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STRUCTURAL RECORD OF VARISCAN THRUSTING AND SUBSEQUENT EXTENSIONAL COLLAPSE IN THE MICA SCHISTS FROM VICINITIES OF KAMIENIEC ZĄBKOWICKI, SUDETIC FORELAND, SW POLAND

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Abstract: Two tectonic units of different metamorphic grade can be distinguished in the mica schists which crop out at the eastern margin of the Sudetic foreland near Kamieniec Ząbkowicki. The Kamieniec unit comprises mica schists containing garnet, staurolite and andalusite porphyroblasts, whereas the Byczeń unit is composed of mica schists having porphyroblasts of albite. The Byczeń unit is situated to the west of the Kamieniec unit in the north of the study area. The reverse order of the two units apparent in the south of that area results from displacement of their tectonic contact along a shallow WSW-dipping normal-slip shear zone cross-cutting earlier steeply dipping structures. Both the Kamieniec and Byczeń tectonic units are exposed on the inverted limb of a large SE-vergent synform, F_2, as indicated by NW asymmetry of mesofolds and by gently inclined cleavage S_2 intersecting the steep foliation S_1. The hinge zone of this fold is occupied by an orthogneiss body and the normal limb is represented by paragneiss of the Chałupki unit exposed further east.

The mica schists in the vicinities of Kamieniec Ząbkowicki have recorded three deformation events, D_1, D_2 and D_3. Deformation D_1 produced the main foliation S_1, which, in the study area is now steeply NW-dipping. The locally preserved L_1 stretching lineation is trending, in general, E–W, although it is locally reoriented on the limbs of younger folds F_2. The axes of the F_2 folds are oriented NE–SW and the accompanying penetrative axial cleavage S_2 show gentle dips to the W, SW or NW. The S_2 foliation is represented either by crenulation cleavage or, more frequently, by transposition foliation that has completely replaced the older foliation S_1. Intersecting S_2 and S_1 surfaces define penetrative lineation L_2, the most prominent linear structure in the area. Deformation D_3 was confined to low-angle normal-slip shear zones dipping to the SW. The S_3 foliation within the shear zones is parallel to S_2, whereas the L_3 stretching lineation parallels the intersection lineation L_2.

Kinematic indicators point to an E-directed overthrusting of the Byczeń unit by the Kamieniec unit during the D_1 event. The tectonic juxtaposition of both units resulted in metamorphic grade inversion. The subsequent deformation D_2 involved an irrotational shortening in the NW–SE direction, which produced the large-scale NE–SW-trending synform F_2. Its western, inverted limb was subjected to an intense subvertical shortening. The progressive shortening was followed by development of normal-slip shallow-dipping shear zones D_3 showing top-to-SW or to-WSW sense of shear. The normal-slip shearing was related to SW-directed extensional collapse D_3 at the eastern margin of the Sudetic foreland.

Key words: mica schists, deformation, metamorphism, Sudetes, Variscan belt.

Abstrakt: W łupkach łyszczykowych okolic Kamieńca Ząbkowickiego wydzielamy dwie jednostki tektoniczne Kamieńca i Byczenia, różniące się stopniem metamorfizmu. Pierwsza z nich obejmuje łupki łyszczykowe z porfiroblastami granatu, staurolitu i andaluzytu, podczas gdy do drugiej należą łupki z porfiroblastami albitu. W skali całego metamorfiku Kamieńca Ząbkowickiego jednostka Byczenia występuje generalnie na zachód od jednostki Kamieńca, tak jak ma to miejsce w rejonie wsi Stolec. Odwrotne rozmieszczenie wychodni tych jednostek między Kamieńcem Ząbkowickim a Byczeniem jest efektem przemieszczenia na połogiej, zrzutowo-normalnej strefie ścinania o upadzie ku WSW. Orientacja kliważu S_2 nachylonego mniej stromo niż foliacja S_1 oraz północno-zachodnia asymetria fałdów mezoskopowych dowodzą, że obie jednostki tektoniczne występują na krótszym skrzydle makrosynformy obalonej ku SE. Dłuższemu skrzydłu synformy odpowiadają natomiast wychodnie paragnejsów wschodniej części metamorfiku Doboszowic (jednostka Chałupek).

W łupkach łyszczykowych z okolic Kamieńca Ząbkowickiego wyróżniliśmy trzy zespoły struktur deformacyjnych odpowiadające trzem etapom deformacji D_1, D_2 i D_3 o zasięgu regionalnym. W etapie D_1 powstała foliacja S_1 zapadająca dziś w obszarze badań stromo ku NW oraz, zaznaczająca się tylko sporadycznie, lineacja z rozciągania L_1. Generalny przebieg lineacji L_1 jest zbliżony do kierunku E–W, choć lokalnie uległa ona reorientacji na skrzydłach młodszych fałdów F_2. Podczas etapu D_2 foliacja S_1 została zdeformowana w fałdy F_2 o osiach

NE–SW. Kliważ osiowy fałdów F_2 ma łagodne nachylenie ku W, SW lub NW. Miejscami ma formę kliważu krenulacyjnego, a miejscami tworzy nową penetratywną foliację S_2 zacierającą starsze powierzchnie S_1. W efekcie przecięcia kliważu S_2 ze starszą foliacją S_1, powstała penetratywna lineacja intersekcyjna L_2 o przebiegu NE–SW, będąca główną strukturą linijną w badanym terenie. Deformacja D_3 skoncentrowała się w strefach ścinania o upadzie ku SW, w których foliacja S_3 jest równoległa do S_2, a lineacja z rozciągania L_3 jest równoległa do L_2.

Analiza wskaźników kinematycznych dowodzi, że deformacja D_1 wiązała się z transportem tektonicznym ku E. Etap D_2 zachodził natomiast w efekcie koaksjalnego skrócenia o kierunku NW–SE. Konsekwencją rosnącego skrócenia było powstanie niskokątowych, normalnych stref ścinania D_3 o zwrocie "strop-ku-SW" lub "ku-WSW". W etapie D_1 jednostki tektoniczne Kamieńca i Chałupek nasunęły się kolejno na jednostkę Byczenia, co doprowadziło do tektonicznej inwersji stopnia metamorfizmu. W etapie D_2 powstała makrosynforma F_2 o osi NE–SW. Jej krótsze skrzydło uległo silnemu skróceniu w kierunku pionowym. W etapie D_3 rozwinął się kolaps ekstensyjny ku SW, a wzdłuż wschodniej krawędzi bloku sowiogórskiego powstała przesuwcza, lewoskrętna strefa dyslokacyjna Niemczy.

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INTRODUCTION

The characteristics and history of tectonic deformation in rock complexes of the eastern part of the Fore-Sudetic Block have remained an object of mutually conflicting interpretations (Dziedzicowa, 1985, 1987; Cymerman & Jerzmański, 1987; Cymerman & Piasecki, 1994; Achramowicz, 1994; Mazur & Puziewicz, 1995a; Nowak, 1995). The controversy has concerned both the sequence and kinematics of ductile deformation events in that area. Our research on mica schists from the vicinity of Kamieniec Ząbkowicki (Fig. 1) was aimed at providing new constraints on the deformation history of the eastern part of the Fore-Sudetic area. Another objective was to integrate the data collected previously in the Niemcza Shear Zone and the Doboszowice Metamorphic Complex (Fig. 1). The new information obtained during our study allowed us to complete the earlier interpretation of Mazur & Puziewicz (1995a) and to put forward a model explaining the tectonic evolution of the crystalline complexes located between the Góry Sowie Massif and Niedźwiedź Massif (Fig. 1).

GEOLOGICAL SETTING AND PREVIOUS STUDIES

To the east of the Góry Sowie Massif and of the Niemcza Shear Zone there occurs a N–S elongated schist belt (Fig. 1). This schist belt is referred to, here, as the Kamieniec Ząbkowicki Metamorphic Complex. The northern part of the complex is aligned N–S that is along the eastern margin of the Niemcza Zone whereas its southern part forms an inlier in the vicinity of Kamieniec Ząbkowicki. The mica schists contain intercalations of quartzo-feldspatic schists

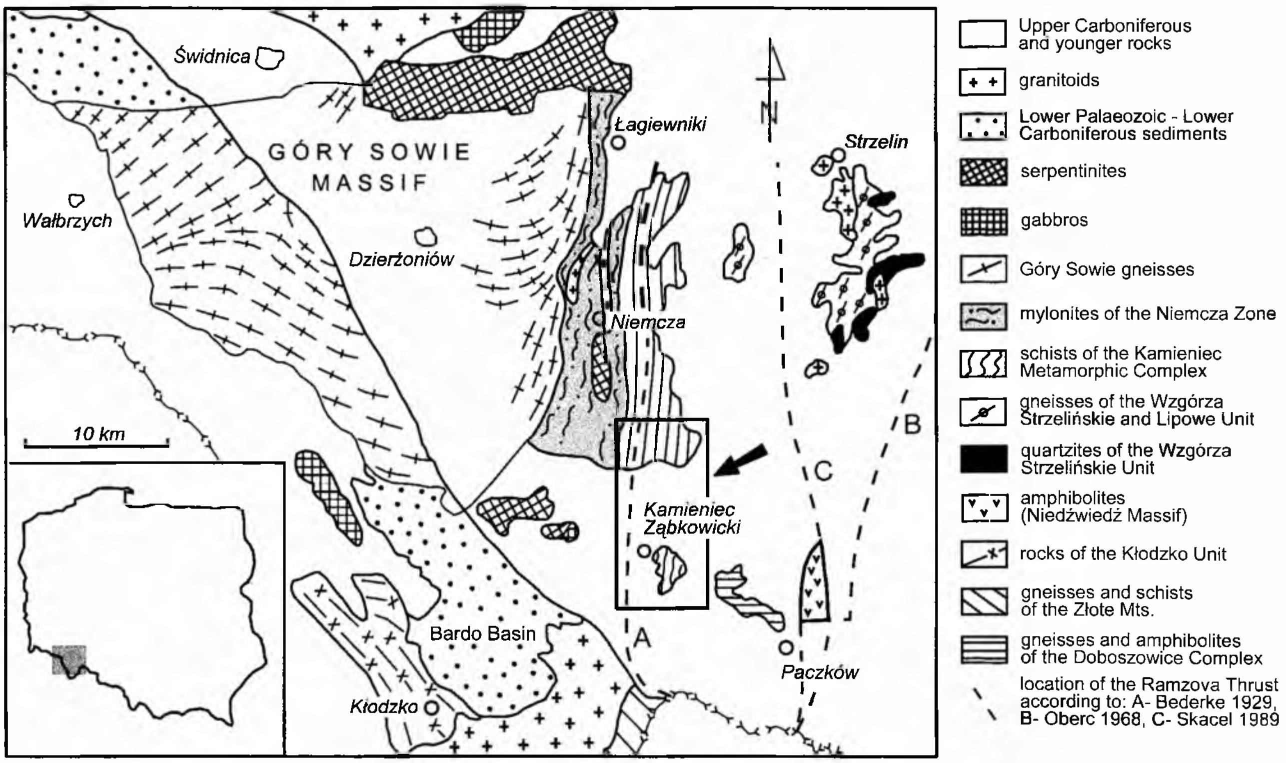


Fig. 1. Regional setting of the study area (box indicated by an arrow)

