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Deformational history of metavolcanic rocks from the Kamieniec Ząbkowicki Metamorphic Belt (Fore-Sudetic Block, southwest Poland): a quartz [c]-axis lattice preferred orientation study

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ABSTRACT:

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The Kamieniec Ząbkowicki Metamorphic Belt (Fore-Sudetic Block, southwest Poland) consists mainly of mica schists. Based on mesostructural features, their deformational history has been interpreted in different ways and not quite consistently with the results of microstructural studies. Since the schist complex comprises acid metarhyolites – quartzo-feldspathic schists – which are well suited to microstructural analysis, we attempted to study quartz [c]-axis lattice preferred orientation (LPO) in these rocks in order to compare the results with those obtained by other authors and check against the proposed sequences of tectonic events in the region. The quartzo-feldspathic schists are fine- to medium-grained rocks with varying amounts of K-feldspar porphyroclasts. Most of these porphyroclasts are accompanied by symmetric or asymmetric pressure shadows. Their asymmetry uniformly indicates a top-to-the SSW shear sense along W-dipping foliation in a strike-slip regime. Quartz [c]-axis LPO indicates that the deformation took place mainly at plane strain with a non-coaxial component, with a top-to-the SSW or NNE sense of movement, and an apparent flattening field. The thermal conditions of deformation of the quartzo-feldspathic schists were within the limits of the amphibolite facies (550–600ºC). Integration of the micro- and mesofabric data indicated the superposition of two tectonothermal events: the main one with sinistral strike-slip, top-to-the SW kinematics consistent with the asymmetry of the porphyroclasts, and a subsequent overprint with dextral, transpressional, top-to-the NE kinematics. There is a visible dependence of the quartz LPO on the degree of mylonitization in the quartzo-feldspathic schists. A westward increase in mylonitic deformation is observed in the study area.

Key words: Quartz [c]-axis lattice preferred orientation; Quartzo-feldspathic schists; Deformational history, Kamieniec Ząbkowicki Metamorphic Belt; Fore-Sudetic Block.

INTRODUCTION

In the Kamieniec Ząbkowicki Metamorphic Belt (Fore-Sudetic Block, southwest Poland), mica schists predominate in a variety of schist rocks (Text-figs 1, 2). Based on mesostructural features, the deformational history of these rocks has been interpreted in different ways and not quite consistently with the results of the microstructural studies (Dziedzicowa 1970, 1973, 1985; Achramowicz *et al*. 1997; Nowak 1998; Mazur and Józefiak 1999; Bartz and Puziewicz 1999). The discrepancies seem to arise partly from different responses to tectonic stresses depending on the different rheologies of the schist varieties. This refers particularly to the quartz-rich rocks and to the types of microfabric developed. Since the schist complex comprises acid metavolcanic rocks which are well suited to microstructural analysis, we attempt in this work to study quartz [c]-axis lattice preferred orientation in these rocks in order to compare the results with those obtained by other authors and to check against the proposed sequences of tectonic events in the region.

A study of quartz lattice preferred orientation (LPO) can provide a set of structurally useful information on: (1) strain path or kinematic framework; (2) magnitude and symmetry of finite strain; (3) crystallographic glide systems active during deformation i. e. thermal conditions of deformation (Schmid and Casey 1986; Law 1990; Okudaira *et al*. 1995; Stipp *et al*. 2002). According to Law (1990), the validity of shear sense deduced from the quartz LPO can be tested by means of a comparison with other microscopic shear-sense indicators. Although the complete quartz LPO interpretation should be based on both <a>- and [c]-axis analyses (Passchier and Trouw 1996), only the latter are presented in this study as they can be compared with the earlier [c]-axis data obtained for quartzo-feldspathic schists (Dziedzicowa 1970, 1973), mica schists (Mazur and Józefiak 1999) and quartzo-graphitic schists (Bartz and Puziewicz 1999).

GEOLOGICAL SETTING AND PREVIOUS STUDIES

The Kamieniec Ząbkowicki Metamorphic Belt is situated in the eastern part of the Fore-Sudetic Block, north-east part of the Bohemian Massif, and is largely concealed by Tertiary and Quaternary cover (Text-fig. 1). Overviews of the geology of the region can be found in Franke and Żelaźniewicz (2000) and Aleksandrowski and Mazur (2002). The study area is located in the central part of the Kamieniec Ząbkowicki Metamorphic Belt (Text-figs 1, 2).

A protolith age of some schist variants from the Kamieniec Ząbkowicki Metamorphic Belt was estimated as Ediacaran–Cambrian on the basis of some problematical *Acritarcha* (Gunia 1979). Metasediments in the adjacent Niemcza Shear Zone were assigned to the Lower Carboniferous (Dziedzicowa and Górecka 1965). Syntectonic granodiorites intruded in this zone at 340–330 Ma (U-Pb zircon, Oliver *et al*. 1993; Pb-Pb zircon, Kröner and Hegner 1998; Rb-Sr whole-rock, Kennan *et al.* 1999). Protoliths of metaigneous rocks of the Kamieniec Ząbkowicki Metamorphic Belt remain undated, but greenschist to amphibolite facies metamorphism occurred around 332 Ma (Ar-Ar hornblende; Steltenpohl *et al*. 1993). In the neighbouring Strzelin Massif, Ar-Ar data on white micas yielded cooling ages between 285 and 279 Ma (Szczepański 2002).

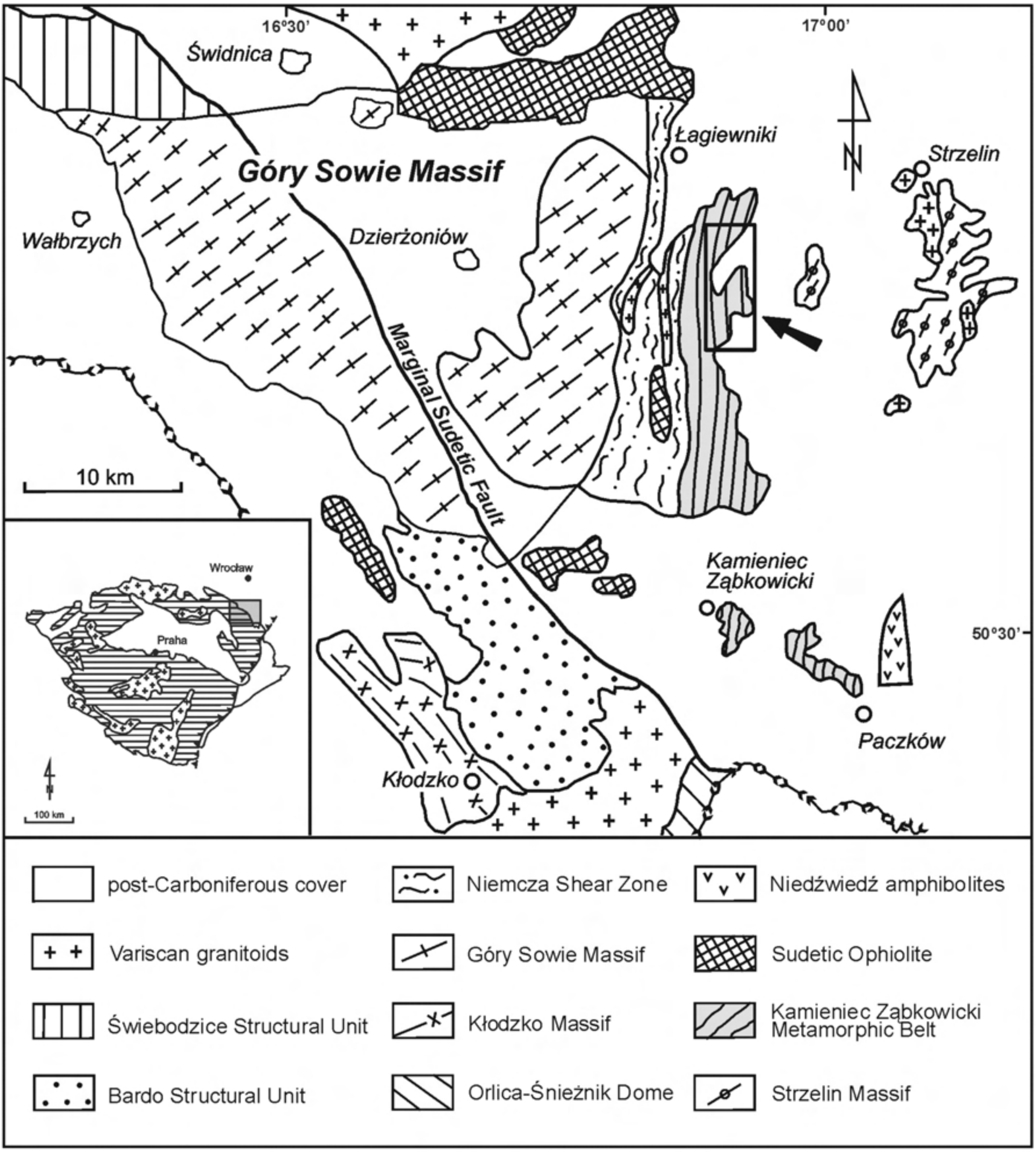
In the Kamieniec Ząbkowicki Metamorphic Belt, the dominant mica schists are accompanied by intercalations of quartzo-feldspathic schists, quartzo-graphitic schists, crystalline limestones, amphibolites (Dziedzicowa 1975, 1985, 1987; Nowak 1998; Mazur and Józefiak 1999) and eclogites (Achramowicz *et al*. 1997). Dziedzicowa (1987) postulated that the quartzo-feldspathic schists were derived from acid volcanogenic rocks of rhyolitic composition. There are the metarhyolites that were selected for our study. The locations of the exposures sampled are shown in Text-fig. 2.

