (Text-fig. 2C, 4F).

Usually thicker than the quartz ribbons are polymineralic layers with which they alternate, being composed of two feldspars, quartz and fine micas. In such layers, single K-feldspar (Kfs) grains may have an aspect ratio as high as 1:4 (Text-fig. 2D, E, 3D, E). The original Kfs grains became plastically elongated, especially when they occur in mica-rich polymineralic layers – the former groundmass of the initial granite. Despite a uniform kinematic sense of mesoscopic shear criteria, augen observed in the XZ sections show various inclinations to the foliation, often in the opposite direction. Such attitudes testify to a rather random orientation of Kfs phenocrysts in the original granite. Evidence of rotation of the Kfs augen toward the main foliation in either direction to reduce the inclination may suggest coaxial strain or a dominantly pure shear component in the strain history of the deformed metagranite.

Original microcline crystals turned to porphyroclasts deformed both brittlely and plastically (Text-fig. 2D, 3D, 4A, C, D), often replaced by myrmekite at the edges

parallel to the shearing direction and to the elongation direction of the grains that may have been accompanied by quartz dominated tails (Text-fig. 3D, E). Some quartz tails are made of more or less equant grains with high angle boundaries that may have been caused by annealing in sites sheltered from the normal pressure.

Other samples classified as L>S tectonites from the vicinities of Dolina Strążyska (samples S1, S2, S3, S10), Lasówka (S5, S5.1), Mostowice (S6, S11) and Rudawa (S13) also represent similar rodding gneisses of petrographic types (2) and (3). All these rocks appear to be characterized by mainly a top-to-the S kinematics, an observation that has so far passed by without comment, except by Cymerman (1997). However, careful examination of rocks of the Duszniki-Rudawa L>S tectonite zone shows more complex structural records. Besides contractional structures like σ -type clasts, there is evidence of extensional features of the S-C' type or low-angle extensional shearing which coalesces with the main foliation. Such kinematics is a distinct feature of the Duszniki-Rudawa L>S tectonite belt. East of this zone, most kinematic indicators in the orthogneisses generally point to a northerly direction of shearing (Text-fig. 5).

In the Spalona gneiss body, the L>S tectonites occur mainly between the Spalona Pass and Jagodna Mt. (Text-figs 1, 5). Lenticular augen gneisses are exposed in an abandoned quarry some 600 m to the north of the pass (sample S12). The coarsest augen gneiss variants occur in this part of the Góry Bystrzyckie Mts. (Text-fig. 4A). In sample 12, lenticular quartz layers are built of grains of different dimensions with rather intricate, lobate boundaries indicative of grain boundary migration recrystallization. These grains have often been elongated at an angle of 30–50° to the layer borders, i.e. to the mesoscopic foliation (Text-fig. 4B, D, F). Such a type of microfabric suggests a top-to-the-S/SE sinistral kinematics, which is corroborated by the asymmetry of Kfs porphyroclasts of sigma-type (Text-fig. 4A, C). However, there are Kfs augen that were disrupted in the S-C' manner and evidently extended parallel to the foliation (Text-fig. 4A) during the top-to-the-S shearing. Biotite is occasionally chloritized along the C' traces, which might indicate multiple deformation along the same kinematic paths but at lower temperature.

The Kfs porphyroclasts were usually accompanied by tails (pressure shadows) which continue into fine-grained polymineralic layers composed of recrystallized K-feldspar, quartz and micas (Text-fig. 4B, C, D). Former K-feldspar phenocrysts yielded to extensive replacement as fine-grained polymineralic aggregates, the transformation being assisted by fluids as shown/stressed by the presence of small mica shreds distributed within it. The aggregate has a discrete fabric

made by elongate grains with 1:1.5 to 1:3.5 aspect ratio (Text-fig. 4A, C–F). However, not all K-feldspars yielded to such replacement. A part of the smaller crystals underwent a remarkable elongation due to a crystal plasticity mechanism (Text-fig. 3D). Mica flakes, mainly biotite, from the former granite were concentrated into laminae within quartz layers or between quartz and polymineralic layers. The S-shape or mica fish structure of many of them point to the localization of shearing along the mica laminae (Text-fig. 2D, E, 3D). In quartz layers adjacent to the polymineralic ones, grains display an almost rectangular subgrain pattern of chess-board extinction type, suggestive of the prism $\langle a \rangle$ and $\langle m \rangle$ slip at rather low pressure but relatively high temperature (Kruhl 1996, 1998).

In gneisses from the Duszniki-Rudawa L>S tectonite belt, some K-feldspar grains which happened to be sheltered in mica felts did not recrystallize dynamically and remain unstrained, whereas others have yielded to plastic elongation, especially when occurring in mica-rich polymineralic layers – the former groundmass of the initial granite. In contrast, some Kfs porphyroclasts set in a quartzo-feldspathic matrix (1) became disrupted with fragments torn apart (Text-fig. 3D), (2) were recrystallized, extended and rimmed by the newly grown Kfs phase which also contributed to the neighboring pressure shadows and was dispersed further away within quartzo-feldspathic aggregates, whilst yet others (3) yielded to myrmekitization at the edges parallel to the foliation traces (Text-fig. 3C) and to subgrain rotation recrystallization at the edges normal to the elongation direction, assisted then by the formation of quartzo-feldspathic tails, whether symmetric or asymmetric (Text-fig. 4). In the same samples, common grain boundary migration and occasional grain boundary rotation in quartz are in evidence. Besides, new biotite (porphyro-) blasts overprinted earlier, white mica-dominated aggregates and some were turned into mica fish structures, which indicates multiple shear events, probably with one increment later than the overprint of the biotite. Displacements parallel to the foliation traces (in the \sim XZ planes) are common, but another characteristic feature of these rocks is the presence of both S-C and S-C' fabrics along the same layers. If the mineralogy remains unchanged, in particular along the C' traces, we assign this feature to a high strain rate during the same deformation event, yet in places where biotite is replaced by chlorite, a younger event at lower temperatures is envisaged, irrespective of possible kinematic switches. Such observations suggest that the formation of the quartz microfabric in the Spalona gneisses was a protracted process that involved strain partitioning with changing strain rate and kinematics in a general shear

regime at temperatures of the amphibolite facies and in a multiple deformation history.

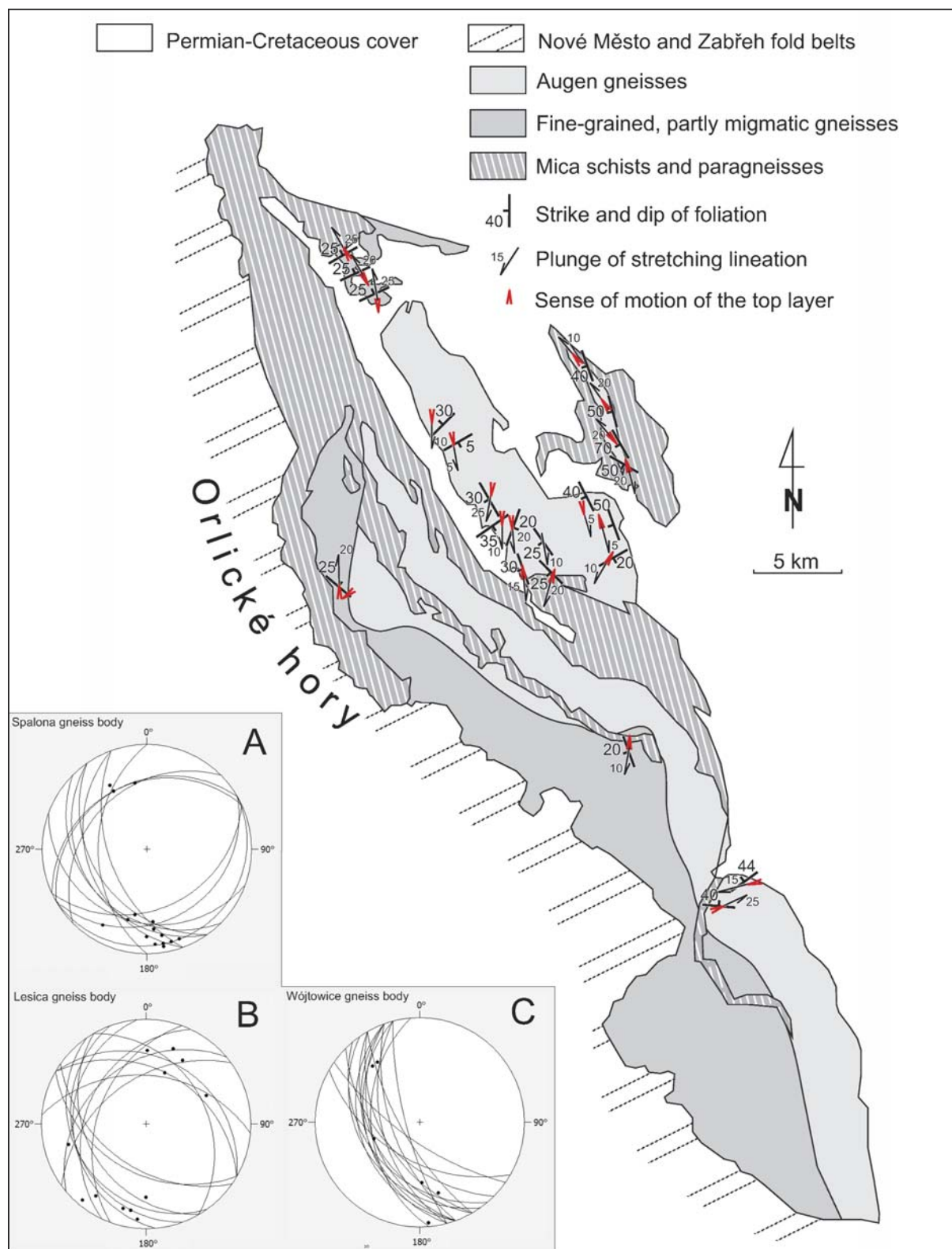
Augen gneisses also occur in the area to the south and east of the Spalona Pass (Text-fig. 1). In sample 12.1, collected on the road to Międzyzlesie to the south of the pass, pinkish K-feldspar augen are smaller and more flattened than in sample S12, which imparts a more layered appearance to these gneisses. Augen are often asymmetric or happen to be fractured obliquely to the foliation, with fragments displaced both in a contractional (S-C type structure) or extensional (S-C' type) manner. Mica streaks and felts anastomosingly wrap round the augen. The K-feldspar porphyroclasts, like in sample S12, were subject to replacement to varying extents, some wholesale, by the fine-grained quartzo-feldspathic aggregate interwoven with preferentially oriented white mica flakes. Such aggregates mainly contributed to polymineralic layers, where dynamic recrystallization was assisted by mineral transformations. The aggregate also developed along the fractures, which points to its mobility. Asymmetric porphyroclasts with tails and mica fishes point to a top-to-the north oblique thrust (sinistral strike-slip) kinematics. On the W-dipping foliation, a stretching lineation plunging to the south is overprinted by a mineral lineation expressed by mica arrays plunging to the SSW, which suggests that thrusting to the north was followed by another deformational event accompanied by recrystallization of mica and possibly also quartz. Such overprinting is usually difficult to observe in L>S tectonites because these rocks possess only poorly developed foliation.