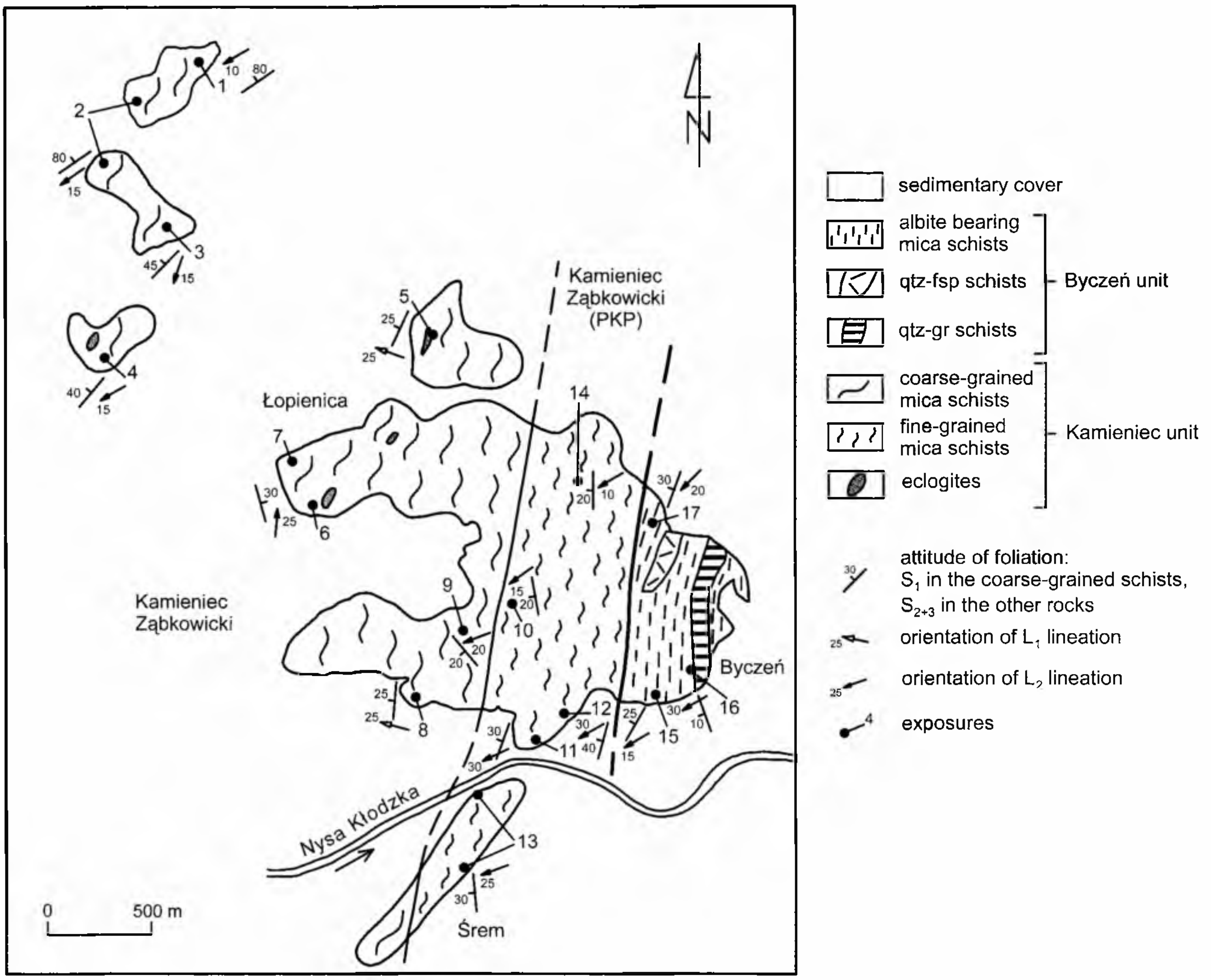


Fig. 2. Geological sketch map of the vicinity of Kamieniec Ząbkowicki modified after Baraniecki (1956) and Gaździk (1957) and location of the most important exposures

and marbles and subordinate lenses of quartzo-graphitic schists, amphibolitic schists and eclogites (Fig. 2, 3).

The penetrative foliation in the Kamieniec Ząbkowicki Metamorphic Complex dips to the SW, W and NW at variable angles. The dip of foliation increases westwards, towards the contact with the Niemcza Shear Zone (Mazur & Puziewicz, 1995b). The stretching lineation is, in general, plunging to the SW at a low angle.

The sequence of tectonic deformation in the Kamieniec Ząbkowicki Metamorphic Complex was previously studied by Dziedzicowa (1975, 1985, 1987) who distinguished three deformation events. The penetrative, almost vertical foliation S_1 developed during the first event. This foliation was subsequently deformed by F_2 folds which showed subhorizontal axial planes. Axial cleavage S_2 of these folds locally obliterated the older foliation S_1. The last event, D_3, produced similar folds of almost vertical axial planes.

A different deformation sequence for mica schists from vicinities of Kamieniec Ząbkowicki was described recently by Achramowicz *et al.* (1997). In their interpretation, the first deformation event, related to SSW-directed thrusting, produced foliation S_1, which is now preserved exclusively in eclogites. The succeeding events, D_2 and D_3, are to represent the main deformations. The D_2 event brought about normal dip-slip shear zones, characterised by a top-to-SW sense of ductile shear and was accompanied by high temperature metamorphism of upper amphibolite facies. The D_3 deformation operated under dextral transpression regime. It was due to regional E–W shortening and resulted in easterly vergent thrusting followed by development of dextral strike-slip and/or wrench-normal faults. This deformation sequence (Achramowicz *et al.*, 1997) represented a modified version of earlier interpretations published by Achramowicz (1994) and Achramowicz *et al.* (1995).

A similar history of deformation is postulated by Nowak (1998). The earliest structures were defined, according to this author, by HP mineral assemblage and were probably related to the D_1 thrusting. A subsequent exhumation was mostly related to low-angle normal faults (D_2), and resulted in SW-vergent structures, coeval with emplacement of granitoid magmas (e.g. Strzelin–Žulova plutons). The temperature peak of metamorphism took place at the end of the D_2 event. Further uplift and exhumation was associated with transpression and thrusting to the east (D_3) in a colli-

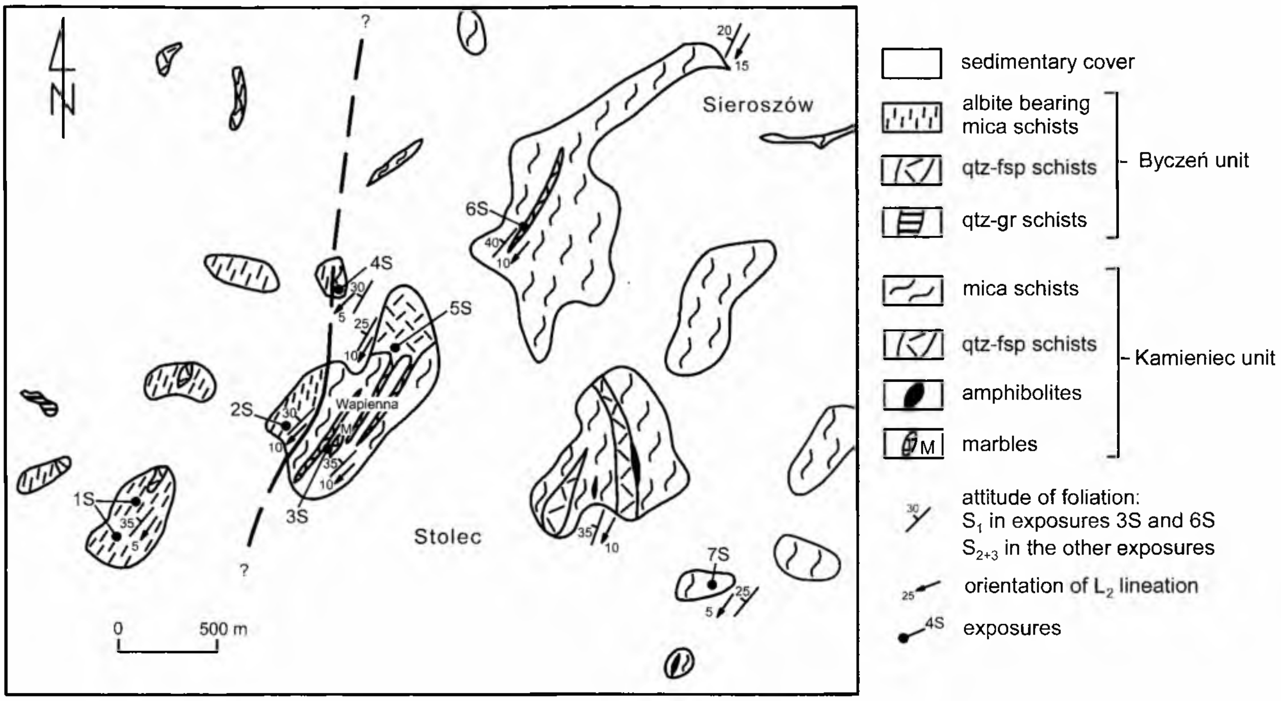


Fig. 3. Geological sketch map of the vicinity of Stolec modified after Badura (1979) and Badura & Dziemiańczuk (1981) and location of the most important exposures

sional setting between the Saxothuringian and Moravosilesian terranes. Late orogenic extension (D_4) partly transposed the WSW-dipping S_2 foliation in shear zones under normal faulting regime.

A succession of four consecutive deformation events was suggested for the eastern part of the Fore-Sudetic block by Cymerman (1986, 1991) and Cymerman & Jerzmański (1987). In a more recent work, Cymerman and Piasecki (1994) suggest that deformation and metamorphism in that area were mainly related to the formation of NNE-directed overthrusts. This hypothesis reflects the recently widespread concept of tectonic evolution of the entire eastern margin of the Bohemian massif. This concept assumes that the nappe complexes of the Moldanubian zone and of the West Sudetes (Lugicum of Suess 1926) are overthrust towards the NE to NNE, on top of the Moravo-Silesian zone of the Variscides (Schulmann, 1991; Fritz & Neubauer, 1993; Schulmann *et al.*, 1995).