The sequence of tectonic deformations in the Kamieniec Ząbkowicki Metamorphic Belt was studied by various authors, who arrived at the contradictory conclusions summarized in Table 1.

Dziedzicowa (1973, 1975, 1985, 1987) distinguished five deformational events. During the first event, isoclinal folds with penetrative, almost vertical, axial-plane foliation S_1 developed. This foliation set was subsequently involved in F_2 folds associated with the subhorizontal axial-plane cleavage S_2, which locally obliterated the older S_1 foliation. The F_3 event produced upright folds with almost vertical axial planes. During the F_4 and F_5 events small-scale kink folds were superimposed on the earlier ones (Table 1).

Mazur and Puziewicz (1995) proposed that rock units to the east of the Góry Sowie Massif twice underwent nappe stacking during the D_1 and D_2 events under amphibolite facies conditions, with eastern and northeastern vergence respectively. The D_3 event involved regional tectonic extension under amphibolite or greenschist facies conditions, resulting in top-to-the SW normal-slip shearing along slightly inclined foliation planes and sinistral strike-slip shearing along subvertical foliation planes (Table 1).

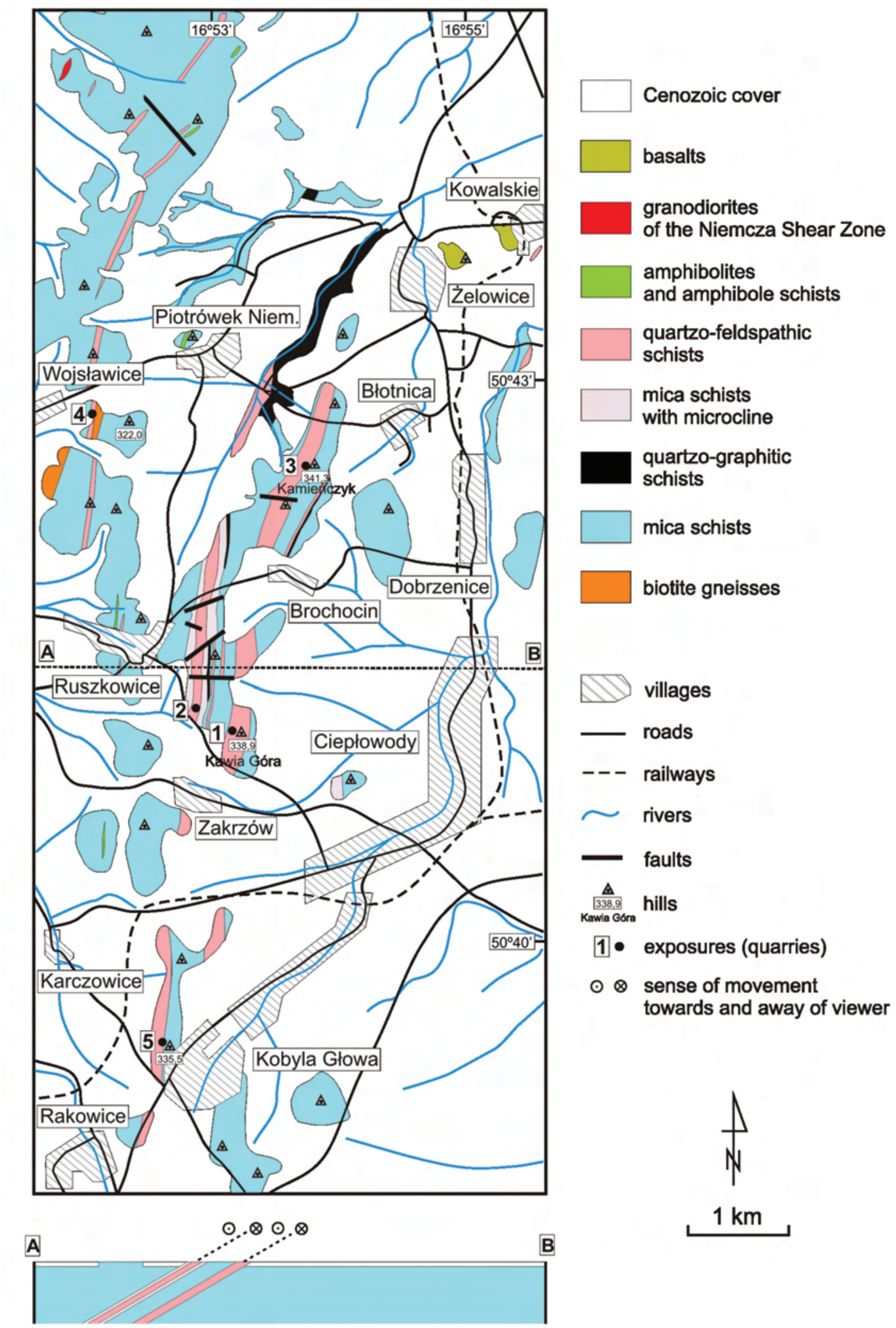
Mazur and Józefiak (1999) assumed the existence of two tectonic units which differed in metamorphic grade by 60–100ºC and 0–5 kbar, and corresponded to the fine-grained mica schists (lower unit) and coarse-grained mica schists (upper unit) respectively. Such a subdivision was not observed by Nowak (1998) and the two units were only distinguished south of the area where the studied metarhyolites crop out.



Text-fig. 1. Sketch map of part of the Sudetes and the Fore-Sudetic Block (after Bartz 2001, modified). Location of the study area is shown by box. Inset shows the position of the region in the Bohemian Massif. Regional tectonic terminology as proposed by Żelaźniewicz and Aleksandrowski (2008)

Mazur and Józefiak (1999) also assumed three deformational events evidenced by only locally observed structures. However, they found some kinematic indicators that pointed to an E-directed D_1 overthrusting of the tectonic units distinguished by them. The subsequent D_2 deformation was accomplished by a non-coaxial shear component with top-to-the NE kinematics and was associated with an irrotational NW-SE shortening. According to these authors, the progressive shortening was followed by development of the normal-slip shearing D_3 with an opposite sense of motion, showing top-to-the SW/WSW kinematics on shallow-dipping planes (Table 1).

In contrast, Achramowicz *et al*. (1997) recognized that the earliest D_1 event was associated with SSW-directed thrusting. The D_2 event was also characterised by a top-to-the SW sense of ductile shearing, but with normal kinematics. The D_3 deformation operated under a dextral transpressional regime during regional E-W shortening.