L>S tectonites also crop out in the southern part of the Góry Bystrzyckie Mts. (Text-fig. 1), where both foliation and stretching lineation have a different orientation to the dominant NW/N direction (Text-fig. 5). Two samples were collected east of the Gniewosów-Kamieńczyk schist belt at the southern tip of the Spalona body, where layered and less often augen gneisses occur. The two samples are similar but, compared with the northern part of the body, are richer in biotite. In sections parallel to the XZ planes, foliation is marked by thin quartz ribbons alternating with thin mica layers and with thicker polymineralic layers composed of both feldspars and quartz (Text-fig. 7E–H). Later biotite flakes up to 1.5 mm in size overprint these structures. However, in sections parallel to YZ plane, the foliation is significantly less distinct.

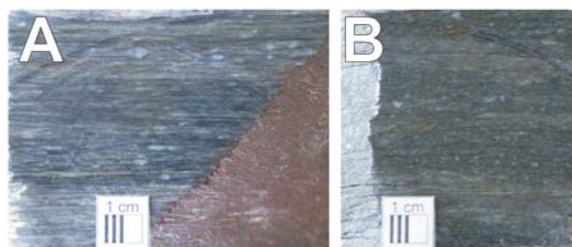
Lesica (-Řičky) gneiss body

In contrast, L<S to L=S tectonites from the Lesica gneiss body structurally depart from the Spalona rocks. The body is situated to the SW/S of the Niemojów-Czer-

QUARTZ C-AXIS FABRICS IN CONSTRICTIONALLY STRAINED ORTHOGNEISSES



Text-fig. 5. Sketch map showing orientation of structural elements in the studied samples. Inset: the same elements in stereographic projections (lower hemisphere Schmidt net). A – Spalona body: stretching lineation plunges mainly southwards, foliation is involved in S-plunging folds and refolded around the NE-SW horizontal axis; B – Lesica gneiss body: more scattered elements reflect its more complex history (see explanation in the text); C – Wójtowice gneiss body: stretching lineation rotates within relatively uniformly oriented foliation planes



Text-fig. 6. Mylonitic quartz-sericite schist, sample S4 from Duszniki, L<S tectonite. A – section parallel to the foliation and normal to the lineation, B – section normal to the lineation

wony Strumień schist belt and represents the realm of migmatitic, albeit sheared, gneisses (Text-fig. 1).

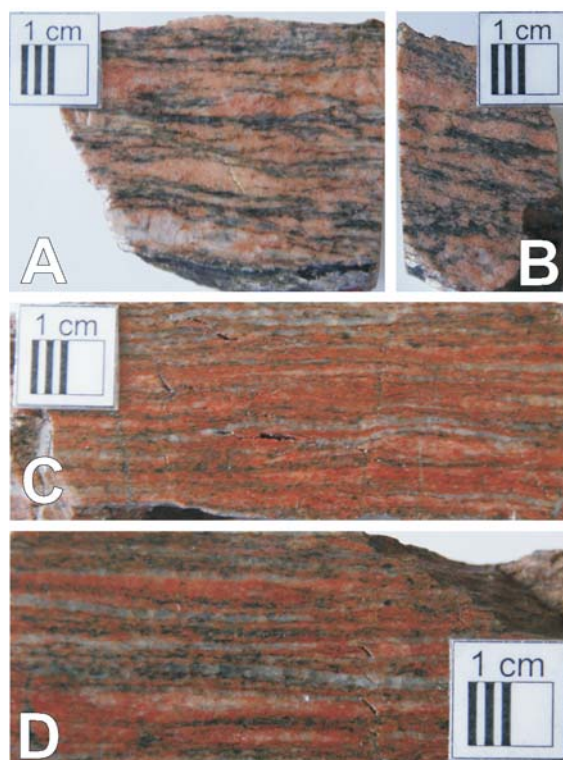
Sample L1 (Text-figs 1, 7A, B) is a flaser to layered gneiss dominated by pinkish, lenticular, multimineral layers composed of elongate grains of quartz, plagioclase and K-feldspar. Although plastically deformed, the minerals do not show signs of dynamic recrystallization. Instead, high-angle straight boundaries occur between grains that have only weak signs of optically identifiable strain. Intervening layers consist of white mica flakes that stabilize boundaries of box-like rectangular quartz grains. Such features are typical of a high-temperature metamorphic rock and the way the minerals have been arranged and segregated resembles migmatites. In addition to a migmatitic appearance, this gneiss characteristically does not possess augen. Accordingly, sample L1 is considered a migmatitic gneiss sheared at high temperature conditions. S-C structures are in evidence and prove helpful in revealing kinematics in the XZ sections (Text-fig. 7A), whereas the flaser layering appear only slightly less distinct in the YZ sections (Text-fig. 7B) in contrast to the Spalona gneisses.

Another sample (L2) of sheared migmatitic gneiss comes from the Zdobnice, the Czech Orlické hory Mts. (Text-figs 1, 7C, D), from which the melt-derived neosome yielded a U-Pb zircon age of ~485 Ma (Żelaźniewicz *et al.* 2006). It is a thinly layered gneiss, free of augen, composed of two feldspars, quartz, biotite and muscovite, relict garnet and pseudomorphs after an unknown mineral (Al_2SiO_5 ?) now altered into an aggregate of white mica and plagioclase. The rock is a S>>L tectonite type (Text-fig. 7 C, D) with perfect foliation expressed by parallel arrangement of monomineral quartz ribbons and composite polymineralic layers composed of feldspars, quartz and both micas. On the foliation surface, there is only a mineral lineation, marked by the parallel arrangement of mainly white mica flakes, whereas a stretching lineation is very faint and augen are missing. The quartz ribbons developed from greyish quartz lenticles that occurred already in a migmatitic protolith. They might imply high strain, which is however in this case

rather improbable because the pseudomorphs, albeit extended and disrupted, do not show signs of strong deformation. Quartz-feldspar contacts are commonly straight and polygonized, as commonly observed in migmatites. In sections normal to the foliation and parallel to the weak stretching lineation, the asymmetry of micas fishes and small feldspar grains indicate a top-to-the-N kinematics. However, in the quartz grains, oblique subgrains and deformation bands developed that point to a movement in the opposite direction toward the S/SW. This kinematics is probably connected with two younger mineral lineations, expressed independently by feldspar and mica, and discernible on the foliation plane. Finally the rock was kinked and the contractional kink folds may be interpreted as a record of late NE-SW compression in the region.

Wójtowice gneiss body

L>S and L=S tectonites (samples: W1–W4, W3.1) also occur in the area between Nowa Bystrzyca and Paszków (Text-figs 1, 8). There is ca. 1 km wide and 13 km long belt of orthogneisses set in mica schists and paragneisses (Wójtowice unit of Dumicz 1964), which



Text-fig. 7. Sheared migmatitic gneisses from the Lesica(-Řičky) gneiss unit, sample L1 from Niemojów (A, B) and sample L2 from Zdobnice (C, D). A – section parallel to the stretching lineation and normal to the foliation; B – section normal to the stretching lineation; C – section parallel to the stretching lineation and normal to the foliation; D – section normal to the stretching lineation

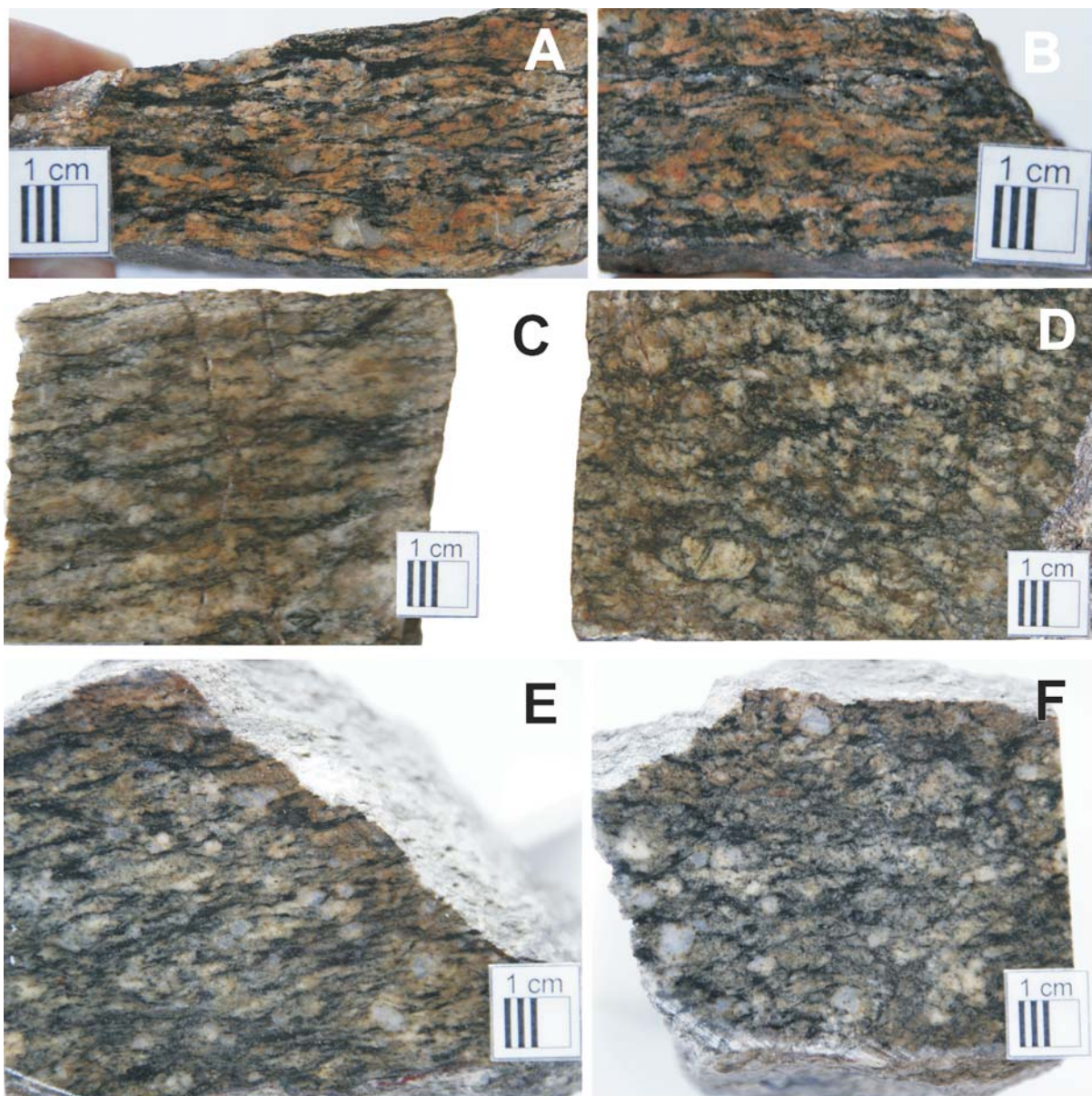
QUARTZ C-AXIS FABRICS IN CONSTRICTIONALLY STRAINED ORTHOGNEISSES

probably originated as a granite vein intruded into the surrounding schists. These are mainly lenticular augen gneisses characterized by moderately to steeply SWward dipping foliation and less distinct linear structures (Text-fig. 5). The Wójtowice gneisses (Text-fig. 8) differ from the Spalona gneisses (Text-figs 2, 3, 4) in their higher contents of biotite and feldspars but smaller amount of quartz which appears as small lenses and scarce ribbons, whilst Kfs augen are practically missing.