Recently, Mazur & Puziewicz (1995a) and Mazur *et al.* (1995) recognised three ductile deformation events, D_1, D_2 and D_3, in the metamorphic rocks east of the Góry Sowie Massif. The first two deformations D_1 and D_2 were related to nappe overthrusting towards the E and NE, respectively, under amphibolite facies conditions. They presumably represented the main contractional deformations on the eastern margin of the Bohemian Massif and were associated to regional thrusting of the West Sudetes over the East Sudetes. The D_3 event involved regional tectonic extension resulting in top-to-SW normal-slip shearing along slightly inclined foliation planes and sinistral strike-slip shearing along subvertical foliation planes (Mazur & Puziewicz, 1995a, b). The latter case corresponded to the regional-scale strike-slip Niemcza Shear Zone which developed along the eastern margin of the Góry Sowie block during the D_3 event (Fig. 1). Penetrative mylonitization D_3 involved not only gneisses within the Niemcza Shear Zone but also mica schists in the adjacent part of the Kamieniec Complex (Mazur & Puziewicz 1995b). However, in the southern part of this complex Mazur & Puziewicz (1995a) and Mazur *et al.* (1995) observed only local D_3 shear zones cross-cutting the older pervasive D_2 fabric.

METHODS

Our study is based on observations and measurements made in 42 exposures of mica schists from the vicinity of Kamieniec Ząbkowicki and in 10 exposures from the vicinities of Stolec. Locations of the most important exposures are shown on geological sketch maps (Figs 2, 3) and are compiled in Table 1. All microscopic observations and measurements were made using oriented thin sections cut parallel to the lineation and perpendicular to the foliation. 63 samples underwent microscopic examination: out of these 47 were collected in the vicinities of Kamieniec Ząbkowicki and 16 in the vicinity of Stolec. Kinematic analysis was focused on the evaluation of the sense of shear using meso- and microscopic indicators.

The orientation of quartz <c> axis was measured on the universal stage in thin sections from 33 samples: 26 of them collected near Kamieniec Ząbkowicki and 7 coming from the vicinities of Stolec. In this paper we present 21 from among the total of 33 resultant stereograms. Preferred orientation of quartz <c> axis was analysed since the mica schists of the study area show distinct differentiation among quartz and silicate layers and domains. In such a case quartz aggre-

Table 1

Location of exposures shown in the Figures 2 and 3

No of exp.	Location
1	Approximately 1.5 km north of Kamieniec Ząbkowicki, east of the railway to Jaworzyna Śląska, rocks at top of the hill 270.2 m
2	Approximately 1.5 km north of Kamieniec Ząbkowicki, to the west of the railway to Jaworzyna Śląska, steep scarp 50 m west of exposure 1
3	Small quarry approximately 800 m north of Kamieniec Ząbkowicki, SW slope of the hill 282.9 m
4	Quarry in the northern part of Kamieniec Ząbkowicki, near to railway viaduct
5	Small quarry near to the railway to Jaworzyna Śląska, 400 m west of Kamieniec Ząbkowicki railway station
6	Rocks at top of the hill 272.7 m in Kamieniec Ząbkowicki
7	Approximately 50 m north of exposure 6, quarry behind the houses in Łopienica
8	Approximately 1.5 km east of Kamieniec Ząbkowicki, scarp along the road towards Byczeń, near to the bridge across Budzówka brook
9	Small quarry on the north slope of Albert Hill, 20 m to the south of the tourist path from the castle to the temple, at top of the hill 290.6 m
10	Quarry on NW slope of the hill 300.2 m, approximately 30 m east of exposure 9 at the forest roads crossing
11	North scarp of the valley of the river Nysa Kłodzka in Byczeń
12	Quarry on the SW slope of the hill 308.0 m, at the periphery of Byczeń
13	Scarps and trenches on the west and east slopes of the hill 271.9 m, south bank of the river Nysa Kłodzka
14	Quarry at top of the hill 290.6 m, near to the temple
15	Quarry in Byczeń, 20 m west of the road to Kamieniec Ząbkowicki railway station
16	Quarry in Byczeń on SE slope of the hill 272.3 m
1S	West of Stolec, two small quarries on SW slope of the hill 353.0 m
2S	Small quarry to the west of Stolec, 100 m west of summit of Wapienna Hill (398.0 m)
3S	Large quarry on south slope of Wapienna Hill (398.0 m), west of Stolec
4S	Small crag between Wapienna Hill and the hill 341.8 m
5S	Quarry on NW slope of Wapienna Hill
6S	Quarry north of Stolec on west slope of the hill 377.6 m, near to the road to Sieroszów
7S	Quarry at top of the hill 357.5 m, east of Stolec

gates are appropriate for analysis of crystallographic orientation in spite of a high total content of micas in the rock (Walniuk & Morris, 1985). The orientation of <c> axis was only measured in grains enclosed in monomineral quartz assemblages. In consequence, the influence of micas admixture on the deformation mechanism of quartz grains was minimised. In rock domains rich in mica flakes, quartz is deformed mainly by intercrystalline mechanisms: grain boundary sliding and pressure solution due to high number of quartz-mica contacts (Starkey & Cutforth, 1978; Morris, 1978; Shelley, 1982). These mechanisms do not produce a lattice preferred orientation of quartz and the grains tend to remain strain-free (Nicholas & Poirier, 1976). On the other hand, monomineral quartz domains are deformed by intracrystalline mechanisms: dislocation glide and dislocation creep which result in a well-defined lattice orientation (Walniuk & Morris, 1985). Therefore, quartz <c> axis patterns obtained for monomineral quartz domains are useful for analysis of deformation kinematics in the study mica schists.

LITHOLOGY AND PETROGRAPHY

Vicinities of Kamieniec Ząbkowicki

Mica schists from the vicinities of Kamieniec Ząbkowicki (Fig. 2: exposures 1–14) are composed of quartz, muscovite, biotite, garnet, plagioclase (10–25% An), andalusite, staurolite and chlorite. Accessory minerals are tourmaline, apatite, zircon, allanite, rutile, and illmenite. The mica schists comprise two main structural varieties: coarse- and fine-grained schists (Józefiak, 1995).

The fine-grained schists (exp. 10–14) are differentiated into regularly alternating quartz-muscovite and muscovite-biotite laminae whereas the coarse-grained schists (exp. 1–9) consist of elongated quartz aggregates enveloped by muscovite-biotite layers. Irregular muscovite concentrations, up to 25 mm long, are locally present in both varieties of mica schists. Individual muscovite grains within these aggregates are isometric or slightly elongated and display random orientation.

Mica layers in both varieties of schists contain numerous garnet porphyroblasts up to 3 mm across in the fine-grained and up to 4–10 mm across in the coarse-grained variety. Staurolite, chlorite, plagioclase and andalusite represent significant, but less frequent components of the mica layers. Most garnet crystals in the coarse-grained schists are replaced by pseudomorphs of biotite, chlorite, muscovite, plagioclase, staurolite and of iron hydro-oxides which include small relics of garnet. Linear and S-shaped inclusion trails are still visible in less altered garnets from coarse- and fine-grained mica schists. Inclusion trails contain mainly rutile, illmenite, quartz and subordinate chloritoide, staurolite, chlorite, kyanite, margarite, paragonite, muscovite and tourmaline. Well-developed pressure-shadows around garnets are filled with quartz, muscovite, biotite and, infrequently, with plagioclase and staurolite.

The mica schists from the vicinities of Kamieniec Ząbkowicki contain all three polimorphs of Al_2SiO_5. The coarse-grained schists comprise post-kinematic crystals of andalusite up to 6 mm long. They enclose numerous muscovite, biotite, quartz, staurolite, plagioclase, ilmenite and rutile inclusions aligned parallel to the foliation planes. In places, andalusite overgrows margins of partly altered garnet porphyroblasts. Syn- to post-kinematic andalusite grains (up to 1 mm) occur, in the fine-grained schists, as well. They are often deformed and, less frequently, contain spiral inclusion trails. Scarce sillimanite is represented by intergrowths of fibrolite in muscovite, garnet and quartz. Fibrolite is also visible in pressure shadows of staurolite grains and around analusite porphyroblasts. Prismatic crystals of sillimanite are only locally present in the coarse-grained schists, enclosed within muscovite aggregates. Kyanite was found only as intergrowths in garnet in the coarse-grained mica schists. Dziedzicowa (1966) and Nowak (1995) described scarce individual grains of this mineral occurring within mica layers.

Plagioclase (10–25% An) in the coarse-grained schists forms large crystals up to 4 mm long, lengthened parallel to the foliation. Smaller grains make up elongated aggregates together with mica plates, iron oxides and, locally, with andalusite crystals. In the fine-grained schists small plagioclase grains (10–25% An) occur within mica layers. Locally, in both varieties of mica schists oligoclase is accompanied by albite blasts.

Staurolite is present only in some parts of mica shists within mica layers or muscovite aggregates. Its prismatic crystals are 0.1 mm to 0.7 mm long. Numerous randomly oriented staurolite grains together with these of muscovite and biotite define, in places, thin elongated trails, which envelope garnet porphyroblasts.

Chlorite represents only a subordinate component of mica layers. Its grains usually parallel foliation but, locally, display random orientation. Chlorite is the dominant mineral phase in most pseudomorphs substituting garnet porphyroblasts.

Vicinities of Byczeń

Fine-grained mica schists containing albite crop out in the vicinities of Byczeń (Fig. 2). In contrast to mica schists from the vicinities of Kamieniec Ząbkowicki, they contain numerous porphyroblasts of albite (Fig. 4) and are devoid of staurolite and andalusite. Albite-bearing mica schists are composed of alternating quartz and mica layers and of fine-grained matrix. The latter consists of numerous mica and chlorite flakes scattered among smaller grains of quartz and plagioclase (20–24% An). Accessory minerals are tourmaline, apatite and opaques. Both in the fine-grained matrix and in mica layers, there occur few relics of garnet. They are preserved as irregular clasts or as small remains within pseudomorphs. Very small garnet blasts, below 0.05 mm across, are locally visible.