Text-fig. 2. Geological sketch-map of the central part of the Kamieniec Ząbkowicki Metamorphic Belt (after: Badura 1979; Badura and Dziemiańczuk 1981; Cwojdziński and Walczak-Augustyniak 1983; Wójcik 1968, modified) with the location of the exposures of the quartzo-feldspathic schists studied. Simplified cross-section along the line A–B (dashed); vertical scale equal to horizontal. Kinematics of the shear zones shown schematically

Dziedzicowa (1973, 1975, 1985, 1987)	Mazur and Puziewicz (1995)	Achramowicz et al. (1997)	Nowak (1998)	Mazur and Józefiak (1999)
F_1. Isoclinal, E-vergent folds with penetrative, axial-planar foliation S_1. F_2. NE-trending and SE-verging folds, with subhorizontal axial plane cleavage S_2. F_3. Upright folds with no axial plane mineral growth. F_4-F_5. Kink folds superposed on the earlier ones.	D_1. E-vergent nappes. D_2. NE-vergent nappes. D_3. Left-lateral strike-slip shearing (top-to-the SW kinematics on W-dipping planes).	D_1. SSW-directed thrusting. D_2. Top-to-the SW ductile, normal shearing with stretching lineation and SW-verging folds. D_3. ESE-verging folds (sheath-type in intensively sheared zones) and SE/ESE stretching lineation. D_4. Kink folds and localized normal shearing top-to-the W/WSW.	D_1. E-W folds with N- or S-vergence related to thrusts. D_2. SW-vergent folds and shearing with NE-trending mineral/stretching lineation; main foliation S_2. D_3. E-vergent thrusting and folding, W-plunging mineral lineation. D_4. Kink folds and localized normal shearing top-to-the W/WSW.	D_1. E-vergent thrusts and W-E lineation. D_2. NE-trending, NW-vergent, inclined folds with axial planes dipping gently to the SE. D_3. Top-to-the SW/WSW extensional crenulation cleavage with stretching lineation.

Table 1. Deformation events recognized in the Kamieniec Ząbkowicki Metamorphic Belt by various authors

A similar sequence of tectonic deformations was reported by Nowak (1998), who linked them directly to a sequence of metamorphic transformations and recognized that the earliest structures were defined by an HP mineral assemblage and were most likely related to D_1 thrusting of unspecified kinematics, albeit associated with E–W trending folds and mineral lineation. The subsequent deformation (D_2) resulted in SW/SSW-vergent structures (folds, porphyroclasts) and was accompanied by ductile low-angle normal faulting under amphibolite facies conditions. The succeeding uplift and exhumation was associated with transpression and thrusting to the east (D_3). Late orogenic extension (D_4) partly reactivated the WSW-dipping S_2 foliation along shear zones in a normal fault regime under greenschist facies conditions (Nowak 1998).

Earlier studies of quartz [c]-axis fabric in the quartzo-feldspathic schists by Dziedzicowa (1970, 1973) showed that quartz deformation was associated with the F_2 event, prior to the upright folding F_3 (Table 1). Mazur and Józefiak (1999) interpreted the quartz [c]-axis LPO pattern in the mica schists as a composite product of two superimposed deformations: D_2 and D_3. Bartz and Puziewicz (1999) connected the observed quartz [c]-axis orientation patterns in the quartzo-graphitic schists from the Kamieniec Ząbkowicki Metamorphic Belt with the D_3 deformation *sensu* Mazur and Józefiak (1999). They found that in the quartzo-graphitic schists of metasedimentary origin, more intensively deformed zones were dominated by different strain components: plane strain (top-to-the SSW), general constriction and general flattening.

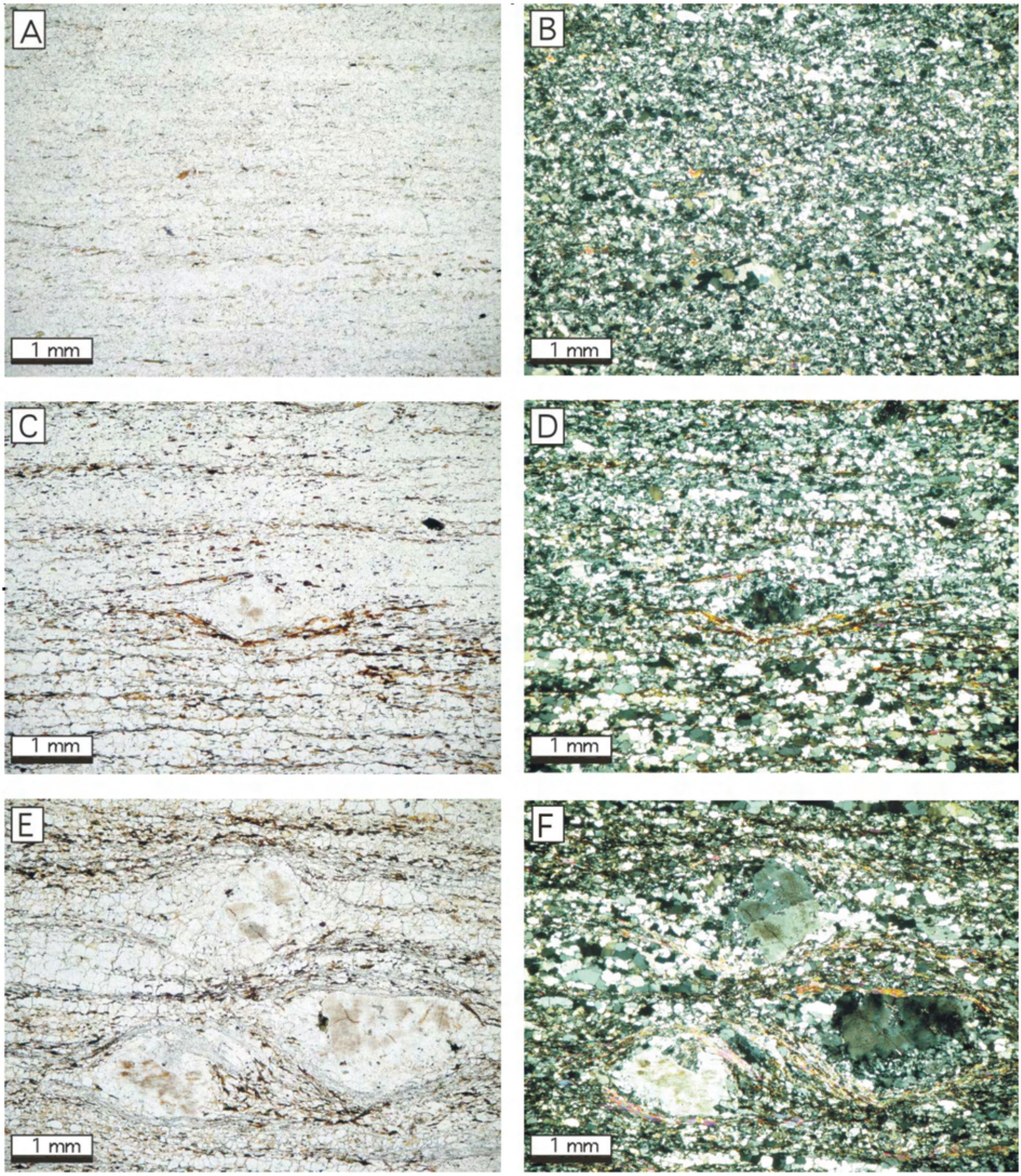
SAMPLED ROCKS

Our observations show that the metarhyolites (quartzo-feldspathic schists) that grade laterally into microcline schists (Text-fig. 2) consist mainly of quartz and feldspars with subordinate muscovite prevailing over biotite. The accessory minerals include chlorite, andalusite, zircon, apatite, allanite and opaques. The quartzo-feldspathic schists are fine- to medium-grained rocks with varying amounts of K-feldspar porphyroclasts. On this basis, we distinguished three varieties of quartzo-feldspathic schists: (I) free from porphyroclasts, (IIa) with sparse porphyroclasts and (IIb) rich in porphyroclasts (Gurgurewicz and Bartz 2001; Text-fig. 3). The degree to which the porphyroclasts are preserved is taken as an indication of the intensity of mylonitic deformation experienced by the metarhyolites; the schist variety (I) without porphyroclasts being the most mylonitized.