In L~S samples (Text-fig. 8 A, B), in the section parallel and normal to the stretching lineation, there is greyish ribbon or lensoid quartz and more irregular elongate reddish spots composed of polymineralic fine-grained

aggregates of quartz and recrystallized feldspars ($PI > Kfs$) accompanied by newly formed muscovite shreds dispersed in the aggregate or arranged in felts parallel to the foliation. In the intervening dark stripes, biotite is 2–10 times coarser. The polymineralic aggregate spots contain more or less elongate Kfs porphyroclasts. In the quartz lenses, grain-to-grain contacts indicate recrystallization by grain boundary migration.

In L>S samples (Text-fig. 8C–F), lensoid quartz and elongate polymineralic aggregates can be observed only in XZ sections, whilst in the YZ sections they are more or less equant and only slightly flattened in the foliation plane, expressed best by biotite flakes. In the Wójtowice



Text-fig. 8. Orthogneisses from the Wójtowice gneiss body. Samples W1 (Nowa Bystrzyca), sample W2 (Równia Łomnicka), sample W3 (Wójtowice). A, C, E – sections parallel to the stretching lineation and normal to the foliation; B, D, F – sections normal to the stretching lineation

body, the foliation that generally dips to the SW/WSW becomes better developed northwards as minerals and mineral aggregates, observed in sections perpendicular to the lineation, become more and more flattened as the gneiss body tapers out. K-feldspar augen appear as sigma type porphyroclasts which together with occasional S-C structures and asymmetric paragneiss enclaves point to a top-to-the NW kinematics in an oblique dextral strike-slip regime. Locally, the S/SSW-plunging (~20–35°) stretching lineation was overprinted by the biotite lineation which plunges at an angle of 0–20° to SE/SSE (Text-fig. 5).

RESULTS OF MICROSTRUCTURAL ANALYSIS

Selected samples

In six selected samples of L, L>S, LS and S>L tectonites, the quartz c-axis orientation was measured separately for three different domains: quartz ribbons, quartz-feldspar aggregates and quartz in tails at Kfs porphyroclasts. The results are shown in Text-fig. 9.

In sample S9, from the northern part of the Spalona gneiss body (Text-figs 1, 5, 9), the c-axis pole figure for quartz ribbons apparently resembles type I cross girdle (Text-fig. 9A.3). The wide opening angle of the small circle components of this girdle indicates a relatively high temperature of deformation, which is consistent with common microstructural evidence of grain boundary migration recrystallization. Also poles close to the X axis suggest the prism <c> slip characteristic of high temperature deformation. Considering the elongation of the maximum at Y and slight asymmetry of the pattern, the microfabric may indicate constrictional deformation with some plane strain component, which corroborates well the L>S type of the tectonite. An apparent type I cross girdle seems to be a pseudo-girdle. Indeed, a single girdle pattern is rather characteristic of rocks deformed in planar shear zones and this is not the case of sample S9 characterized by the prolate strain.

A diffuse LPO pattern obtained for quartz grains of the quartzo-feldspathic aggregate in sample S9 (Text-fig. 9A.4) is less informative, yet the operation of a prism <a> slip system may be inferred. All other poles lie close to the rim and form a girdle around the Y axis. It might be resolved into small circle girdles around the X and Z axes, which would hint at the operation of both

constriction and flattening strains, eventually resulting in nearly orthorhombic symmetry of the pattern. However, it is also likely that the pattern was affected by the presence of feldspar grains which, recrystallizing concurrently in the aggregate, forced the activation of more slip systems in quartz. Recrystallization of feldspar requires temperatures in excess of 450–500°C, the thermal conditions in which prism <a> slip and rhomb <a> slips in quartz are usually favored. Activation of these glide systems might accomplish the quartz LPOs.

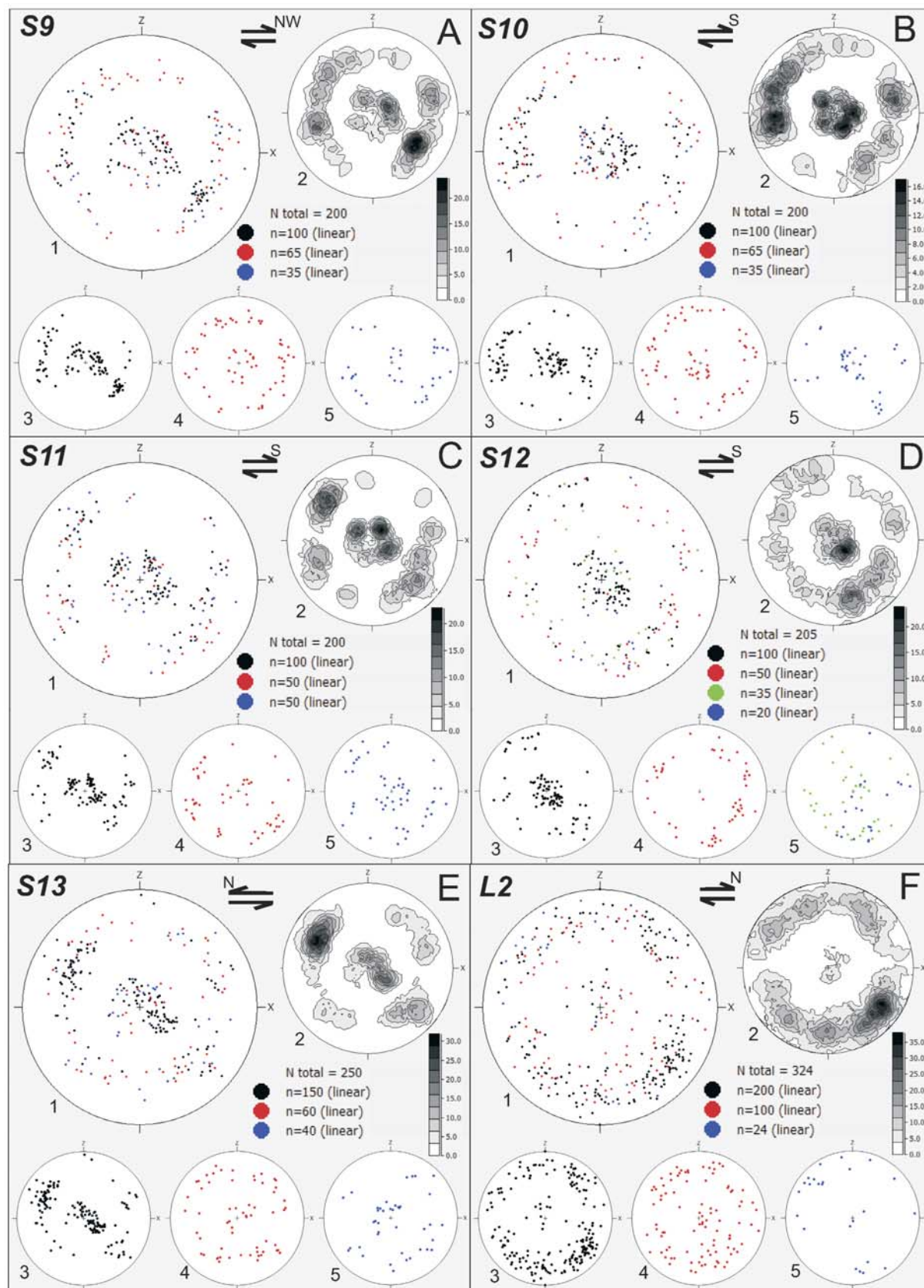
In sample S9, for quartz tails accompanying Kfs augen, two small circle girdles around the X axis or maxima close to X may be envisaged (Text-fig. 9A.5). Constrictional strain geometry and prism <c> slip may be inferred, thus being similar to the pattern found in the quartz ribbons. A prism <a> slip system, but also relatively high strain, are suggested by the maximum around the Y axis. The tail quartz seems predisposed to keep records of kinematic strain path. Although a part of the tails is symmetric, the others are associated with sigma-type Kfs porphyroclasts that indicate both a top-to-the-SE and top-to-the-NW kinematics. Such opposite asymmetry may be attributed to rotations of originally oppositely inclined rigid objects in an overall coaxial strain. However, traces of S-C' type structures which can be observed in the XZ sections of sample S9 point to the top-NW idea. They overprint the quartz ribbons and mica felts and thus are interpreted as a later feature. Such observations suggest that the Spalona gneisses underwent multiple deformations, despite their apparently simple mesofabric of L>S type. Moreover they also suggest that the original microfabric may have been changed during subsequent increments to an extent difficult to discern.

The case of the gneisses from which sample S9 was taken is even more complex, as in sections parallel to the YZ plane of the finite strain ellipsoid another set of younger weak mica cleavage is locally identifiable. The two foliation sets intersect along the stretching lineation. The second foliation set dips at a larger angle than the first.

Summing up, the distinction of the three quartz-bearing domains has helped to understand the CPO pattern revealed by the synoptic contour diagram (Text-fig. 9B) by showing that the microfabric S9 is to be treated as an effect of mixing. Taking this into account, the observed pole figure is considered to be a composite feature that evolved in the constrictional regime close to the

Text-fig. 9. Quartz c-axis pole figures for selected samples of the Spalona gneisses (A–E) and Zdobnice gneiss (F). For each sample, numbers on diagrams at bottom left denote: 1 – synoptic point plot; 2 – synoptic contour diagram; 3 – poles from quartz ribbons (black dots); 4 – poles from quartzo-feldspathic aggregates (red dots); 5 – poles from tails at K-feldspar porphyroclasts (blue dots) and in sample S12 poles from quartz mica in layers (green dots). Black arrows indicate kinematics as observed in hand specimens and thin sections. A – sample S9 (L>S tectonite) from Duszniki Zdrój; B – sample S10 (L>S tectonite) from Dolina Strążyska S of Duszniki; C – sample S11 (L>>S tectonite) from Mostowice; D – sample S12 (L>S tectonite) from Spalona; E – sample S13 (L>>S tectonite) from Rudawa; F – sample L2 (L<S tectonite) from Zdobnice

QUARTZ C-AXIS FABRICS IN CONSTRICTIONALLY STRAINED ORTHOGNEISSES



orthorhombic symmetry and plane strain regime under medium metamorphic conditions.