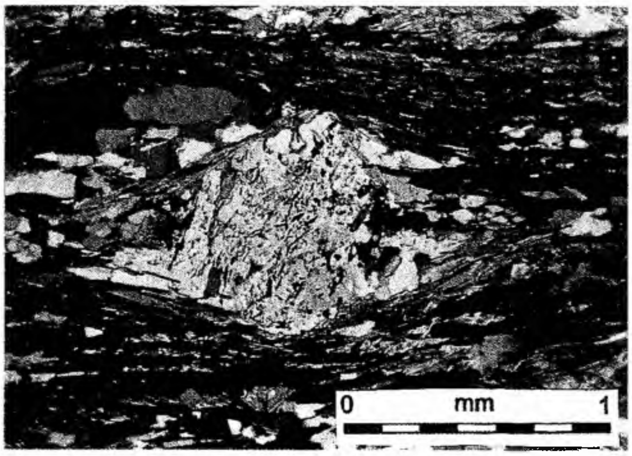


Fig. 4. Synkinematic albite porphyroblast in mica schist (Byczeń unit)

Vicinities of Stolec

Mica schists from the vicinities of Stolec (Fig. 3) are characterised by a significant variation of structure and mineral composition. The fine-grained mica schists of monotonous composition crop out to the west of Stolec (exp. 1S and 2S). They consist mainly of quartz, muscovite, biotite and plagioclase (15–30% An). Accessory minerals are represented by tourmaline, apatite (locally up to 3.5 mm long) and opaques. Their planar fabric is defined by mica layers and quartz lenses alternating with the fine-grained matrix composed of quartz, plagioclase and mica. Some horizons of mica schists contain numerous porphyroblasts of synkinematic albite, up to 3 mm in diameter.

To the west and north of Stolec (exp. 6S, 7S) the mica schists display medium-grained structure and more diversified composition. In addition to quartz, muscovite, biotite and plagioclase, these rocks are rich in garnet, staurolite and chlorite. Andalusite and sillimanite represent their less abundant components. Staurolite prisms, up to 1 mm long, occur in the mica layers. They locally cluster in elongated concentrations parallel to foliation planes. Garnet forms porphyroblasts reaching up to 4 mm across. They contain numerous S-shaped or spiral inclusion trails. Inclusions contain mainly quartz and opaques but less frequent rutile and plagioclase are also present. Few andalusite prisms are up to 1mm long. They display random orientation with respect to foliation.

Locally, north of Wapienna hill (exp. 4S), mica schists contain synkinematic chlorite, which is accompanied by green biotite, andalusite, staurolite and garnet. Plagioclase (1–14% An) represents only subordinate mineral phase. Andalusite blasts in this variety of mica schists display clearly synkinematic character. They enclose S-shaped or spiral trails of quartz and illmenite inclusions.

METAMORPHISM

According to Dziedzicowa (1966), the Kamieniec Ząbkowicki Metamorphic Complex consists of two contrasting domains: the north-western and the eastern one. The former is composed of mica schists locally containing garnet and sillimanite, whereas the latter comprises mica schists of more varied mineral composition, including garnet, staurolite, andalusite and kyanite. Crystallization of andalusite probably post-dated the origin of kyanite (Dziedzicowa 1987). The temperature and pressure of metamorphism in the mica schists near to Kamieniec Ząbkowicki is estimated by Dziedzicowa (1973) at 550–570°C and 6.5 kbar.

Nowak (1995, 1998) suggested that consecutive tectonic deformations were accompanied in the mica schists by a clockwise P-T path with a pressure peak in its earlier stage and a temperature peak during the later events. This path indicates compression and crustal thickening during the initial stage of metamorphism, continuing until pressure peak conditions were achieved during the continental collision. The minimum pressure and temperature conditions for the peak of pressure were estimated by Nowak at 11–12 kbar and 400–430°C. A subsequent decompression took place under conditions of rising temperature, in the amphibolite facies field, ultimately reaching the temperature peak under the conditions of 579 ±35°C and 7.4 ±0.2 kbar. After the temperature peak of metamorphism was achieved, further decompression was almost isothermal up to the andalusite stability field. A record of early HP metamorphism, inferred for mica schists, is preserved in eclogites from the vicinities of Kamieniec Ząbkowicki which were metamorphosed under temperature of ±575°C and pressure of 15 kbar (Achramowicz, 1997).

Recent investigations of Józefiak (1994, 1996) indicate that coarse- and fine-grained mica schists preserved record of different metamorphic conditions. The coarse-grained schists achieved peak metamorphism conditions under a temperature of 570–640°C and pressure of 8–13 kbar (mineral assemblage Ms+Bt+Grt+Pl±St±Ky±Cld), whereas the fine-grained schists recorded a temperature of 510–540°C and pressure of 7.0–8.5 kbar. Mica schists in close proximity to eclogites preserved evidence for a higher grade metamorphism under a temperature of 610–630°C and pressure of 10–13 kbar. The final metamorphic event in both varieties of mica schists is represented by the mineral assemblage Ms+Bt+Grt+Pl+And±Sil±St. The temperature and pressure during this event were characterised by the occurrence of andalusite which was locally replaced by sillimanite. The stability field of this assemblage corresponds to a temperature above 530°C and pressure below 4 kbar.

DEFORMATION

Three generations of deformational structures were recognised in the mica schists from the vicinities of Kamieniec Ząbkowicki. They are interpreted as reflecting three deformation events D_1, D_2 and D_3 of regional extent. Numbering of the distinguished deformation stages refers to the scheme adopted in the earlier papers of Mazur & Puziewicz (1995) and Mazur *et al.* (1995). The first, D_1, deformation produced foliation S_1 and lineation L_1. The next, D_2, event resulted in development of F_2 folds, crenulation cleavage and foliation S_2 and lineation L_2. The latest deformation, D_3, gave rise to the origin of lineation L_3 and foliation S_3, in general parallel to S_2.

Structural observations from the neighbourhood of Kamieniec Ząbkowicki show that foliation S_1 and lineation L_1 are penetrative in the coarse-grained mica schists whereas the younger foliation S_{2+3} is dominant in the fine-grained schists. Our division of mica schists into the coarse- and fine-grained varieties (Fig. 2) is, therefore, consistent with structural data concerning a type of development of the penetrative foliation.

The coarse-grained mica schists are exposed in the vicinities of Kamieniec Ząbkowicki whereas the fine-grained schists crop out around Byczeń (Fig. 2). Locally, bands of fine-grained schists, up to few tens of metres thick, occur within the coarse-grained variety (exposure 4). Further to the north, in the vicinities of Stolec (Fig. 3), no interrelationship between the size of grain and the type of a penetrative foliation can be observed. An equivalent of the coarse-grained rock variety in that area is represented by mica schists exposed on the Wapienna Hill (exp. 3S, 6S). The latter rocks are characterised by penetrative foliation S_1. On the contrary, in other mica schists cropping out around Stolec (Fig. 3), foliation S_{2+3} is the dominant planar structure, similarly as in the fine-grained schists. Consequently, the characteristics of the coarse- and fine-grained varieties of mica schists presented below are extended to include their structural equivalents in the vicinities of Stolec.

Deformation D_1

The foliation of the coarse-grained mica schists (S_1) is defined by alternation of quartz and mica layers and by parallel alignment of mica plates. Foliation S_1 displays a variable attitude (Fig. 2) since it mostly dips to the NW at high to moderate angles (exp. 1, 2, 3) or shows gentle eastward inclination (exp. 6, 7). The orientation of foliation S_1 shown on stereograms (Fig. 5a, b) displays a great-circle girdle distribution around an axis plunging gently to the WSW (exp. 1, 2) or to NE (exp. 6, 7). This orientation distribution results from reorientation of S_1 on limbs of F_2 folds. A constant orientation of S_1 can be observed only in exposures 5, 8 and 9 which are located near the contact with fine-grained schists (Fig. 2). In these three localities, foliation S_1 dips gently towards the W (Fig. 6a, b). Stretching lineation L_1 is defined by elongation of mica aggregates and quartz rods on foliation S_1. The general trend of the L_1 lineation is W–E to WNW–ESE (Fig. 7b). Most often the lineation L_1 is entirely obliterated by a younger lineation, L_2, which represents the dominant linear structure in the coarse-grained schists. Lineation L_1 is reoriented on limbs of the F_2 folds. Therefore, its orientation shown on stereograms (Fig. 5c, 7b) is scattered along circles around the axis parallel to the axis of the foliation girdle. On steeper limbs of the F_2 folds (dipping to the NW) lineation L_1 plunges towards the west at moderate angles, whereas on less inclined limbs (dipping to the SE) L_1 trends WNW–ESE (Fig. 5c). The maximum on stereoplots which represents the lineation of gentle plunge towards the WNW, is dominant on the synoptic diagram of L_1 structures since the majority of measurements were collected in exposures 5 and 8 characterised by a shallow dip of foliation S_1 (Fig. 6). For the same reason the main maximum on the synoptic diagram of S_1 planes represents foliation dipping to the W at a low angle (Fig. 7a). In the vicinities of Stolec (exp. 3S and 6S), foliation S_1 is scattered along a girdle around the axis trending NE–SW (Fig. 8a). The dominant orientation of S_1 in that area is represented by foliation dipping steeply to the NW.

Numerous large garnet porphyroblasts occur in the coarse-grained mica schists. They display features suggesting synkinematic growth during the deformation D_1. Their growth is indicated by sigmoidal inclusion trails (Fig. 9b) visible in many porphyroblasts. A synkinematic origin of garnet crystals is also evidenced, following Bell *et al.* (1986), by the presence of stright-line inclusion trails which

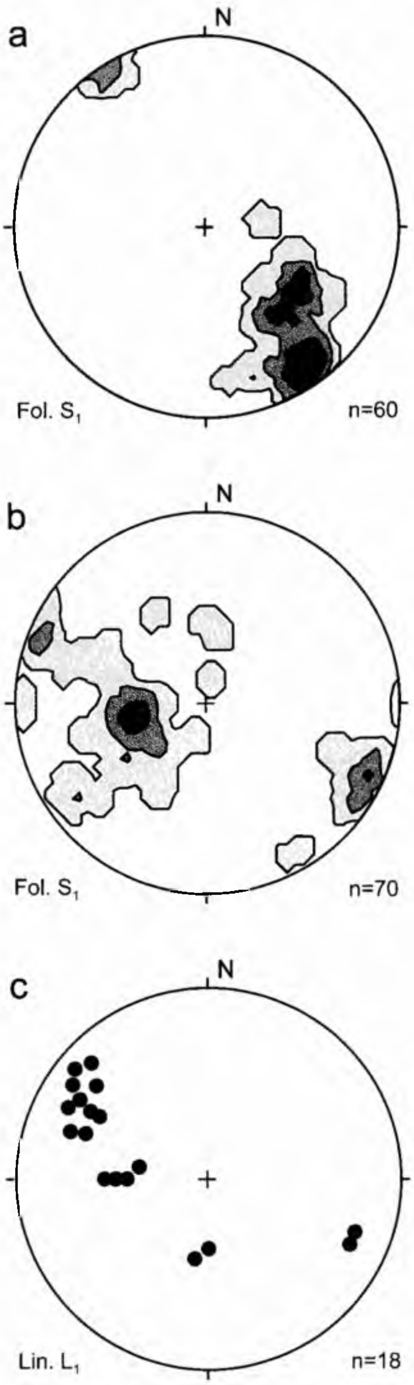


Fig. 5. Attitude of foliation S_1 and lineation L_1 in coarse-grained mica schists from exposures 1, 2, 6 and 7 in the vicinity of Kamieniec Ząbkowicki. Equal-area net, lower hemisphere. In stereograms **a** and **b** 1, 6 and 12% contours per 1% area. **a** – foliation S_1 in exposures 1 and 2 (60 measurements, max. 26.7%), **b** – foliation S_1 in exposures 6 and 7 (70 measurements, max. 17.1%), **c** – lineation L_1 in exposures 1, 2, 6 and 7 (18 measurements)