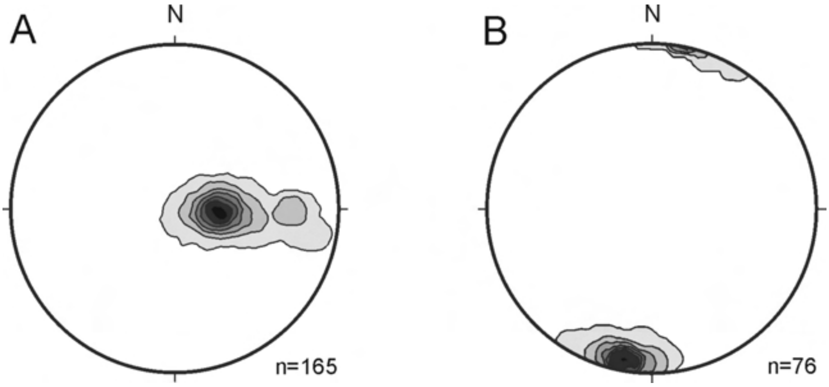
The quartzo-feldspathic schists are characterized by the presence of a penetrative foliation expressed by parallel arrangement of the mica layers and quartz or quartzo-feldspathic bands (Gurgurewicz and Bartz 2000, 2001). The foliation dips uniformly to the west at low to moderate angles (Text-fig. 4A). The lineation is typically of stretching type and defined by elongated K-feldspar porphyroclasts, quartz rods and sparse mica aggregates. It is almost horizontal, with a NNE–

SSW trend (Text-fig. 4B). Most of the K-feldspar porphyroclasts are accompanied by symmetric or asymmetric pressure shadows (Text-fig. 5). Asymmetric pressure shadows have been utilized as kinematic indicators. Their asymmetry uniformly indicates a top-to-the SSW shear sense along W-dipping foliation in a strike-slip regime.

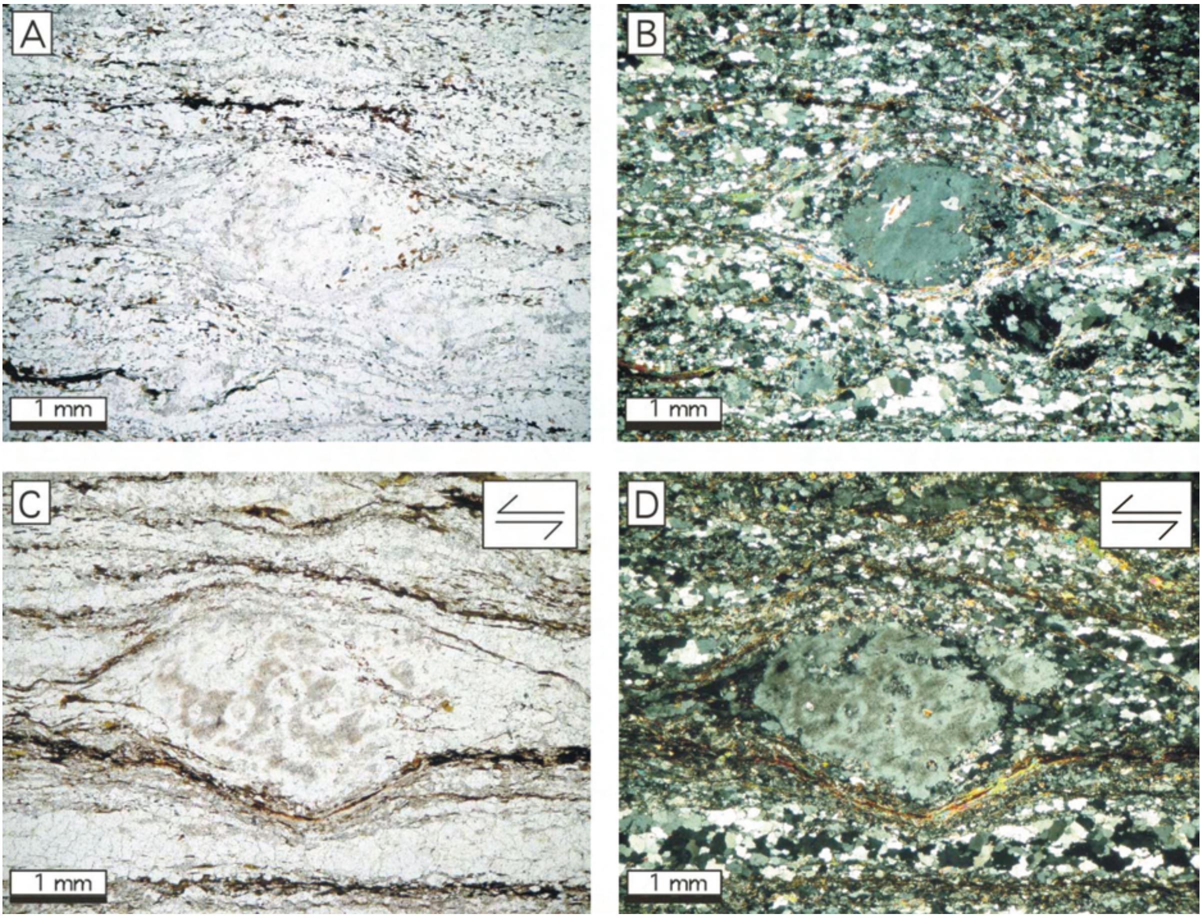
The above characteristics are directly comparable (Table 1) with the D_3 sinistral strike-slip event of Mazur and Puziewicz (1995), well compatible with the D_2 event of Achramowicz *et al*. (1997) and Nowak (1998), and roughly consistent with the D_3 extensional crenulation cleavage-forming event of Mazur and Józefiak (1999).



Text-fig. 3. Variants of the quartzo-feldspathic schists: (I) free from porphyroclasts (A – one polar, B – crossed polars; sample J2004), (IIa) with sparse porphyroclasts (C – one polar, D – crossed polars; sample 858) and (IIb) rich in porphyroclasts (E – one polar, F – crossed polars; sample 851)



Text-fig. 4. Attitude of foliation (poles to the plane) and stretching lineation in the quartzo-feldspathic schists. Schmidt net, lower hemisphere. A - foliation (165 measurements), B - lineation (76 measurements). Intervals at: 1, 6, 12, 18, 24, 30 %