Quartz ribbons in other four selected samples of L>S and L>>S tectonites (S10 to S13) from the Spalona body reveal microfabric patterns similar to that in sample S9 (Text-fig. 9B–E). In all cases, it is roughly similar to an asymmetric type I cross girdle, with significant small circle girdle components, inclined at a low to moderate angle to the foliation.

Quartzo-feldspathic domains in these samples also present similar pattern which consists of a maximum centered at Y and a diffuse girdle around the Y axis, located close to the rim of the diagram. The pattern may be alternatively interpreted as that proposed for sample S9.

What distinguishes samples S10 and S13 is the microfabric which developed in the pressure shadows of Kfs porphyroclasts (Text-figs 9 B.5, C.5, D.5, E.5). Apart from common maxima centered on the Y axis (probable prism <a> slip), they tend apparently to form small circle girdles around the X axis in samples S10 and S11 (L>>S tectonite) and rather indefinite patterns in samples S12 and S13. In sample S13, quartz grains with straight boundaries at the contacts with neighboring mica flakes were additionally distinguished (green points, Text-fig. E.5) and these produced considerable scatter on the diagram. It can be probably explained by strong controls exerted by other minerals on the recrystallizing quartz grains. Despite their elongation in the foliation plane parallel to the stretching lineation, thus forming a shape fabric, they were probably forced to activate <a> slips on prism and rhomb glide systems differently oriented to the principal strain axes. Such an observation is consistent with the inference made from the crystallographic relationships in the quartzo-feldspathic aggregates.

In view of the above, a rather contrasting picture is presented by sample L2 which is a L<S (~S) tectonite from a sheared migmatitic gneiss. No type I girdle is discernible in quartz ribbons and the microfabric developed an almost orthorhombic pattern. It may possibly be resolved into two small circle girdles centered on the X axis and two small circle girdles centered on the Z axis (Text-fig. 9E). Quartzo-feldspathic aggregates in sample L2 reveal an LPO pattern similar to that observed in the L>S tectonites. Small circle girdles around the Z axis of the finite strain ellipsoid may be interpreted as a flattening strain, which possibly occurred before the switch to constrictional deformation. The high symmetry of the LPO pattern indicates a mainly non-rotational strain. Compared to other samples, c-axis maxima are shifted closest to the rim of the diagram, whereas poles located close to the Y axis are scarce. Such a pattern might suggest a lower temperature of deformation; however, the

maxima close to the X axis, similar to other samples, indicate a prism <c> slip that requires a rather high temperature to be activated. A similar inference is offered by the quartz seams in which elongate Kfs grains are embedded (Text-fig. 9E). Some other maxima near the circumference may indicate a basal <a> slip system. This, however, may be artificial and only reflect the earlier orientation of quartz grains and small circle girdle distribution of their c-axes as the rock does not carry any sign of a greenschist facies overprint.

Other samples

The Spalona body

Samples S1 to S4, which come from the northern part of the Spalona gneiss body, (Text-figs 1, 10A–D) represent L>S tectonites with kinematic indicators pointing to a top-to-the-f 5

The Lesica body

Sample L1 from Niemojów is a S>L tectonite and belongs to the Lesica gneiss body which is built mainly of sheared migmatitic gneisses (Text-figs 1, 7A, B). The pole diagram is not straightforward (Text-fig. 10J). It may be viewed upon as initially type II cross girdle which later partly changed toward asymmetric, type I girdle, or as two distorted small circle girdles partly transformed to type I cross girdle. Distribution of the pole maxima might be interpreted as due to activation of prism <c>, prism <a> and rhomb <a> slip systems under medium grade metamorphic conditions. A top-to-the-NW kinematics inferred from the asymmetry of the microfabric is consistent with the S-C internal fabric of feldspar lenses and locally shape fabric of these lenses. No feldspar augen is present.

Another sample, L2, of the migmatitic gneisses has been described above.

The Wójtowice body

The L>S tectonites which dominate in this gneiss body display rather complex microfabric patterns (Text-fig. 10K, L, M). The quartz LPO pattern in sample W1 resembles a single girdle which may have possibly developed from an earlier type II cross girdle (Text-fig. 10K). The inclination of the apparent single girdle to the foliation is inconsistent with mesoscopic kinematic indicators. Maxima gathered around Y suggest that prism <a> slip system was dominantly activated. Other pole concentrations indicate contributions from basal <a>, rhomb <a> and prism <c> systems. The overall pattern

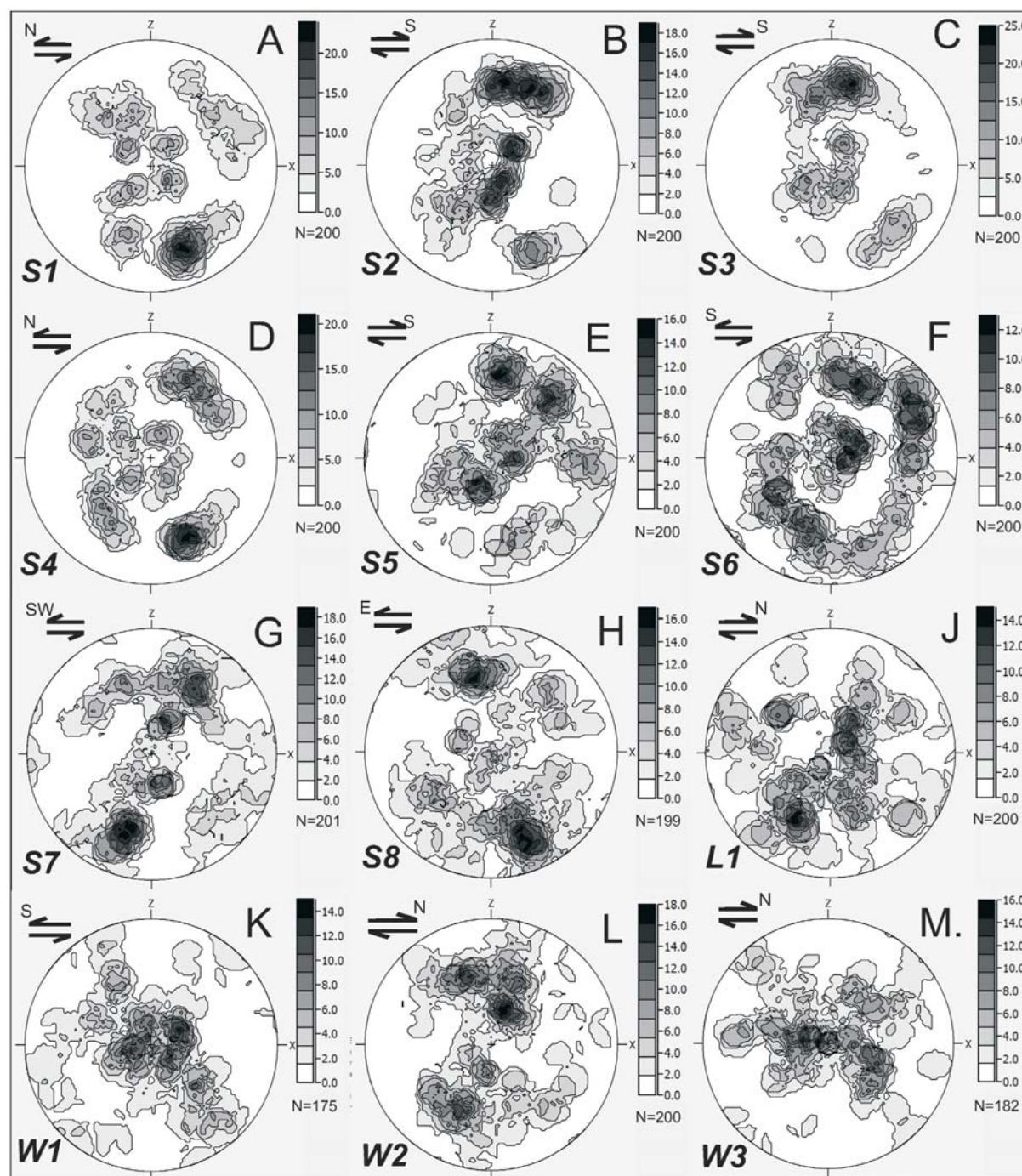
QUARTZ C-AXIS FABRICS IN CONSTRICTIONALLY STRAINED ORTHOGNEISES

resembles that observed in sample S7, kinematic inconsistencies between meso- and micro-fabrics inclusive. These data point to multiple deformations under a range of temperature conditions.

The quartz microfabric of sample W2 resembles a type I cross girdle, or initially a type II cross girdle later transformed to a single girdle (Text-fig. 10L). The incli-

nation of this girdle is, however, incompatible with mesoscopic shear criteria which indicated opposite, top-NW kinematics. In the <c> axis pole plot, six maxima in the rhomb <a> position suggest that the very slip system was mainly active during multiple deformation.

In sample W3, the quartz LPO pattern is also complex (Text-fig. 10M) and resembles sample S8. It may



Text-fig. 10. Synoptic contour diagrams showing quartz LPO patterns in gneisses from the Spalona (samples S), Lesica (sample L1) and Wójtowice (samples W) gneiss bodies. Black arrows indicate kinematics as observed in hand specimens and thin sections. Further explanations in the text

be interpreted as two small circle girdles centered on Z, yet slightly asymmetric, and transformed into a type II cross girdle, or as a type II cross girdle. Three maxima close to Y belong to an elongate array of poles located in the XY plane or close to the X axis of the finite strain ellipsoid. The somewhat asymmetric pattern may indicate a component of rotational deformation with the sense of vorticity consistent with mesoscopic shear criteria which suggest a top-to-the-NW/N kinematics.

In the Wójtowice gneisses, a stretching lineation (feldspar, quartz) is poorly developed and overprinted by a weak mineral (mica) lineation plunging to the SW. This evidently confirms multiple deformation under metamorphic conditions. However, it is difficult to assess – as in other studied samples – the amount of quartz recrystallization during later tectonometamorphic increments. This might be one of the reasons that led to the development of complex microfabrics. Therefore, the planes of the projection in diagrams for samples W1–W3 along with the measured poles were rotated to bring the plot planes to parallelism with the younger mineral lineation. However, this operation did not improve the legibility of the microfabric patterns and thus it cannot be stated that the younger recrystallization notably erased earlier features.