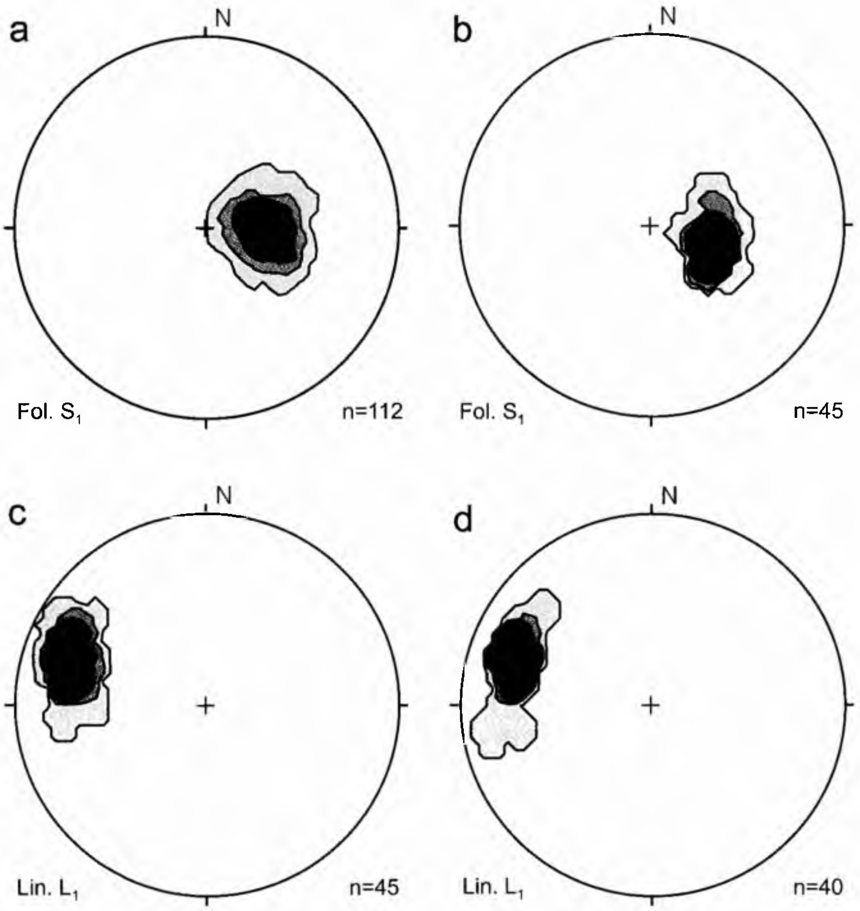


Fig. 6. Attitude of foliation S_1 and lineation L_1 in coarse-grained mica schists from exposures 5 and 8 in the vicinity of Kamieniec Ząbkowicki. Equal-area net, lower hemisphere. In all stereograms 1, 6 and 12% contours per 1% area. **a** – foliation S_1 in exposure 8 (112 measurements, max. 46.4%), **b** – foliation S_1 in exposure 5 (45 measurements, max. 68.9%), **c** – lineation L_1 in exposure 8 (45 measurements, max. 51.1%), **d** – lineation L_1 in exposure 5 (40 measurements, max. 70.0%)

are oblique or perpendicular to the S_1 foliation (Fig. 9c). Garnet porphyroblasts are accompanied by pressure shadows representing the most common kinematic indicator in the coarse-grained schists. Their asymmetry indicates a top-to-E or top-to-ESE sense of shear along shallow to moderately dipping foliation S_1.

Deformation D_2

Foliation S_1 is deformed by mesoscopic F_2 folds of amplitude ranging from several dozen of centimetres to few metres. F_2 axes trend NE–SW, parallel to lineation L_2, with their axial planes dipping gently to the NW or SE. In the exposures located around Stolec and to the west of Kamieniec Ząbkowicki (e.g. exp. 6, 3S), the F_2 folds are recumbent and display distinct NW asymmetry. Their longer limbs dip to the NW, whereas the shorter limbs are slightly inclined to the SE (Fig. 10). In exposures located near to the boundary between the coarse- and fine-grained mica schists (e. g. exp. 8), the F_2 folds are tight or almost isoclinal and their asymmetry is less apparent. The axial cleavage of the F_2 folds is represented by crenulation cleavage S_2. In the longer limbs

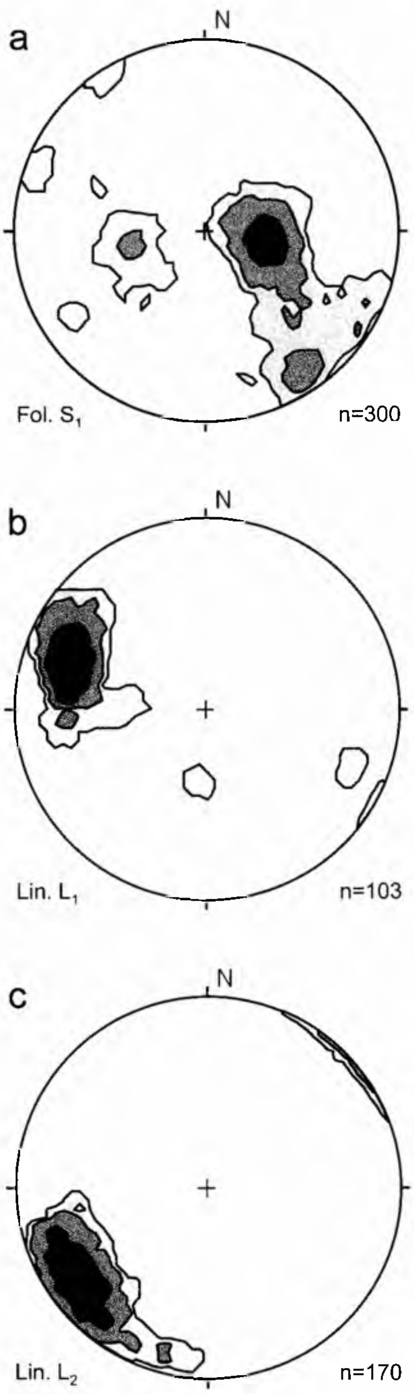


Fig. 7. Synoptic stereograms of foliation S_1, lineation L_1 and lineation L_2 in coarse-grained mica schists from the vicinity of Kamieniec Ząbkowicki. Equal-area net, lower hemisphere. In all stereograms 1, 3 and 12% contours per 1% area. **a** – foliation S_1 (300 measurements, max. 26.3%), **b** – lineation L_1 (103 measurements, max. 48.5%), **c** – lineation L_2 (170 measurements, max. 32.9%)

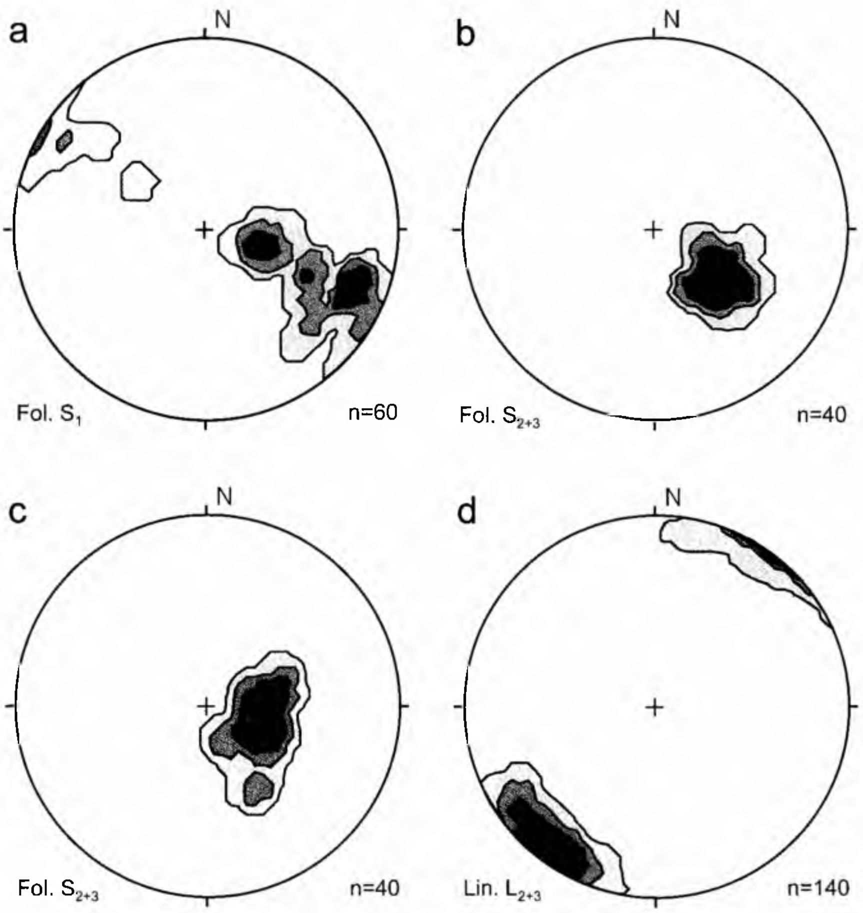


Fig. 8. Attitude of foliation and lineation in mica schists from the vicinity of Stolec. Equal-area net, lower hemisphere. In all stereograms 1, 6 and 12% contours per 1% area. **a** – foliation S_1 in the mica schists from exposures 3S and 6S (60 measurements, max. 23.3%), **b** – foliation S_{2+3} in the mica schists from exposures 1S and 2S (40 measurements, max. 50%), **c** – foliation S_{2+3} in the mica schists from exposure 7S (40 measurements, max. 40%), **d** – lineation L_{2+3} from all exposures (140 measurements, max. 49.2%)

of folds (inclined to NW) the cleavage S_2 dips approximately to the S at a low angle whereas in the shorter limbs (inclined to E or SE) it is dipping towards the N (Fig. 10, 11). Variable dip of the cleavage in the hinges and limbs of asymmetric F_2 folds results from its fan-like orientation. On the contrary, in the hinges of tight or isoclinal F_2 folds, cleavage S_2 displays approximately constant orientation dipping gently to the W or NW, parallel to the axial planes of folds.