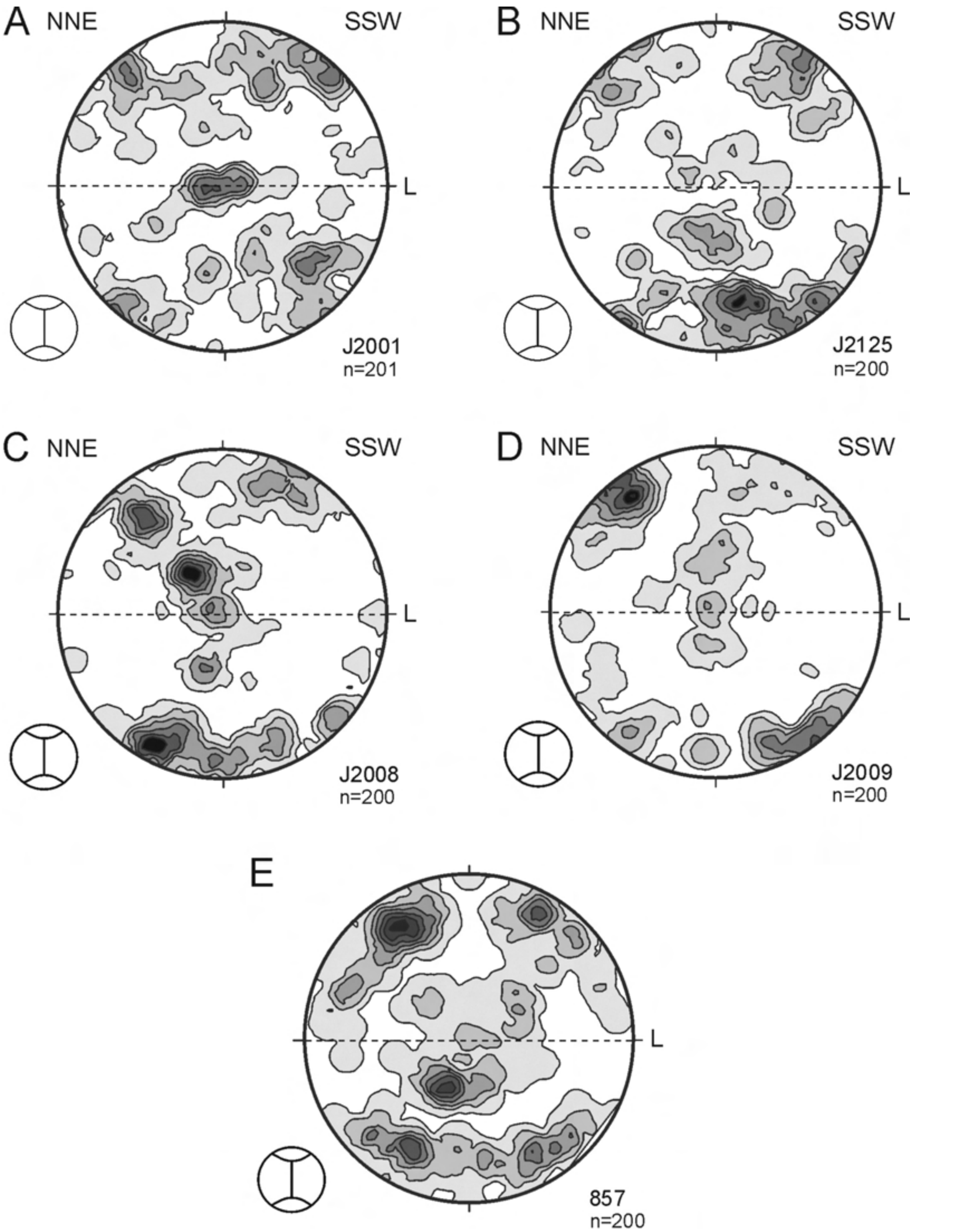
Text-fig. 5. Symmetric (A – one polar, B – crossed polars; sample B1101) and asymmetric (C – one polar, D – crossed polars; sample J2001) pressure shadows around K-feldspar porphyroclast in the quartzo-feldspathic schist variety IIb

MICROSTRUCTURAL STUDIES

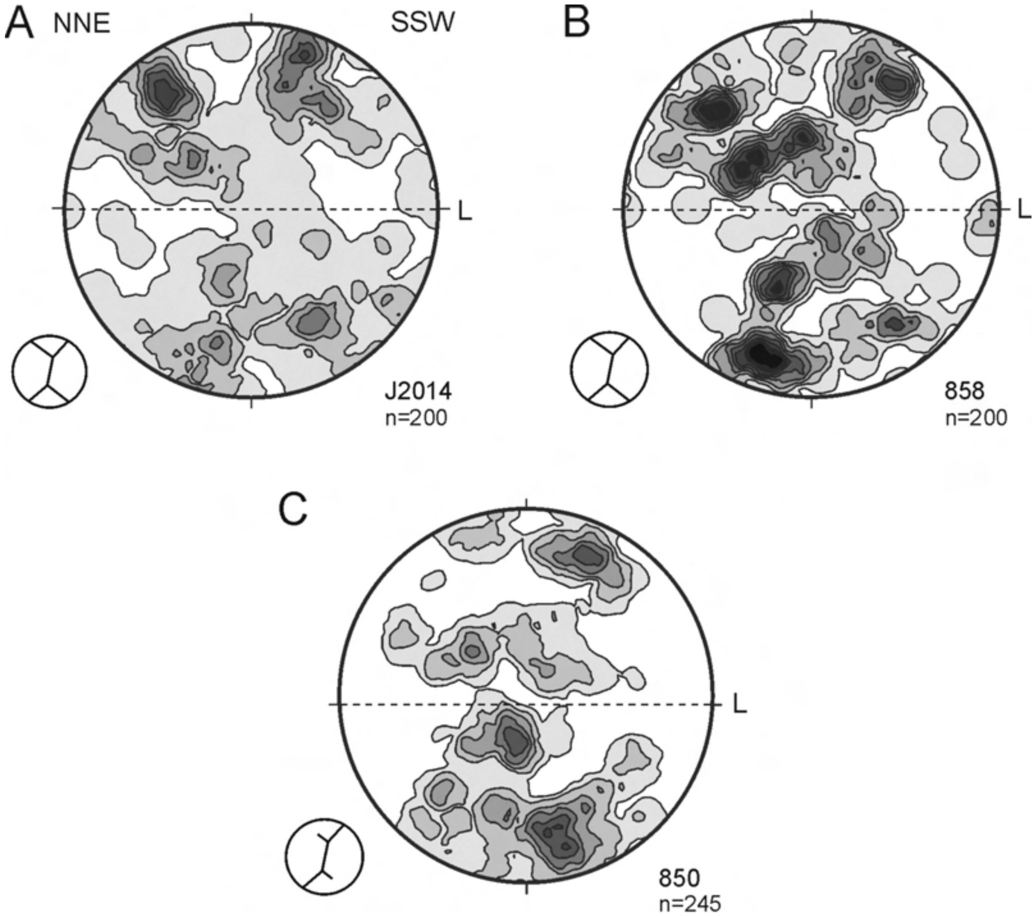
Methods

Quartz may deform by both intercrystalline or intracrystalline mechanisms, but only the latter produces quartz LPO. Among other factors, the quartz content (Walniuk and Morris 1985) and its distribution with respect to micas in the rock influence the kind of deformation mechanism (Shelley 1982; Walniuk and Morris 1985). In the quartzo-feldspathic schists, their main constituents tend to form individual thick quartzo-feldspathic and thin mica layers. Thus, quartz-mica contacts and the resultant intercrystalline deformation through grain-boundary sliding or pressure solution play a minor role in the quartz deformation. We therefore only used quartz from the interior of the quartzo-feldspathic layers for LPO measurements.

Eighteen oriented and three supplementary non-oriented samples of the quartzo-feldspathic schists were microstructurally investigated using a five-axis universal stage mounted on a Leitz Wetzlar petrographic microscope. Thin sections were cut perpendicular to the meso-



Text-fig. 6. Quartz [c]-axis patterns in the quartzo-feldspathic schists from the Kamieniec Ząbkowicki Metamorphic Belt: type I crossed girdles. Equal-area net, lower hemisphere stereograms. Density contours are at 1.5 % intervals. Projection on the XZ plane of the strain ellipsoid. Attitude of foliation (dashed line) corresponds to a plane perpendicular to the figure. Lineation (L) is parallel to the X-axis of the strain ellipsoid



Text-fig. 7. Quartz [c]-axis patterns in the quartzo-feldspathic schists from the Kamieniec Ząbkowicki Metamorphic Belt: type I crossed girdles evolving into a single girdle. Equal-area net, lower hemisphere stereograms. Density contours are at 1.5 % intervals. Projection on the XZ plane of the strain ellipsoid. Attitude of foliation (dashed line) corresponds to a plane perpendicular to the figure. Lineation (L) is parallel to the X-axis of the strain ellipsoid

scopic foliation and parallel to the mineral elongation lineation (XZ section of the finite strain ellipsoid). The orientation of the [c]-axis in at least 200 individual quartz grains was measured in each sample. All the data collected were plotted on the lower hemisphere, equal area projection (XZ plane of the deformation ellipsoid). Fabric skeletons were prepared on the basis of pole figures.