DISCUSSION

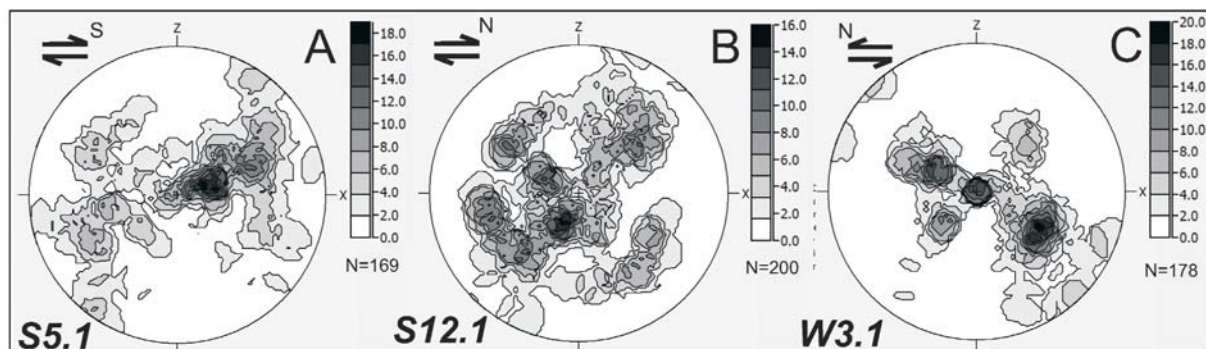
The principal tenets and terminology in microstructural analysis have been mentioned in the “Methodology...” section. Most published examples refer to rocks that were deformed under plane strain or flattening strain; very few deal with constrictional deformation. In the preceding section, the same nomenclature has been applied to characterize the obtained quartz LPO patterns, although some terms are used rather descriptively and depart from the original defi-

nition. This refers to such terms as cross girdles of types I and II and single girdles which in our cases seem to be mainly pseudo-girdles.

Microstructural interpretations are relatively straightforward in quartz-bearing rocks that underwent a single episode of (progressive) shear deformation. Current views consider temperature as the main factor that controlled the activation of particular system(s) of intracrystalline slips under a range of metamorphic conditions in coaxial or non-coaxial strain regimes, which can be read from the pole figures on LPO diagrams. However, such figures for multiply deformed rock are more complex and it may often be difficult to tell on such diagrams the memory fabric from the effects of younger recrystallization, which can bring about misinterpretations.

There is growing evidence that temperature is not necessarily the most important factor in quartz texture formation. The process is also controlled by deformation, strain partitioning, or the pre-existing grain orientation (Toy *et al.* 2008; Peternell *et al.* 2010). Early formed quartz LPOs can be modified later, for instance at lower temperatures during exhumation. However, the lack or scarcity of suitably oriented grains to activate a particular slip system may force the reactivation of the old system(s). For instance the Y-maximum fabric can weakly be transformed by a basal $\langle a \rangle$ slip, so that even at lower temperatures prism $\langle a \rangle$ or rhomb $\langle a \rangle$ slips may continue to operate (Toy *et al.* 2008).

Despite an apparently simple L>S mesofabric, the Góry Bystrzyckie gneisses show evidence of multiple deformation on meso and micro-scales. Therefore the obtained quartz LPO patterns are complex features which have probably recorded a fabric evolving in a constrictional regime. The results of quartz c-axis measurements described in the previous section were interpreted by drawing on these facts. Several aspects of these interpretations are discussed below.



Text-fig. 11. Synoptic contour diagrams to test quartz $\langle c \rangle$ axis microfabric patterns identified in gneisses from Lasówka, Spalona and Wójtowice. Black arrows indicate kinematics as observed in hand specimens and thin sections. Further explanations in the text

Domainal differences

In five selected samples of the Spalona gneisses (Text-fig. 9A–E), quartz LPO patterns usually permit us to identify two or more maxima of c-axis orientation. One is always close to the Y axis of the finite strain ellipsoid, whereas a few others are oriented at an angle of $\sim 45^\circ$ to the X axis or close to it. Although quartz grains from the three distinguished domains contribute to these maxima, subsets can be isolated with grain cluster orientations around Y and close or inclined to X. Quartz c-axis orientations close to Y and X predominate in pressure shadows which form tails of Kfs porphyroclasts, whereas in quartzo-feldspathic aggregates the c-axes scatter widely around X and Z. Some relationships between microstructure and crystal orientation can thus be established. In the case of the ribbons and pressure shadows, the asymmetry of the LPOs with respect to the external XYZ reference suggest non-coaxial strain components. Similarities in quartz LPO patterns between the quartz ribbons and tails may suggest that in the L>S tectonites the two domains developed concurrently. In quartz grains, intracrystalline deformation was presumably partitioned into prism <a> and prism <c> slip systems. The latter clustered point maxima close to the X axis and clearly tended to form small circle girdles around X, yet slightly asymmetrically disposed with respect to it.

Less obvious is the microfabric pattern revealed in quartz-feldspar aggregate domains in the same rocks (Text-fig. 9A–C). Some poles to <c> axes cluster around Y, whereas most of them scatter along a “large” small circle at an angle of $60\text{--}70^\circ$ to Y and thus occupy rather indefinite positions, the cause and significance of which, without more detailed studies, may be only speculative. While a part of this circular distribution of poles may indicate girdles around both X and Z axes, still a prism <c> slip may be inferred for the other part. The prism <a> slip would explain the Y maximum, which might suggest a rather high temperature or elsewhere that many quartz grains in the aggregate retained orientation from the earlier stage and were positioned in a way favoring that slip system. On the other hand, the main reason for such a distribution may be the influence from neighbouring feldspar grains in the aggregate, unless the domain partly records inheritance and partly annealing. In the latter option, aggregates would recrystallize later or longer than the deformational episode.

Our studies show that the domainal differences in quartz microfibrils recognized in the selected samples are common in the Spalona orthogneisses but uncommon in the sheared migmatitic gneisses. Quartz grains from ribbons and tails are suitable for microstructural analysis, whereas quartz grains from quartzo-feldspathic aggregates

produce rather diffuse pole figures, and thus are not very informative, which is probably due to the presence of feldspar grains that recrystallized concurrently in such aggregates.

Strain and slip system

Both the microstructures and LPOs indicate at least two, possibly three, intracrystalline quartz deformation modes. These may have been connected with different deformation episodes/increments. On the other hand, unless one of them took actually place earlier (prism <a> slips at higher temperatures of amphibolite-facies) and has been an inherited relic feature, these modes should have operated simultaneously.

In general, small circle girdles are characteristic of prolate strain geometry as predicted by the Lister and Hobbs' (1980) model. Quartz LPOs that developed in constrictional tectonites are unfortunately not often reported. This scarcity inhibits comparisons of our patterns with other natural examples. Sullivan *et al.* (2010) published data for metargillites from California that were metamorphosed in the amphibolite facies, in which they found microfibrils transitional between true double-girdles and type II cross girdles and small circle girdles around X, thus generally consistent with the models of Lister and Hobbs (1980) and Schmid and Casey (1986). The prolate shapes of rodded K-feldspar and quartz grains/aggregates (Żelaźniewicz 1988; Cymerman 1997) of the Spalona gneisses (Text-figs 2A–B, 3A–B) show that deformation of these rocks occurred in the field of apparent constriction. Evidence for elongation in the XZ plane is additionally given by the presence of S-C' type structures. Given a temperature control on microfabric development in the L>S Spalona gneisses, the common operation of prism <c>, rhomb and prism <a> slips is to be inferred. Indeed, lenticular quartz layers are composed of grains of different dimensions with rather intricately lobate boundaries indicative of grain boundary migration recrystallization at relatively high temperatures around 560°C (Kruhl 1996, 2001). Given strain geometry control on the microfabric, small girdles around the X axis are to be expected. Actually, the pole figures (Text-figs 9, 10) point to the operation of these two controls and the observed quartz LPOs' figures. Taking into account that the L>S microfabric is common in the Spalona gneisses, we suggest that the strain geometry was not less important than temperature for developing the microstructure patterns in these rocks.

Maxima close to X require activation of prism <c> slip system. In samples S9–S11, pole maxima which cluster around Y presumably indicate plane strain conditions and suggest that rhomb to upper prism <a> slip at

temperature $>500^{\circ}\text{C}$ may have operated simultaneously with the prism $\langle c \rangle$ slip. Thus temperature control is also an obvious factor.

In synoptic contour diagrams (Text-fig. 9A–C), the poles from the quartzo-feldspathic aggregates significantly influence the overall quartz LPO pattern. The overall microfabric patterns, as well as those read from the ribbon and tail quartz, show nearly orthorhombic to monoclinic symmetry, which may be taken to indicate the coaxial and non-coaxial components of deformation, respectively. Monoclinic symmetry has traditionally been linked with higher strain zones, but many more recent studies also document triclinic symmetry from such zones. The slight asymmetry of the observed patterns with respect to the external XYZ framework, if taken as a kinematic indicator, agrees well with a top-to-the S/SW kinematics recognized in hand specimens and thin sections.

Temperature control

In sample S10, the quartz $\langle c \rangle$ axes LPO plots around Y, which may indicate plane strain conditions and a temperature $>500^{\circ}\text{C}$, correspond well with core and mantle structures of some feldspar porphyroclasts. Such structures are interpreted as evidence for bulging ($450\text{--}600^{\circ}\text{C}$) dynamic recrystallization (Pryer 1993). Dynamically recrystallized quartz grains in ribbons within the Spalona gneisses display well-developed boundaries characteristic of a grain boundary migration mechanism that records relatively high-temperature ($>500^{\circ}\text{C}$, $500\text{--}650^{\circ}\text{C}$), which is consistent with grain boundary area reduction (Bons and Urai 1992) and polygonization. White mica flakes arranged parallel to the foliation plane contribute to elongated quartz grain boundaries.

Typically, in plane strain and/or simple shear regime, the $\langle c \rangle$ -axis girdle fabric appears to be a result of combined basal, rhomb and prism $\langle a \rangle$ slip-systems (Stipp *et al.* 2002). At a temperature of $\sim 500^{\circ}\text{C}$, prism $\langle a \rangle$ slip system may become the dominant activity and the girdle fabric can change to a single maximum in the Y axis. A fabric transition of this kind can coincide with the change of recrystallization mechanism from subgrain boundary rotation to grain boundary migration. Although the two recrystallization mechanisms evidently occurred in the studied samples, we did not find enough evidence to claim such a fabric transition as the deformation was mainly constrictional. The question whether early quartz microfabric was a relatively stable feature or became obliterated during younger deformational episodes may not be easy to answer.

The common lack of pole figures produced by a basal $\langle a \rangle$ slip system suggests that the general shear regime op-

erated under temperature conditions characteristic of the amphibolite facies, as indicated by the activity of the prism $\langle a \rangle$ and prism $\langle c \rangle$ slip systems. Such an inference is consistent with all P-T estimates calculated by various methods for mica schists and other multiply deformed metasedimentary rocks of the Stronie-Młynowiec group in either limb of the Orlica-Śnieżnik Dome (Jastrzębski *et al.* 2010; Szczepański 2010; Skrzypek *et al.* 2011). They indicate the peak metamorphic P-T conditions occurred in the OSD metasedimentary and metavolcanic rocks at $560\text{--}620^{\circ}\text{C}/7\text{--}9$ kbar (Jastrzębski 2005, 2009; Murtezi 2006; Skrzypek *et al.* 2011), apparently at 340 Ma (Skrzypek, pers. comm., Jastrzębski *et al.* 2013); thus the data are in agreement with the microstructural proxies. It follows from the compatible temperature data that both the metasediments and metagranites were deformed at similar crustal levels.