Variable orientation of the foliation S_1 (Fig. 5, 7, 8) shows that the F_2 folds reach the size exceeding a scale of individual exposures. Their axes plunge gently to the SW (WSW) or to the NE, comparable to the axes of girdles on foliation stereograms (Fig. 5, 8). The distribution of maxima on foliation S_1 stereograms (Fig. 5, 8) indicates the NW asymmetry of the map-scale F_2 folds, similar to the asymmetry of mesoscopic folds (Fig. 10). The poles to the foliation are clustered in two maxima lying on a great-circle girdle. The two maxima represent planes dipping steeply to the NW and gently to the SE or NW which correspond to the longer and shorter limb of folds, respectively. The NW asymmetry of the F_2 folds is also indicated by geometric re-

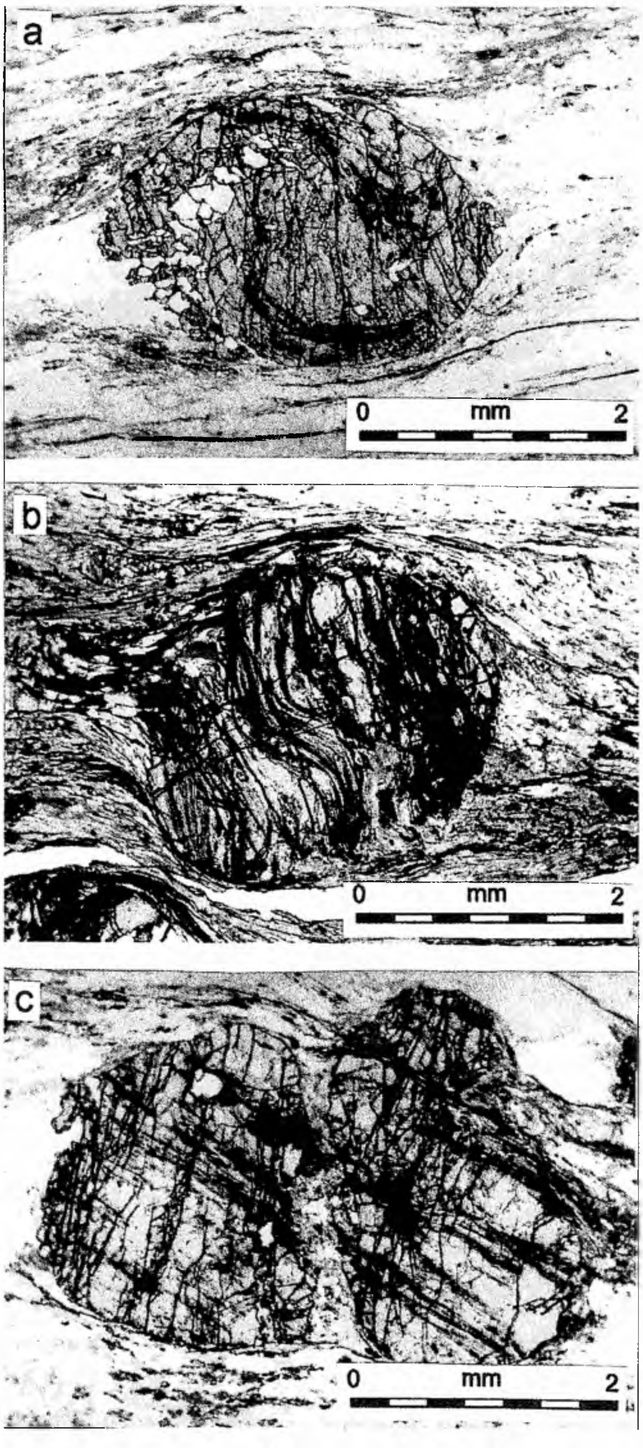


Fig. 9. Shape varieties of inclusion trails in garnet porphyroblasts: **a** – spiral inclusion trails, **b** – sigmoidal inclusion trails, **c** – stright-line inclusion trails

lationship between the foliation S_1 and cleavage S_2. Most localities expose longer NW limbs of the folds (foliation S_1 steeper than cleavage S_2) whereas exposures showing shorter SE limbs (cleavage S_2 steeper than foliation S_1) are less frequent. The two maxima on a stereogram in Figure 11 represent different orientation of cleavage S_2 on the opposite limbs of F_2 folds.

Consecutive stages of development of planes S_2 from crenulation cleavage to new foliation were found in the rocks (Fig. 12). In the coarse-grained variety of schists, the foliation S_1 is deformed by tight symmetric folds with sharp hinges and the amplitude ranging from 1 to 20 mm. Axial planes of these folds correspond to the S_2 crenulation cleavage. The S_2 planes are locally imprinted by parallel alignment of micas (Fig. 12a) but, generally, they do not obliterate the older, S_1, foliation. In contrast, the S_2 planes represent the main penetrative foliation in the fine-grained mica schists. New foliation S_2 is defined in these rocks by alternation of mica and quartz-mica layers and by parallel alignment of individual micas. Mica layers correspond to the cleavage domains whereas relics of the older foliation S_1 are still preserved in quartz-mica laminae (Fig. 12b). In the most strained portions of the fine-grained mica schists the foliation S_1 is preserved only as inclusion trails in porphyroblasts and as isolated hinges of intrafolial folds (Fig. 13). The latter folds represent micro- or mesoscopic isoclinal structures developed due to the deformation of individual quartz laminae. Their axial planes parallel the foliation S_2.

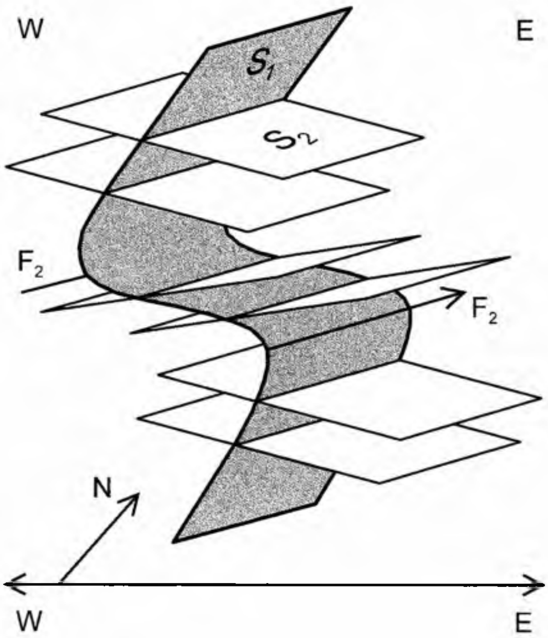


Fig. 10. Geometry of F_2 folds of NW asymmetry and axes trending NE–SW to ENE–WSW. Cleavage S_2 is slightly inclined to SW in steep limbs of folds and to NNW in the shorter, subhorizontal limbs

The penetrative foliation S_2 remains constantly oriented throughout the whole area. It dips consequently to the WNW at a low angle (Fig. 8, 14). It is thus parallel to orientation of F_2 axial planes. On the stereograms (Fig. 11), the transposition foliation S_2 shows no scatter characteristic for the crenulation cleavage in the coarse-grained mica schists.

The lineation L_2 includes stretching lineation defined by alignment of micas and intersection lineation formed in the coarse-grained mica schists by intersection of the foliation S_1 and the cleavage S_2. The orientation of L_2 in the study area is fairly constant (Fig. 7c, 8, 14). The lineation L_2 trends NE–SW or ENE–WSW, approximately parallel to hinges of F_2, and plunge gently to the SW or WSW. There is no difference between the orientation of L_2 in the coarse- and fine-grained mica schists. On the S_1 foliation planes,

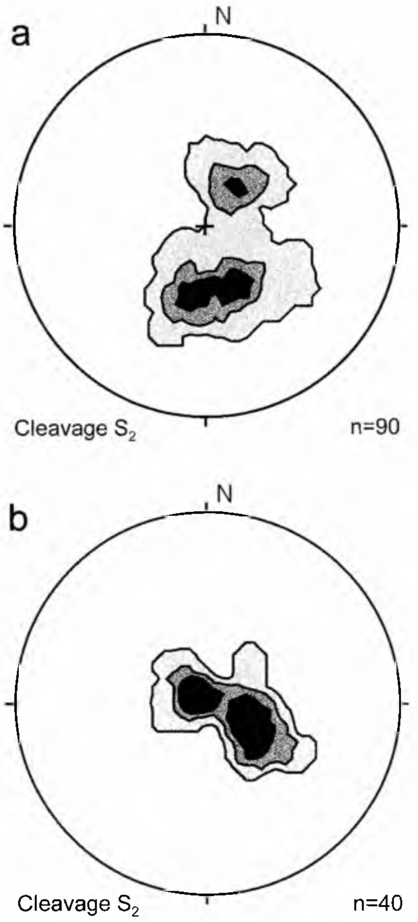


Fig. 11. Attitude of crenulation cleavage S_2 in coarse-grained mica schists. Equal-area net, lower hemisphere. In all stereograms 1, 6 and 12% contours per 1% area. **a** –crenulation cleavage S_2 in the vicinity of Kamieniec Ząbkowicki (90 measurements, max. 17.8%), **b** – crenulation cleavage S_2 in the vicinity of Stolec – exposures 3S and 6S (40 measurements, max. 35%)

lineation L_2 almost entirely obliterates the older lineation L_1. A superposition of both lineations, L_1 and L_2, is visible only locally. The trend of L_1 is usually closer to the E–W direction than that of L_2 lineation.