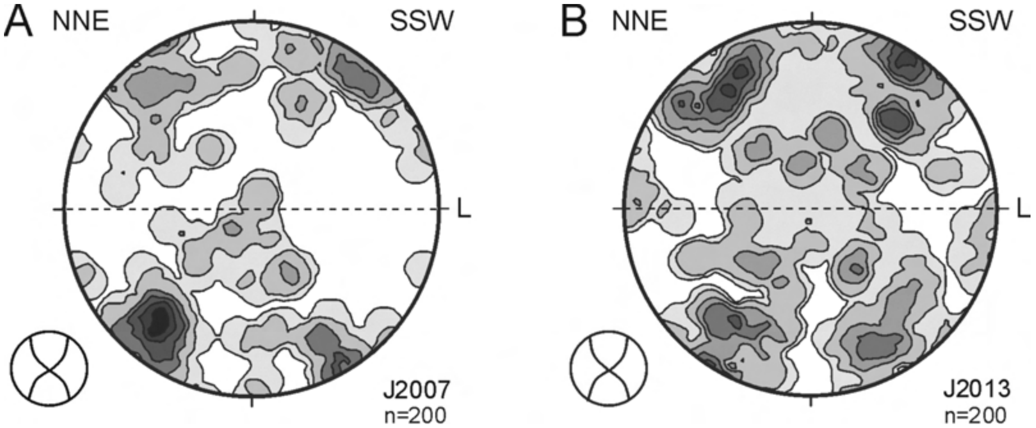
Results

Quartz [c]-axis patterns obtained for the quartzo-feldspathic schists represents five main types of pole distribution: (1) type I crossed girdles; (2) type I crossed girdles evolving into a single girdle; (3) type II crossed girdles; (4) a single girdle inclined to the foliation; and (5) strongly diffused or random scatter.

Type I crossed girdles were observed on pole figures for five samples: J2001, J2125, J2008, J2009 and 857 (Text-fig. 6). The form of the scatter (Text-fig. 6) suggests well-developed submaxima lying close to the Z-axis of the finite strain ellipsoid. Submaxima placed close to the Y-axis and intermediate between the Y- and Z-axis are better or less well expressed and are only clearly visible on the diagrams for samples J2001 (Text-fig. 6A), J2008 (Text-fig. 6C) and 857 (Text-fig. 6E). Most of the pole figures are characterised by internal symmetry, some of them are internally asymmetric.

Diagrams representing samples J2014, 850 and 858 (Text-fig. 7) show type I crossed girdles evolving into a single girdle. All of them display both internal as well as external asymmetry. The girdles resulting from our measurements (Text-fig. 7) are relatively well populated but more or less diffused. Submaxima close to the Z-axis can be recognized, albeit they are not particularly well developed (cf. Text-fig. 7).

Samples J2007 and J2013 display type II crossed girdles (Text-fig. 8) The girdles are unequally populated and one seems to be better defined then the other. This particular scatter (Text-fig. 8A) exhibits internal asymmetry with two Z-submaxima.



Text-fig. 8. Quartz [c]-axis patterns in the quartzo-feldspathic schists from the Kamieniec Ząbkowicki Metamorphic Belt: type II crossed girdles. Equal-area net, lower hemisphere stereograms. Density contours are at 1.5 % intervals. Projection on the XZ plane of the strain ellipsoid. Attitude of foliation (dashed line) corresponds to a plane perpendicular to the figure. Lineation (L) is parallel to the X-axis of the strain ellipsoid

Patterns representing monoclinic symmetry were found for quartz [c]-axis LPO in samples J2203, J2204, J2202, J2205, J2126 (Text-fig. 9). All the single girdles are diffuse and partly discontinuous, but the fabric remains distinctly asymmetric. Strong Z-submaxima are commonly well expressed (Text-fig. 9), as are the Y-submaxima (Text-fig. 9A, B, D). In contrast, the lack of intermediate submaxima between the Z- and Y-axis of the finite strain ellipsoid is apparent (cf. Text-fig. 9).

The random scatter of quartz [c]-axis orientations in samples J2012 and J2206 gives no useful information on either kinematics or the deformation conditions.

The rest of the pole figures obtained for the quartzo-feldspathic schsists (samples J2124, J2004, J2011 and B1101; Text-fig. 10) exhibit discontinuous girdles. All of them display well developed maxima located close to the Z-axis of the finite strain ellipsoid; in three cases asymmetric scatters can be observed. In this group of samples, a total lack of Y-maxima is apparent, but diagrams for samples B1101, J2011 and J2124 exhibit weakly expressed maxima intermediate between the Z- and Y-axis of the finite strain ellipsoid (Text-fig. 10).

DISCUSSION AND CONCLUSIONS

Type of deformation

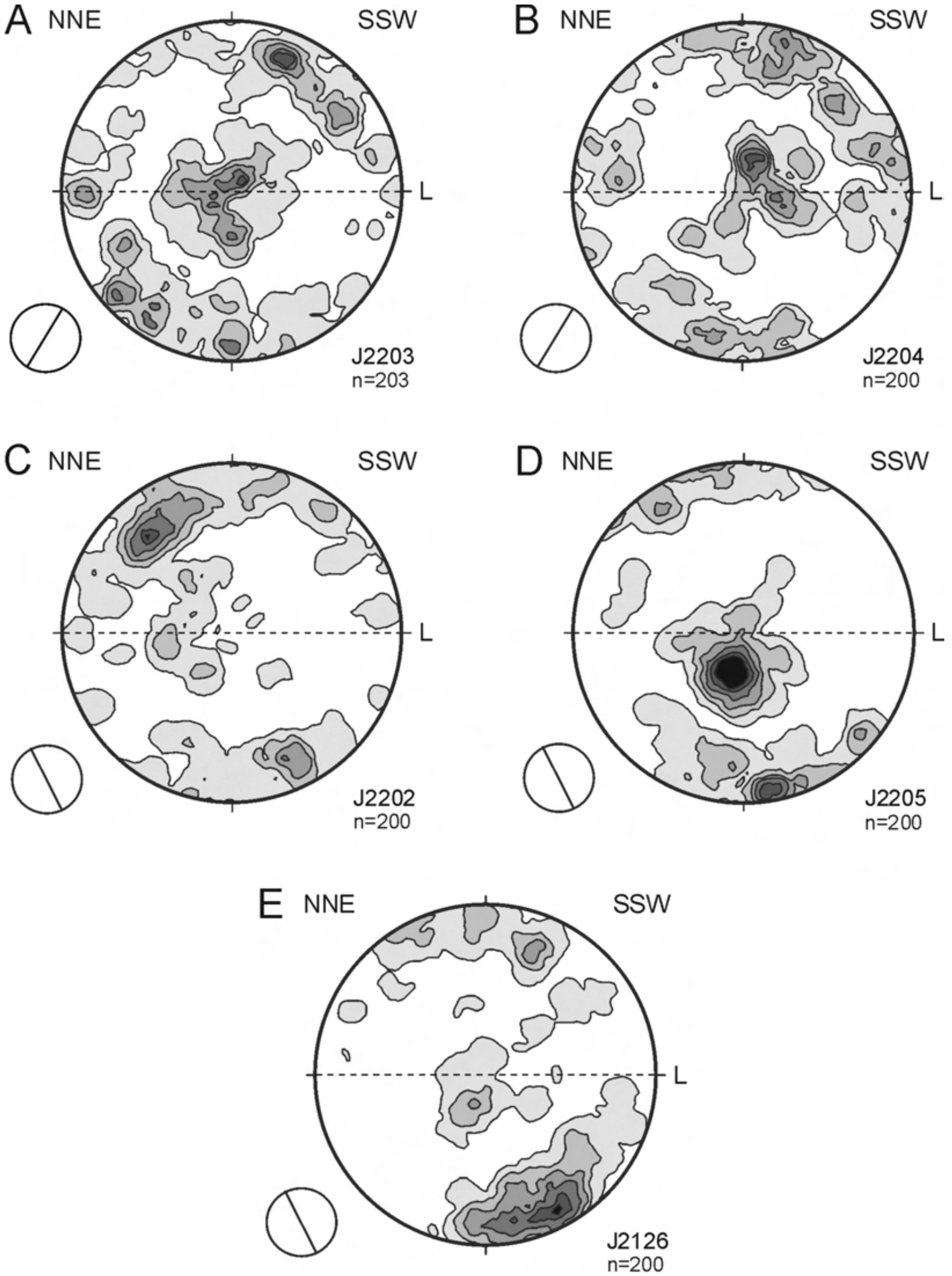
The type I crossed girdles pattern is usually interpreted as a result of coaxial deformation, close to the plane strain (Lister and Hobbs 1980; Schmid and Casey 1986; Law 1990; Passchier and Trouw 1996). The transitional types of type I crossed girdles evolving into a single girdle may result from: (1) increasing strain in a simple shear regime or (2) an increasing non-coaxial component of the strain path (Schmid and Casey 1986; Law 1990). The results of fabric modelling presented by Etchecopar and Vasseur (1987) predicted type I crossed girdles occurrence at low strains and single girdle at higher strains. An analogous conclusion was drawn from the experiments carried out by Dell'Angelo and Tullis (1989). With increasing strain, they observed that the type I crossed girdles evolved into the type I crossed girdles with an additional strong asymmetric submaximum, and then into a broad asymmetric single maximum. The scatters on Text-fig. 6C, D are similar to the latter and comparable with the distribution typical of the plane strain (Text-fig. 6). They may thus indicate low-strained rocks that deformed in a general shear regime, not in the plane strain path deduced at first glance.