Shearing

A less important factor was shearing, which should result in true girdles and this explains why such girdles are missing from the LPO patterns in the studied rocks. These inferences fit well the observed natural mesofabrics of $L>S$ to $L>>S$ tectonites from the Spalona body (Text-figs 2, 3), which all display a distinct quartz and feldspar rodding structure, relatively weak mica foliation and occasional Kfs porphyroclasts of sigma type. The tectonites are interpreted to have formed under a combination of general constriction and plane strain components, owing to the activation of prism $\langle a+c \rangle$ slips under amphibolite facies conditions.

Samples S12 and S13 from the central part of the Spalona gneiss body present almost the same characteristics as samples S9–S10. The only departure is the difference between pole figures obtained for the quartz ribbons and pressure shadows, as the latter, although also composite, appear asymmetric and oriented at right angles to that displayed by the ribbons (Text-fig. 10E, D). One possible explanation is that the trails of mantled Kfs porphyroclasts are built on feldspar dynamically recrystallized from the core, whereas quartz in the trails may come from the surrounding matrix and from the breakdown of Kfs associated with new white mica formation. This may be the case in sample S10, in which the tail quartz grains pinned by mica tend to follow the pattern shown by the ribbon quartz (Text-fig. 10D.5, green points), whilst other grains tend to form a girdle with an orientation different by $\sim 90^{\circ}$. The asymmetry of the latter is consistent with an overall kinematics of a top-SW sense of movement. The stretched Kfs grains show S-C' structures with C' planes (Text-fig. 4A), the presence of which may suggest a rather fast strain rate during the de-

formation that transposed the original granite into the augen gneiss. Some of the C' planes in multiminerale mica layers are accompanied by chlorite growing at the expense of biotite, which indicates a lower temperature than that inferred for the origin of quartz and feldspar rodding. A greenschist facies overprint in an extensional regime is a corollary, which contributes to the evidence for multiple deformation of the gneisses, albeit with the same top-SW kinematics.

In sample S13, S-C' type structures are also in evidence and C' traces are underlined occasionally by chlorite flakes. The presence of chlorite in both samples seems to argue for multiple deformation, with later increment(s) being accomplished at lower temperature. This increment might also have affected and distorted the quartz microfabric.

The observed feldspar grain-boundary mobility confirms temperatures in the amphibolite facies when the rodding developed in the apparent constriction field proved by structural studies (Żelaźniewicz 1988, 1991; Příkryl *et al.* 1996; Cymerman 1997). The constrictional strain ($\infty > k > 1$) may have had the plane strain component or have been followed by the plane strain.

We suggest that the deformation proceeded under overall conditions of general shear which is a three-dimensional deformation that deviates from pure or simple shear regardless of whether the finite strain ellipsoid is oblate, plane, or prolate regardless of slip direction (Bailey *et al.* 2004). When strike-slip or dip-slip offsets are produced, the strain is transpressional or transtensional, respectively.

Microtextural observations suggest that the quartz microfabric formation in the Spalona gneisses was a protracted process that involved strain partitioning with changing strain rate and kinematics in a general shear regime at amphibolite facies temperatures and a with a multiple deformation history.

Opposite sense of shear

The opposite sense of shearing found in the studied samples can be explained by a dominantly coaxial regime in which the objects tend to rotate toward the fabric attractor to reduce an acute angle with it. However, in 15 thin sections prepared from different gneiss samples collected at exposure S10, only two show a reverse sense of movement, which cannot be accounted for by pure shear or folding. In this case, a feasible explanation is a variable but relatively fast strain rate. In tectonically differentiated rocks like the studied gneiss (Text-fig. 4), strain rates may be partitioned and vary between domains. If a given domain deforms faster or slower than the surroundings, then local reverse shear may be in-

duced and accomplished along the domain boundaries (Hippert and Tohver 1999).

Test of data

The validity of the obtained microfabric patterns was tested by repeating measurements in samples from the same outcrops. Two sets of data were obtained by parallel operators. Eventually, the patterns found in samples S5.1, S12.1 and W2.1 (Text-fig. 11A–C) by one of us can be compared with the patterns in samples S5 and W2 (Text-fig. 10E, L) and S12 (Text-fig. 9D) measured by the other. The results proved generally reproducible despite noticeable but not critical differences.

The L>S tectonite from Lasówka (samples S5, S5.1) produced asymmetric pole figures with maxima around the Y axis and close to the X axis. In sample S5.1, a composite pattern resembles a type I cross girdle which embraces two small circle girdles around X. Both diagrams indicate prism <a> and prism <c> slip systems that in sample S5 were more efficiently helped by rhomb <a> slips.

Samples S12 and S12.1 (L>S tectonite) are also similar in having a pattern that contains several maxima arranged in a specific way. It is characterized by a strong cluster of poles close to the Y axis which is surrounded by an outer garland of pole maxima around Y.

A significant difference is in the sense of shearing observed in the two hand specimens.

The pole figures for samples W3 and W3.1 (L>S tectonite) from Wójtowice resemble a type II cross girdle which is more diffuse in W3 and more evolved in W3.1. In both samples, maxima around the Y axis are in the middle of the array extending at low angle to the foliation traces and the X axis. For sample W3 a flattening strain might be suggested whereas in case of W3.1. more coaxial strain is evident. Kinematic criteria show a top-to-the-N sense of asymmetry and movements.

Migmatitic gneisses

Sample L2, a sheared migmatitic gneiss, differs significantly from the other five samples which have been examined in greater detail (Text-fig. 9F). The pole figure consists of several maxima rather evenly distributed close to the periphery of the diagram, with relatively few poles clustered around Y. In hand specimens, the sample represents an S>>L tectonite, differing from all others that displayed distinct rodding. The microfabric has a nearly orthorhombic symmetry, yet is a composite feature. Maxima close to Z represent a small circle girdle to which basal and rhomb <a> slip might have contributed, yet the main fabric-forming factor was presumably a flattening strain according to the Lister and Hobbs model

(1980). However, strong 35% maxima at an angle of $\sim 40^\circ$ to the X axis suggest prism $\langle c \rangle$ slip and constrictional component at relatively high temperature. We suggest that the constrictional strain, otherwise characteristic of the Spalona augen gneisses, was in migmatitic gneisses imposed on the originally planar fabric defined by migmatitic layering.

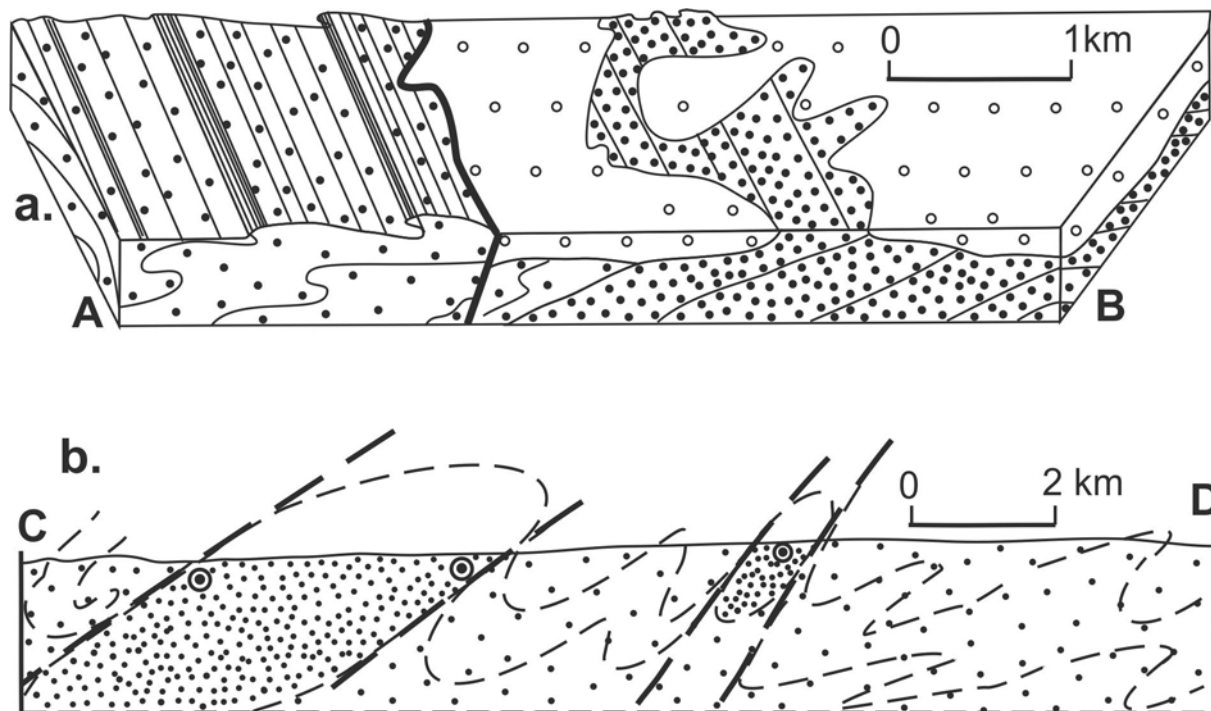
Earlier results

From the sheared migmatitic gneisses (Lesica-Řický unit), referred to as anatectic orthogneisses, Příkryl *et al.* (1996) reported the presence of two perpendicular quartz and feldspar fabrics. In our samples, a fine stretching lineation plunging shallowly to north, expressed by reddish Kfs rods, is parallel with the mica lineation, and this set is overprinted by a feldspar and mica lineation plunging to the NE and by a white mica lineation plunging to the WNW-ESE, which all supports multiple deformation at decreased temperature. We propose that the migmatitic gneisses studied by us were deformed first at relatively high temperature, probably by flattening, and then by constriction and coaxial plane strain in a general shear regime, when basal and rhomb $\langle a \rangle$ slip systems operated. Hence the deformation paths for the migmatitic and augen gneisses significantly coincided. The Příkryl *et al.* (1996) results can be easily reinterpreted in that way,

which can also explain the succession of the W-E and N-S lineation sets observed by these authors.

Our study shows that the overall microfabric patterns in gneisses of the Góry Bystrzyckie Mts. are more complex than those obtained by Cymerman (1997) and Szczepański (2010). Because of the complexities, an approximate image analysis (Stoekherth and Duyster 1999) employed by the latter author produced rather oversimplified LPO patterns that were interpreted as mainly type I and type II cross girdles. Such girdles are often found in the central parts of shear zones. In most cases, the asymmetric single girdles were explained by dextral strike-slip shearing in plane strain and simple shear regime(s), and only a temperature control on the position of pole maxima was indicated. Activation of mainly $\{m\} \langle r, z \rangle$ rhomb $\langle a \rangle$ and less common prism $\langle a \rangle$ glide systems was proposed.