Numerous garnet porphyroblasts occur in the fine-grained mica schist. Most of them are synkinematic with respect to the D_2 deformation (Fig. 9). The most spectacular evidence for synkinematic development of garnet is provided by porphyroblasts with overgrown crenulations of the S_1 foliation still preserved inside them as inclusion trails (Fig. 15a). In many other porphyroblasts the inclusion trails are spiral (Fig. 9a) or sigmoidal which can also be considered as an evidence for synkinematic growth (Bell *et al.*, 1986) concurrent with the development of the S_2 foliation. On the other hand, structural observations cannot exclude that some garnet crystals represent porphyroclasts grown during the earlier D_1 deformation. First of all, it applies to highly flattened grains of this mineral. Less common plagioclase and staurolite porphyroblasts also developed during the D_2 event. Some of them contain inclusion trails of sigmoidal shape or representing crenulations of older foliation S_1. The garnet porphyroblasts are accompanied by pressure

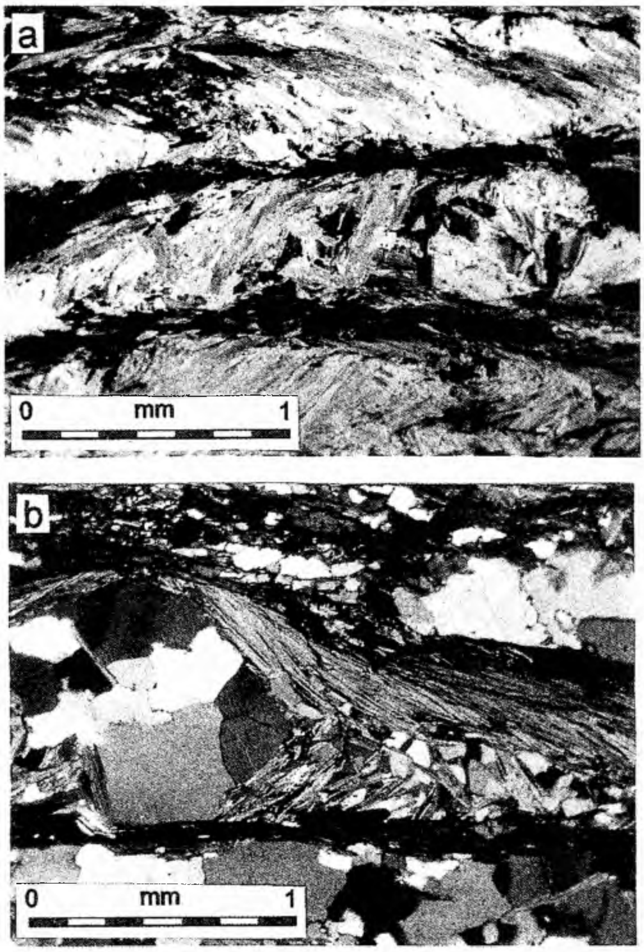


Fig. 12. Foliation S_1 preserved in microlithons between younger foliation planes S_2: **a** – foliation S_2 (horizontal on the photo) developed parallel to axial planes of crenulations of foliation S_1 in coarse-grained schist, **b** – foliation S_1 in fine-grained schist preserved in the hinge of a crenulation micro-fold in foliation S_2 (horizontal on the photo)

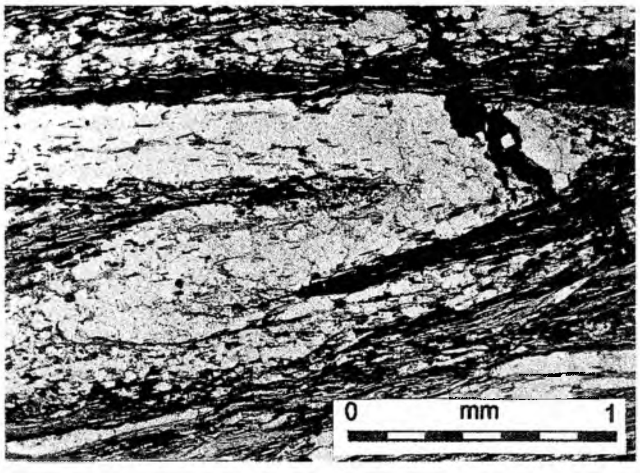


Fig. 13. Intrafolial fold in fine-grained schist. Folded foliation S_1 is preserved between planes of penetrative foliation S_2

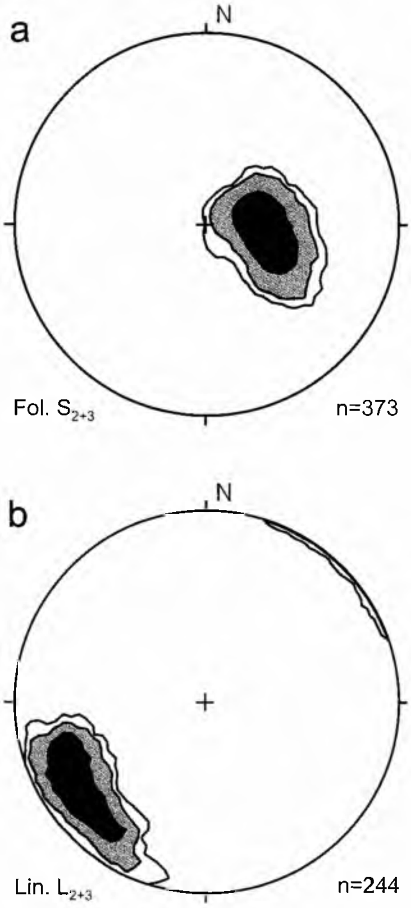


Fig. 14. Attitude of foliation S_{2+3} and lineation L_{2+3} in fine-grained mica schists from vicinities of Kamieniec Ząbkowicki and Byczeń. Equal-area net, lower hemisphere. In both stereograms 1, 3 and 12% contours per 1% area. **a** – foliation S_{2+3} (373 measurements, max. 33.5%), **b** – lineation L_{2+3} (244 measurements, max. 34.0%)

shadows which represent the most common kinematic indicator in fine-grained mica schists. Approximately symmetric pressure shadows indicate that some portions of fine-grained mica schists were subjected to mostly coaxial deformation during the D_2 event. In the mica schists showing approximately symmetric fabric, relics of older foliation S_1 are still preserved as hinges of crenulations between planes of the S_2 foliation (Fig. 12b). They suggest that crenulation cleavage was transformed into the foliation S_2 due to coaxial shortening.

The albite-bearing fine-grained mica schists exposed in the vicinity of Byczeń and to the west of Stolec do not differ structurally from other fine-grained schists. Essentially different is, however, the synkinematic mineral assemblage related to the D_2 deformation event in these rocks. The most important component of this assemblage is represented by numerous albite porphyroblasts (Fig. 4). They often contain sigmoidal inclusion trails suggesting synkinematic growth, contemporaneous with the development of penetrative S_2 foliation. On the other hand, few garnet grains, up to 2 mm across, display features of porphyroclasts and they probably crystallised during the previous D_1 event.

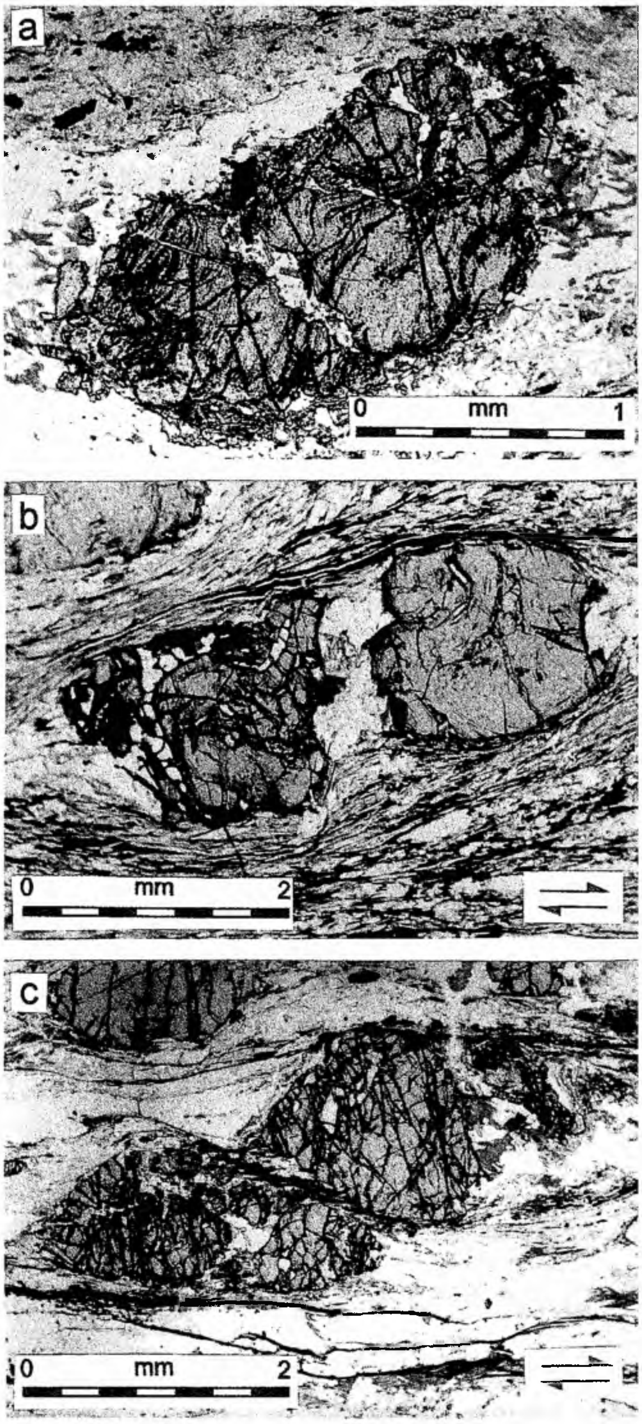
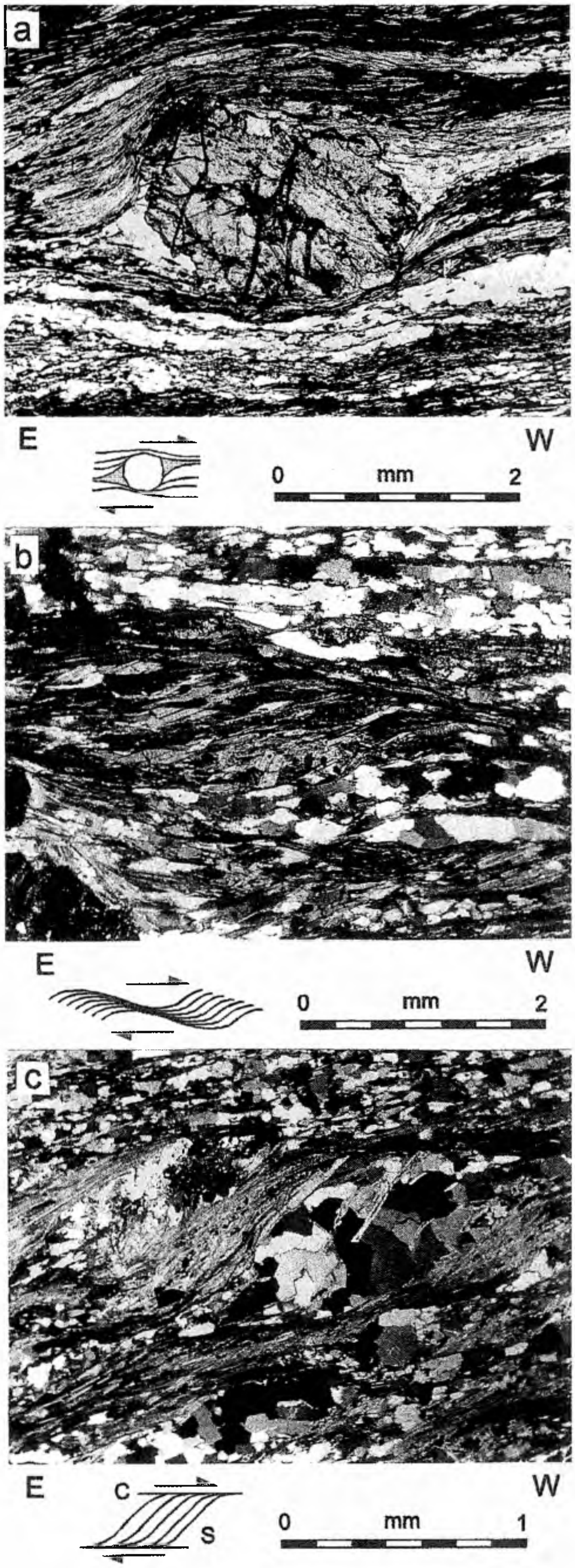