According to Dell'Angelo and Tullis (1989), high-strained rocks should exhibit S-C structures with well developed C' features (extensional crenulation cleavage). No such structures are observed in the rocks which display quartz [c]-axis patterns close to type I crossed girdles. Only a few diagrams show type II crossed girdles. This type of scatter suggests coaxial deformation under general constriction (Schmid and Casey 1986; Law 1990; Passchier and Trouw 1996).

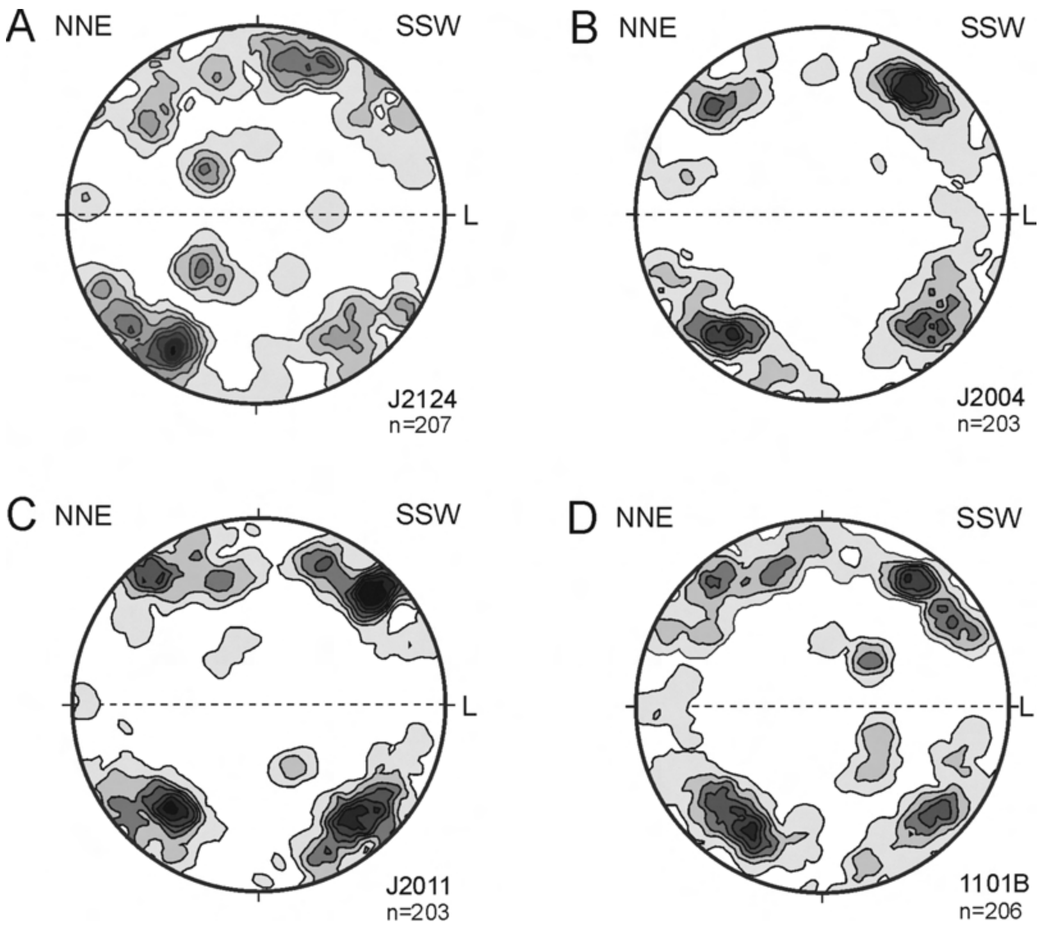
Diagrams with low symmetry suggest non-coaxial deformation (Takeshita *et al*. 1999). Thus single-girdle scatters are interpreted as a result of rotational deformation compatible with a simple shear strain (Schmid and Casey 1986; Law 1990; Passchier and Trouw 1996), moreover their asymmetry can be used to deduce the sense of shear (Law 1990).

In diagrams with incomplete girdles, the approximately symmetrical location of the Z-maxima may lead to an interpretation of predominantly coaxial deformation. Stronger asymmetrical maxima on part of them may suggest the existence of an additional rotational strain component, with a top-to-the SSW sense of movement.

Strongly diffuse or random scatters may reflect very low strain or post-tectonic, static recrystallization (Bouchez and Pecher 1981; Passchier and Trouw 1996). The presence of other mineral phases, especially micas, may lead to heterogeneous flow (Law 1990) and



Text-fig. 9. Quartz [c]-axis patterns in the quartzo-feldspathic schists from the Kamieniec Ząbkowicki Metamorphic Belt: simple shear. Equal-area net, lower hemisphere stereograms. Density contours are at 1.5 % intervals. Projection on the XZ plane of the strain ellipsoid. Attitude of foliation (dashed line) corresponds to a plane perpendicular to the figure. Lineation (L) is parallel to the X-axis of the strain ellipsoid



Text-fig. 10. Quartz [c]-axis patterns in the quartzo-feldspathic schists from the Kamieniec Ząbkowicki Metamorphic Belt: incomplete girdles. Equal-area net, lower hemisphere stereograms. Density contours are at 1.5 % intervals. Projection on the XZ plane of the strain ellipsoid. Attitude of foliation (dashed line) corresponds to a plane perpendicular to the figure. Lineation (L) is parallel to the X-axis of the strain ellipsoid

fabric domains resulting from this process (Pauli *et al*. 1996), nevertheless there is no strict interdependence between the type of scatter and mica content in rock.

The observed quartz [c]-axis LPO indicate that the deformation of the quartzo-feldspathic schists took place mainly at plane strain with a non-coaxial component, with a top-to-the SSW or NNE sense of movement, and an apparent flattening field.

Conditions of deformation

Analysis of the distribution of the quartz [c]-axis submaxima in the girdles indicates the operation of dominant slip systems in the quartz (Law 1990; Passchier and Trouw 1996). These are controlled by P_{H_2O}, the strain rate and, probably most importantly, by the temperature (Baëta and Ashbee 1969; Law 1990; Okudaira *et al*. 1995; Kruhl 1996; Passchier and Trouw 1996). Therefore, the identification of active slip systems in quartz enables estimation of the temperature of deformation. A temperature around 280 ± 30ºC marks the transition from cataclastic to plastic deformation of quartz (Stipp *et al*. 2002). With increasing temperature, slips in <a> direction prevail and activate successively on basal, prism and rhomb planes, which is matched by the location of [c]-axis maxima close to the Z-axis, intermediate between the Z- and Y-axis, and close to the Y-axis of the finite strain ellipsoid respectively (Schmid and Casey 1986; Passchier and Trouw 1996). Above a temperature of 650ºC, the [c] slip system predominates, yielding [c]-axis concentrations close to the X-axis of the finite strain ellipsoid.

In the samples studied, all of the quartz [c]-axis scatters are characterised by strong submaxima close to the Z-axis of the finite strain ellipsoid, while others are weaker or even absent (cf. Text-figs 6–10). Thus, the temperature of deformation did not exceed 650ºC. The observed Y-maxima indicate conditions of the amphibolite facies. The switch between <a> and [c] slips may happen around 550–600ºC (Okudaira *et al*.

1995) or 630 ± 30 ºC (Stipp *et al*. 2002). These findings are consistent with the lack of [c]-axis X-maxima in the quartzo-feldspathic schists from the Kamieniec Ząbkowicki Metamorphic Belt.