Although the pole figures revealed in this study for the quartz ribbons (Text-fig. 9A–D) resemble a type I cross girdle pattern, it is not the case for the Duszniki-Rudawa L>S tectonite belt as it does not agree with the mesofabric observed in the belt, in particular with the perfect rodding structure of L>>S type gneisses (Text-fig. 3A, B). In spite of the simple mesofabric, the L>S tectonites show quite complex yet reproducible patterns of quartz *c*-axis distribution. The microfabrics of the Góry Bystrzyckie gneisses represent a composite feature be-



Text-fig. 12. Tectonic position of the Spalona gneiss body. A – block diagram (A–B line in Text-fig. 1) showing the relationships between the rodding augen gneisses (dense dots) and mica schists (sparse dots) in the vicinity of Duszniki, the northern tip of the Spalona body (after Żelaźniewicz 1978); B – simplified cross-section through the central part of the Góry Bystrzyckie Mts. (line C–D in Text-fig. 1), showing their location in the hinge zones of large-scale folds and the N-ward movement (elongation) which gave rise to opposite strike-slip kinematics at the opposite margins of the Spalona gneiss body

cause of the multiple deformation of the rocks and the common interplay of strain geometry and temperature during deformation. It cannot be explained by a model of a shear zone with the strain intensity varying across it.

Implications for local and regional tectonics

The K-feldspar and quartz rods display a shape fabric represented by a triaxial prolate ellipsoid which evolved in the constrictional field with some non-coaxial rotational strain in the general shear regime. Such an ellipsoid fits well the observed mesofabric and composite microfabric. It is possible that the strain path started under conditions closer to the plane strain and then changed to constriction. Such switch can be accomplished in the hinge zone of a large-scale fold where the elongation occurs parallel to the fold axis. Overturned to recumbent folds (F2) of that dimension were identified by Żelaźniewicz (1978) in mica schists near Duszniki at the northern tip of the Spalona gneiss body (Text-figs 1, 12a). It is suggested that the constrictional fabric characteristic of this body, as well as the evidence of opposite kinematics at its opposite margins, were acquired during easterly vergent folding of two rheologically different lithologies. In the tectonic scheme of the Góry Bystrzyckie Mts., Szczepański (2010) also inferred the existence of large-scale, overturned, easterly vergent folds (F2), in which both orthogneisses and metasedimentary rocks were involved. In detail, however, the two interpretations differ. The detailed structural studies in the Polish Góry Orlickie Mts. and the spatial distribution of small-scale folds of “Z” and “S” asymmetry revealed the presence of a large-scale synform with rodding augen gneisses in its core (Żelaźniewicz 1978; Text-fig. 12a) and the quartz-sericite ultramylonite at the schist/gneiss border (Żelaźniewicz 1984). The synform continues further south (Text-fig. 12b), where irregular relicts of similar quartzitic mylonite horizons also testify to shearing and faulting at that border. In this part of the Orlica-Śnieżnik dome, the field data and outcrop pattern suggest that the rodding augen gneisses do not form slabs which would alternate with schists but more spindle-like bodies. During folding such metagranite bodies promoted bending and localized fold closures in the schistose surroundings. In the overall regime, the bodies were probably detached from a deeper seated metagranitic basement, slightly flattened but mainly elongated and moved northwards parallel to the fold axes (Text-fig. 12b), as implied by the kinematic indicators.

An alternative explanation would require that the weakly foliated metagranite of the Spalona body and schists were involved in the synformal fold in a similar manner. In the inverted limb of the synform, kinematic

indicators would point then to a top-to-the S shearing, whereas those in the normal limb would suggest a top-to-the N/NE movement, with the condition that during the pre-folding event in the metagranite the flat-lying planes developed with the top-to-the N kinematics. However, the latter explanation would also require that the pre-folding shearing affected granites that structurally overlay schists, which seems less probable and realistic. Therefore, we propose 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. In the eastern limb of the Orlica-Śnieżnik Dome, the presence of large-scale, easterly and westerly verging folds was recognized by Don (1964) and Teisseyre (1973). Having compared locations of the rodding gneisses observed in the field with an outcrop pattern shown on the detailed map of the eastern limb of the dome (Don *et al.* 2003), where kilometer-scale folds were identified, one can find that the gneisses appear in the hinge areas of these folds. Similar observations were made by us in the Młyńsko and Międzygórze fold structures. Although more work is needed, these findings concur with the situation found in the western limb of the dome. Therefore other occurrences of rodding gneisses throughout the Orlica-Śnieżnik Dome may be thought to occupy similar structural positions, which points to the significance of large-scale folds in the tectonic structure of the dome. In general, it is proposed that rodding gneisses may serve as a tool for the identification of the large-scale closures of folds developed in the regions which are built of schistose metasediments and metagranites enclosed in them.

CONCLUSIONS

1. In spite of the apparently simple mesofabric of L>S tectonites, the Góry Bystrzyckie gneisses show evidence of multiple deformation on both meso- and micro-scales.
2. Microscopic observations suggest that texture formation in the Spalona gneisses was a protracted, multi-stage process that involved strain partitioning with changing strain rate and kinematics in a general shear regime at amphibolite facies temperatures (450–600°C). These estimates agree with those inferred from the activity of prism <c> and prism <a> slips and are furthermore compatible with the temperature data calculated by a number of authors for the country-rock metasediments. Such consistencies suggest that both the metasediments and metagranites were deformed at similar crustal levels.

3. The K-feldspar and quartz rods display a shape fabric represented by a triaxial prolate ellipsoid which evolved in the constrictional field with some non-coaxial rotational strain in a general shear regime.
 4. The quartz c-axis microfibrils observed in the Spalona rodding augen orthogneisses show complex yet reproducible patterns of quartz c-axis distribution that developed under the joint control of strain geometry and temperature. The quartz pole figures are mixed features represented by or resembling pseudo-girdle patterns.
 5. Quartz grains from quartz ribbons and tails of K-feldspar augens are suitable for microstructural analysis whereas quartz grains from quartzo-feldspathic aggregates are less informative, which is probably due to the presence of feldspar grains that recrystallized concurrently in such aggregates.
 6. The domain differences in quartz microfibrils recognized in the selected samples are common in the Spalona orthogneisses but scarce in the sheared migmatitic gneisses.
 7. The constrictional strain, characteristic of the Spalona augen orthogneisses, was, in the migmatitic gneisses, imposed on an originally planar fabric defined by high-temperature migmatitic layering.
 8. The opposite sense of shearing found on a small scale within the studied samples can be explained by a dominantly coaxial regime in which the inclined objects tend to rotate toward the fabric attractor to reduce an acute angle with it and by different rates of the partitioned strain.
 9. On a larger scale, the opposite kinematics at the opposite margins of the Spalona gneiss body can be explained by large-scale folding. The constrictional fabric of the rodding augen gneisses in the Góry Bystrzyckie Mts. developed in partly or wholly detached bodies of metagranite located in the hinge zones of antiformal folds of macroscopic dimensions and bounded by ductile faults.
 10. Other occurrences of rodding augen orthogneisses 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.
- REFERENCES
- Bailey, C.M., Francis, B.E. and Fahrney, E.E. 2004. Strain and vorticity analysis of transpressional high-strain zones from the Virginia Piedmont, USA. *Geological Society of London, Special Publications*, **224**, 249–264.
- Bons, P.D. and Urai, J.L. 1992. Syndeformational grain growth: microstructures and kinetics. *Journal of Structural Geology*, **14**, 323–334.
- Bouchez, J.L. 1978. Preferred orientations of quartz (a) axes in some tectonites – kinematic inferences. *Tectonophysics*, **49**, 25–30.
- Carreras, J. and Garcia Celma, A. 1982. Quartz of C-Axis fabric variation at the margins of a shear zone developed in shists from cap de Creus (Spain). *Acta Geologica Hispanica*, **17**, 137–149.
- Celma, A.G. 1982. Dominant and fabric heterogeneities in the Cap-de-Creus quartz mylonites. *Journal of Structural Geology*, **4**, 443–455.
- Chopin, F., Schulmann, K., Štípska, P., Martelat, J.E., Pitra, P., Lexa, O. and Petri, B. 2012. Microstructural and metamorphic evolution of a high-pressure granitic orthogneiss during continental subduction (Orlica-Śnieżnik dome, Bohemian Massif). *Journal of Metamorphic Geology*, **30**, 347–376.
- Cymerman, Z. 1997. Structure, kinematics and an evolution of the Orlica-Śnieżnik Dome, Sudetes. *Prace Państwowego Instytutu Geologicznego*, **156**, 3–118.
- Don, J. 1964. Góry Złote i Krowiarki jako elementy składowe metamorfiku Śnieżnika. The Złote and Krowiarki Mts. as structural elements of the Śnieżnik metamorphic massif. *Geologia Sudetica*, **1**, 79–117.
- Don, J., Dumicz, M., Wojciechowska, I. and Żelaźniewicz, A. 1990. Lithology and tectonics of the Orlica – Śnieżnik Dome, Sudetes – Recent State of Knowledge. *Neues Jahrbuch für Geologie Paläontologie Abhandlungen*, **179**, 153–188.
- Don, J., Skácel, J. and Gotowała, R. 2003. The boundary zone of the East and West Sudetes on the 1:50000 scale geological map of the Velké Vrbno, Staré Místo and Śnieżnik Metamorphic Units. *Geologia Sudetica*, **35**, 25–59.
- Dumicz, M. 1964. Budowa geologiczna krystaliniku Gór Bystrzyckich. Geology of the crystalline massif of the Bystrzyckie Mts. *Geologia Sudetica*, **1**, 169–203. [In Polish, with English summary]
- Dumicz, M. 1988. Mesostructural and kinematic characteristics of core gneisses in western part of the Orlica-Śnieżnik Dome, West Sudetes. *Geologia Sudetica*, **31**, 105–111.
- Etchecopar, A. 1977. A plane kinematic model of progressive deformation in a polycrystalline aggregate. *Tectonophysics*, **39**, 121–139.
- Etchecopar, A. and Vasseur, G. 1987. A 3-D kinematic model of fabric development in polycrystalline aggregates: comparisons with experimental and natural examples. *Journal of Structural Geology*, **9**, 705–718.
- Festa, V. 2009. C-axis fabrics of quartz-ribbons during high-temperature deformation of syn-tectonic granitoids (Sila Massif, Calabria, Italy). *Comptes Rendus Geoscience*, **341**, 557–567.

QUARTZ C-AXIS FABRICS IN CONSTRICTIONALLY STRAINED ORTHOGNEISSES

- Grzeškowiak, A. and Żelaźniewicz, A. 2002. On the Significance of Gneissic Enclaves in the 500 Ma Metagranite, the Łądek-Śnieżnik Metamorphic Unit, the West Sudetes. *Geolines*, **14**, 28–29.
- Heilbronner, R. and Tullis, J. 2006. Evolution of c-axis pole figures and grain size during dynamic recrystallization; results from experimentally sheared quartzite. *Journal of Geophysical Research*, **111**, B10202.
- Hippertt, J., Rocha, A., Lana, C., Egydio-Silva, M. and Takeshita, T. 2001. Quartz plastic segregation and ribbon development in high-grade striped gneisses. *Journal of Structural Geology*, **23**, 67–80.
- Hippertt, J. and Tohver, E. 1999. On the development of zones of reverse shearing in mylonitic rocks. *Journal of Structural Geology*, **21**, 1603–1614.
- Hirth, G. and Tullis, J. 1992. Dislocation creep regimes in quartz aggregates. *Journal of Structural Geology*, **14**, 145–149.
- Jastrzębski, M. 2009. A Variscan continental collision of the West Sudetes and the Brunovistulian terrane: a contribution from structural and metamorphic record of the Stronie Formation, the Orlica-Śnieżnik Dome, SW Poland. *International Journal of Earth Sciences* **98**, 1901–1923.
- Jastrzębski, M., Żelaźniewicz, A., Majka, J., Murtezi, M., Bazarnik, J. and Kapitonov, I. 2013. The Devonian-Carboniferous evolution of the Rheic Ocean from a multi-method geochronology study of the Staré Město Belt in the Sudetes (Poland and the Czech Republic). *Lithos*, **170–171**, 54–72.
- Jessell, M.W. and Lister, G.S. 1990. A simulation of the temperature dependence of quartz fabrics. In: Knipe, R.J. and Rutter, E.H. (Eds), *Deformation Mechanisms, Rheology and Tectonics. Geological Society of London, Special Publications*, **54**, 353–362.
- Juroszek, C. 1976. Granitogneisses from Bystrzyca Mountains (Sudetes). *Archiwum Mineralogiczne*, **30**, 173–242. [In Polish, with English summary]
- Kruhl, J.H. 1996. Prism, and basal, plane parallel subgrain boundaries in quartz: a microstructural geothermobarometer. *Journal of Metamorphic Geology*, **14**, 581–589.
- Kruhl, J.H. 1998. Prism- and basal-plane parallel subgrain boundaries in quartz: a microstructural geothermobarometer – Reply. *Journal of Metamorphic Geology*, **16**, 142–146.
- Kruhl, J.H. 2001. Crystallographic controls on the development of foam textures in quartz, plagioclase and analogue material. In: Dresen, G., Handy, M. (Eds), *Deformation Mechanisms, Rheology, and Microstructures. International Journal of Earth Science*, **90**, 104–117.
- Lange, U., Bröcker, M., Armstrong, R., Trapp, E. and Mezger, K. 2005. Sm–Nd and U–Pb dating of high-pressure granulites from the Złote and Rychleby Mts (Bohemian Massif, Poland and Czech Republic). *Journal of Metamorphic Geology*, **23**, 133–145.
- Lange, U., Bröcker, M., Mezger, K. and Don, J. 2002. Geochemistry and Rb–Sr geochronology of a ductile shear zone in the Orlica-Śnieżnik dome (West Sudetes, Poland). *International Journal of Earth Sciences*, **91**, 1005–1016.
- Law, R., Miller, E.L. and Little, T.A. 1994. Extensional origin of ductile fabrics in the Schist Belt, Central Brooks Range, Alaska. Microstructural and petrofabric evidence. *Journal of Structural Geology*, **16**, 919–940.
- Law, R.D., Schmid, S.M. and Wheeler, J. 1990. Simple shear deformation and quartz crystallographic fabrics – a possible natural example from The Torridon Area of NW Scotland. *Journal of Structural Geology*, **12**, 29–45.
- Lister, G.S. and Hobbs, B.E. 1980. The simulation of fabric development during plastic deformation, the effects of deformation history. *Journal of Structural Geology*, **2**, 355–370.
- Mainprice, D., Bouchez, J.L., Blumenfeld, P. and Tubia, J.M. 1986. Dominant C-slip in naturally deformed quartz – implications for plastic softening at high-temperature. *Geology*, **14**, 819–822.
- Marjoribanks, R.W. 1976. The relation between microfabric and strain in a progressively deformed quartzite sequence from Central Australia. *Tectonophysics*, **32**, 269–293.
- Murtezi, M. 2006. The acid metavolcanic rocks of the Orlica-Śnieżnik Dome (Sudetes): their origin and tectono-metamorphic evolution. *Geologia Sudetica*, **38**, 1–38.
- Opletal, M., Domečka, K. and Čech, S. 1980. Geology of the Orlické hory Mountains. 1–202. Academia; Praha. [In Czech, English summary]
- Passchier, C.W. and Trouw, R. A.J. 1998. *Microtectonics*. 289 p. Springer-Verlag; Berlin.
- Pauk, F. 1977. The nappe structure of the Orlické hory-Klodsko Dome. *Prace a Studie - Přír., Pardubice*, **9**, 7–32.
- Peternell, M., Hasalová, P., Wilson, C.J.L., Piazzolo, S. and Schulmann, K. 2010. Evaluating quartz crystallographic preferred orientations and the role of deformation partitioning using EBSD and fabric analyser techniques. *Journal of Structural Geology*, **32**, 803–817.
- Poirir, J.P. and Nicolas, A. 1975. Deformation-induced recrystallization due to progressive misorientation of subgrains, with special reference to mantle peridotites. *Journal of Geology*, **83**, 707–720.
- Přikryl, R., Schulmann, K. and Melka, R. 1996. Perpendicular fabrics in the Orlické hory orthogneisses (western part of the Orlice-Sněžník Dome, Bohemian Massif) due to high temperature E-W deformational event and late lower temperature N-S overprint. *Journal of the Czech Geological Society*, **41**, 156–166.
- Pryer, L.L. 1993. Microstructures in feldspars from a major crustal thrust zone: the Grenville Front, Ontario, Canada. *Journal of Structural Geology*, **15**, 21–36.
- Redlińska-Marczyńska, A. and Żelaźniewicz, A. 2011. Gneisses

- in the Orlica-Śnieżnik Dome, West Sudetes: a single batholithic protolith or a more complex origin? *Acta Geologica Polonica*, **61**, 307–339.
- Schmid, S.M. and Casey, M. 1986. Complete fabric analysis of some commonly observed quartz c-axis patterns. *Mineral and Rock Deformation: Laboratory Studies, American Geophysics Union Monography*, **36**, 263–286.
- Schmid, S.M., Casey, M. and Starkey, J. 1981. An illustration of the advantages of a complete texture analysis described by the orientation distribution function (ODF) using quartz pole figure data. *Tectonophysics*, **78**, 101–117.
- Skrzypek, E., Štípska, P., Schulmann, K., Lexa, O. and Lexova, M. 2011. Prograde and retrograde metamorphic fabrics – a key for understanding burial and exhumation in orogens (Bohemian Massif). *Journal of Metamorphic Geology*, **29**, 451–472.
- Smulikowski, K. 1973. Les roches métamorphiques du Mont Śnieżnik et de la région de Ladek. In: Smulikowski, K. (Ed.), *Revue des problèmes géologiques des zones profondes de l'écorce terrestre en Basse Silésie*, pp. 77–102. Wydawnictwa Geologiczne; Warszawa.
- Smulikowski K., 1979. Polimetamorphic evolution of the crystalline complex of the Śnieżnik and Góry Złote Mts in the Sudetes. *Geologia Sudetica*, **14**, 7–76. [In Polish, with English summary]
- Stipp, M., Stünitz, H., Heilbronner, R. and Schmid, S.M. 2002. The eastern Tonale fault zone: a “natural laboratory” for crystal plastic deformation of quartz over a temperature range from 250 to 700 °C. *Journal of Structural Geology*, **24**, 1861–1884.
- Stoeckhert, B. and Duyster, J. 1999. Discontinuous grain growth in recrystallized vein quartz; implications for grain boundary structure, grain boundary mobility, crystallographic preferred orientation, and stress history. *Journal of Structural Geology*, **21**, 1477–1490.
- Stoeckhert, B., Brix, M.R., Kleinschrodt, R., Hurford, A.J. and Wirth, R. 1999. Thermochronometry and microstructures of quartz – a comparison with experimental flow laws and predictions on the temperature of the brittle–plastic transition. *Journal of Structural Geology*, **21**, 351–369.
- Szczepański, J. 2010. Provenance and tectonometamorphic evolution of the supracrustal series from the Bystrzyckie Mts. Crystalline Massif. 1–166. Wydawnictwo Uniwersytetu Wrocławskiego; Wrocław. [In Polish]
- Teisseyre, H. 1973. Geology of the Śnieżnik Mountain Group. In: Smulikowski K. (Ed.), *Revue des problèmes géologiques des zones profondes de l'écorce terrestre en Basse Silésie*, pp. 59–77. Wydawnictwa Geologiczne; Warszawa.
- Toy, V.G., Prior, D.J. and Norris, R.J. 2008. Quartz fabrics in the Alpine Fault mylonites: Influence of pre-existing preferred orientations on fabric development during progressive uplift. *Journal of Structural Geology*, **30**, 602–621.
- Tullis, J., Stunitz, H., Teyssier, C. and Heilbronner, R. 2000. Deformation microstructures in quartzo-feldspathic rocks. In: Jessell, M.W. and Urai, J.L. (Eds), *Stress, Strain and Structure, Win Means volume. Journal of the Virtual Explorer*, **2**, doi:10.3809/jvirtex.2000.00019.
- Turner, F.J. and Weiss, L.E. 1963. *Structural analysis of metamorphic tectonites*, 545 p. McGraw-Hill; New York.
- Żelaźniewicz A. 1978. Major tectonic structures in the Polish part of the Góry Orlickie. *Geologia Sudetica*, **13**, 67–86. [In Polish, English Summary]
- Żelaźniewicz, A. 1984. Synmetamorphic penetrative mylonitization in orthogneisses of the Bystrzyca Mts, Sudetes. *Acta Geologica Polonica*, **34**, 111–130.
- Żelaźniewicz, A. 1988. Orthogneisses due to irrotational extension, a case from the Sudetes, Bohemian massif. *Geologische Rundschau*, **77**, 671–682.
- Żelaźniewicz, A. 1991. Uwagi o deformacji ortognejsów oczkowych w kopule orlicko-śnieżnickiej. In: Dumicz, M. (Ed.), *Następstwo serii skalnych Śnieżnika w świetle kartografii geologicznej, analizy strukturalnej i badań radiometrycznych. Materiały Konferencji Terenowej Uniwersytetu Wrocławskiego*, Wrocław. 122–136.
- Żelaźniewicz, A., Mazur, S. and Szczepański, J. 2002. The Łądek-Śnieżnik Metamorphic Unit – recent state of knowledge. *GeoLines*, **14**, 115–125.
- Żelaźniewicz A., Nowak I., Bachliński R., Larionov A.N. and Sergeev S.A. 2006. Cadomian versus younger deformations in the basement of the Moravo-Silesian Variscides, East Sudetes, SW Poland: U-Pb SHRIMP and Rb-Sr age data. *Geologia Sudetica*, **37**, 35–52.

Manuscript submitted: 20th August 2013

Revised version accepted: 15th October 2013