The distribution of the [c]-axis maxima may also be controlled by the presence of fluids. The basal <a> glide for quartz was reported for deformation at relatively high temperature (680–700ºC) as a consequence of "dry" conditions of deformation (Hippertt *et al*. 2001). The [c]-axis single Y-maxima may develop as a consequence of high water content and strong hydrolytic weakening even at temperatures typical of the greenschist facies (Joy and Saha 2000).

Based on the obtained quartz [c]-axis LPO we suggest that the thermal conditions of deformation of the quartzo-feldspathic schists fell within the limits of the amphibolite facies (550–600ºC).

Regional structural implications

When integrated with the thin section and field data, most of the asymmetric scatters of quartz [c]-axis orientation observed in the metarhyolite samples suggest a top-to-the SSW shearing in a sinistral strike-slip regime with some oblique component. As records of any older deformation of these rocks are absent or obscured, we assume that it was this regime that produced the quartz microfabric in the rocks studied and characterized the main tectonothermal event in the region under amphibolite facies conditions. This conclusion can be extended to other rock units in the Kamieniec Ząbkowicki Metamorphic Belt.

The D_3 sinistral strike-slip event of Mazur and Puziewicz (1995) appears to agree well with the obtained quartz [c]-axis pattern in terms of kinematics. The same is true of the D_2 event of Achramowicz *et al*. (1997) and Nowak (1998), and the D_3 event of Mazur and Józefiak (1999). According to Nowak (1998), the temperature peak during the D_2 event was achieved under amphibolite facies conditions (579 ± 35ºC and 7.4 ± 0.2 kbar).

The results obtained from the quartz [c]-axis pattern record the D_3 event of Mazur and Józefiak (1999), corresponding to 530ºC and 4 kbar, that followed the peak metamorphic conditions (D_2) under a temperature of 570–640ºC and pressure of 8–13 kbar in the coarse-grained schists and 510–540ºC and 7–8.5 kbar in the fine-grained schists respectively. In the coarse-grained schists, asymmetry of the quartz [c]-axis pattern is taken to indicate E-vergent thrusting (D_1) and a symmetric pattern to indicate coaxial strain during the shortening. In the fine-grained schists, the asymmetric pattern is used to infer a top-to-the SW shearing, whereas the symmetric pattern is interpreted as a relic of D_2 shortening. Mazur and Józefiak (1999) did not explain how the D_2 coxial deformation was to be reconciled with the NE-vergent thrusting D_2.

In this study, a relatively minor group of scatters of quartz [c]-axis orientation indicates an opposite sense of movement (top-to-the NNE). Such incompatibility may reflect either local heterogeneities of the strain gradient and strain path (Bouchez and Pecher 1981) or a local aberration of the flow pattern (Passchier 1983). Another explanation is that the deformation history recorded by the quartzo-feldspathic schists is complex and that the microfabric reflects different stages related to specific senses of shearing and rheological conditions.

The deformation event with a top-to-the SSW sense of shear (D_3) would have post-dated the earlier one with the E/NE sense of tectonic movement (D_2) suggested by the mesostructural observations of Mazur and Puziewicz (1995) and Mazur and Józefiak (1999). The D_3 regional extension was strain partitioned into domains with a prevailing simple shear component and domains with a prevailing coaxial component (cf. Jones and Tanner 1995).

It is difficult to compare our quartz [c]-axis patterns with those obtained by Dziedzicowa (1970, 1973), who studied quartz microfabric in sections cut perpendicular to the foliation and lineation (*ac* planes of the Sander kinematic coordinates).

Quartz [c]-axis data from the metarhyolites point to the reverse sequence: strong sinistral strike-slip shearing (top-to-the SW) was followed by weaker dextral shearing (top-to-the NE) along the same subhorizontal stretching lineation. The observed quartz microfabric sequence compares better with the models that assume top-to-the SW tectonic movements in the region, followed by top-to-the NE movements, as proposed by Achramowicz et al. (1997) and Nowak (1998).

Comparison of the observed quartz [c]-axis patterns with other kinematic indicators (Table 2) shows that:

(1) Both the type I and type II crossed girdles are associated with mesofabrics comprising porphyroclasts with only symmetric or both symmetric and asymmetric pressure shadows (Table 2, samples J2013, J2001, J2125, J2008, J2009), hence these two types of microfabric cannot be taken as records of coaxial vs. non-coaxial deformation;

(2) Apparent symmetry of the mesofabric (lack of kinematic indicators) does not preclude asymmetry of the microfabric (Table 2, samples J2202-J2205);

(3) In view of the above, the coincidence of kinematically contradictory micro- and mesofabrics (Table 2, sample J2126) is taken as an indication of the superposition of two events: the main one with top-to-the SW kinematics and asymmetric porphyroclasts; and a subsequent overprint with top-to-the NE kinematics.

There is visible dependence of the quartz LPO on the degree of mylonitization in the quartzo-feldspathic schists. Most of the fine-grained schists (high-strained variety I) exhibit a single girdle scatter, and a part of medium-grained schists (varieties IIa, b) with K-feldspar porphyroclasts display type I crossed girdles

No. of sample	Quartz [c]-axis pattern	Symmetry of pressure shadows	Schist variety	No. of exposure
J2007	type II crossed girdles, cf. Fig. 8A	-	I	2
J2013	type II crossed girdles, cf. Fig. 8B	symmetric and asymmetric, top-to-the SSW kinematics	IIb	1
J2001	type I crossed girdles, cf. Fig. 6A	symmetric and asymmetric, top-to-the SSW kinematics	IIb	3
J2125	type I crossed girdles, cf. Fig. 6B	symmetric and asymmetric, top-to-the SSW kinematics	IIb	1
J2008	type I crossed girdles, cf. Fig. 6C	symmetric	IIa	2
J2009	type I crossed girdles, cf. Fig. 6D	symmetric	IIa	2
857*	type I crossed girdles, cf. Fig. 6E	-	I	2
J2014	type I crossed girdles evolving into single girdle; top-to-the SSW kinematics, cf. Fig. 7A	symmetric and asymmetric, top-to-the SSW kinematics	IIb	1
858*	type I crossed girdles evolving into single girdle, cf. Fig. 7B	symmetric	IIa	2
850*	type I crossed girdles evolving into single girdle, cf. Fig. 7C	symmetric and asymmetric	IIb	1
J2203	single girdle, top-to-the SSW kinematics, cf. Fig. 9A	-	I	5
J2204	single girdle, top-to-the SSW kinematics, cf. Fig. 9B	-	I	5
J2202	single girdle, top-to-the NNE kinematics, cf. Fig. 9C	-	I	5
J2205	single girdle, top-to-the NNE kinematics, cf. Fig. 9D	-	I	5
J2126	single girdle, top-to-the NNE kinematics, cf. Fig. 9E	symmetric and asymmetric, top-to-the SSW kinematics	IIb	1
J2124	incomplete girdle, cf. Fig. 10A	symmetric and asymmetric, top-to-the SSW kinematics	IIb	1
J2004	incomplete girdle, cf. Fig. 10B	-	I	4
J2011	incomplete girdle, cf. Fig. 10C	symmetric	IIa	2
B1101	incomplete girdle, cf. Fig. 10D	symmetric and asymmetric, top-to the SSW kinematics	IIb	3
J2012	random scatter	symmetric and asymmetric, top-to the SSW kinematics	IIb	1
J2206	random scatter	-	I	4

Table 2. Results of microstructural analysis in the quartzo-feldspathic schists from the Kamieniec Ząbkowicki Metamorphic Belt. Schist varieties: (I) free from porphyroclasts, (IIa) with sparse porphyroclasts and (IIb) rich in porphyroclasts. * – non-oriented sample

(cf. Table 2). The intensity of mylonitic deformation increases westward as evidenced by the grain-size reduction and increasing asymmetry of the quartz [c]-axis patterns (Table 2, Text-fig. 2).

In the metarhyolites of the Kamieniec Ząbkowicki Metamorphic Belt, the quartz LPO recorded plane strain deformation with a non-coaxial component and thermal conditions around 550–600ºC, which points to the peak of regional metamorphism being associated with the regime characterized by top-to-the SW kinematics. These features are more compatible with the model proposed by Nowak (1998), which explains the early, north–south structural and metamorphic zonation of the region better than the models that predict the onset of the tectonometamorphic history with E-vergent thrusting.

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