Fig. 15. Garnet porphyroclasts subjected to the brittle deformation D_3. Displaced fragments of broken porphyroclasts indicate a top-to-SW sense of shear in (**b**) and (**c**). **a** – small crenulations of the S_1 foliation, developed during the D_2 deformation, are preserved in the broken porphyroclast, **b** – synkinematic quartz and biotite occur between two stretched parts of broken porphyroclast, **c** – synkinematic biotite concentrates along the shear plane cross-cutting the porphyroclast

Deformation D_3

Most of the fine-grained mica schists recorded the effects of non-coaxial shearing along S_3 planes essentially

Fig. 16. Examples of kinematic indicators related to the D_3 deformation in the mica schists from the vicinity of Kamieniec Ząbkowicki. In all three cases sense of shear is top-to-SW along the S_{2+3} foliation: **a** – asymmetric pressure shadows around garnet porphyroblast in fine-grained mica schist (Kamieniec unit), **b** – extensional crenulation cleavage in fine-grained mica schist (Kamieniec unit), **c** – S-C structure in albite-bearing mica schist (Byczeń unit)



parallel to foliation S_2. Distinctly asymmetric garnet pressure shadows (Fig. 16a), S-C fabric (Fig. 16c) and extensional crenulation cleavage (Fig. 16b) indicate a top-to-SW or to-WSW sense of shear. The stretching lineation L_3, defined by micas on the S_{2+3} foliation, plunges to the WSW (Fig. 8d, 14b) and is parallel to the lineation L_2. In general, a contribution of non-coaxial shear to the total strain of the fine-grained mica schists, as expressed by the degree of fabric asymmetry, increases eastwards towards the contact with the albite-bearing schists. In the latter rocks an opposite trend is evident – a westward increase of non-coaxial component towards the boundary with the staurolite and garnet bearing mica schists.

The non-coaxial deformation D_3 has modified the older symmetric fabric of the fine-grained mica schists, developed during the D_2 event (Fig. 15). The foliation S_{2+3} was reactivated by non-coaxial shear within D_3 shear zones. Structural observations in the fine-grained schists displaying clearly asymmetric fabric show that some garnet and plagioclase crystals, which had grown during the D_2 event, were subsequently converted into porphyroclasts by the D_3 shearing. These grains are fractured and their fragments displaced along the S_{2+3} foliation planes (Fig. 15b, c). At the same time, a reactivation of the S_{2+3} planes during the D_3 event led to a complete destruction of the S_1 relics. The only traces of the older foliation S_1 are in these rocks represented by inclusion trails, conserved in the D_2 porphyroblasts. An intense modification of the D_2 fabric in the zones of non-coaxial D_3 shear is indicated by relics of the S_2 crenulation cleavage in pressure shadows of garnet porphyroclasts enveloped by penetrative foliation S_3. Further evidence for the superimposed D_3 non-coaxial deformation is provided by the presence of microscopic shear zones which developed parallel to the S_2 crenulation cleavage. Relics of crenulated foliation S_1 are still well-visible outside these shear zones whereas they are entirely transposed into a new foliation, S_3, within zones of the D_3 shear. Superposition of non-coaxial D_3 deformation on the pre-existing crenulation cleavage is also manifested by anastomosing D_3 shear zones enclosing lensoidal microlithons with crenulated relics of S_1. Foliation planes S_1 are deformed in those places into asymmetrical microfolds of sigmoidal shape.

A characteristic component of both the coarse- and fine-grained varieties of mica schists are andalusite porphyroblasts (Fig. 17). They are lacking only in the albite-bearing mica schists. In the coarse-grained schists, andalusite always forms postkinematic porphyroblasts. They usually contain inclusion trails parallel to the foliation S_{2+3} or deformed into small crenulations similar to those which are visible in the surrounding rock (Fig. 17a). In places, postkinematic andalusite has grown in cracks within broken garnet grains (Fig. 17b). Postkinematic porphyroblasts of andalu-

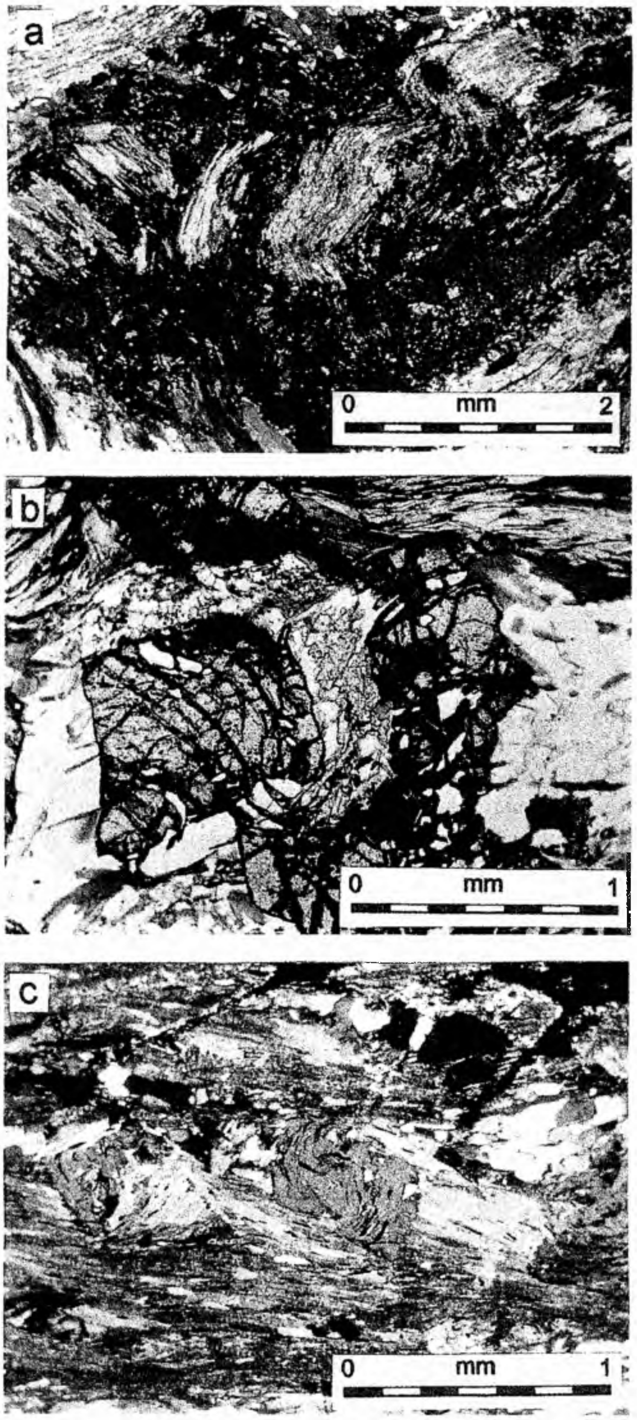


Fig. 17. Andalusite in mica schists (Kamiemiec unit): **a** – small crenulations of foliation, developed during the D_2 deformation, preserved in the postkinematic andalusite porphyroblast from coarse-grained schists, **b** – postkinematic andalusite in the crack of garnet grain from coarse-grained schists, **c** – spiral inclusion trails in the synkinematic andalusite porphyroblasts developed during the D_3 deformation in fine-grained schists

site are also present in the fine-grained schists showing a symmetric D_2 fabric. On the other hand, synkinematic andalusite crystals occur in the fine-grained mica schists characterised by the asymmetric D_3 fabric (Fig. 17c).

ANALYSIS OF QUARTZ <c> AXIS ORIENTATION

Information provided by quartz <c> axis analysis is consistent with the structural data presented above. Quartz <c> axis patterns obtained in the coarse-grained mica schists from the vicinities of Kamieniec Ząbkowicki (Fig. 18) represent three basic types of scatter: (1) single girdle inclined to foliation, (2) (I) type of crossed girdles (Schmid & Casey, 1986) or small circles centred around the poles to foliation S_1 and (3) isotropic scatter. A single girdle is usually interpreted to be result of the simple shear (Schmid & Casey, 1986). Inclination of the girdle to foliation (Fig. 18a, b) indicates a top-to-E sense of shear. Such kinematics is characteristic of the D_1 deformation responsible for the development of the S_1 foliation. It seems that the D_1 quartz fabric in the coarse-grained schist might partly avoid later modification. (I) type of crossed girdles (Fig. 18c, d) and two small circles patterns (Fig. 18e) indicate a coaxial deformation: pure shear and coaxial flattening, respectively (Schmid & Casey, 1986). Coaxial deformation recorded by quartz fabric in most samples is probably related to the D_2 event and the development of crenulation cleavage S_2. An isotropic scatter (Fig. 18f) obtained in the well-foliated mica schist suggests post-deformation static recrystallisation.

Quartz <c> axis patterns from the fine-grained mica schists represent two basic types: (1) single girdle inclined to the foliation (Fig. 19a–d) and (2) (I) type of crossed girdles (Fig. 19g–i). Transitional patterns between these two end members were also found (Fig. 19e, f). An inclination of single girdles (Fig. 19a–d) persistently indicates a top-to-SW or top-to-WSW sense of shear. The single girdles probably represent quartz fabric produced by the D_3 simple shear, whereas the crossed girdles show symmetric fabric developed due to the coaxial D_2 event.

Quartz <c> axis patterns obtained in the mica schists from the vicinities of Stolec (Fig. 20) conform to the same rules as those described above, for the schists exposed around Kamieniec Ząbkowicki. Quartz <c> axis diagrams display an entire spectrum of transitional patterns from a single girdle inclined to foliation to (I) type of crossed girdles (Fig. 20). Some diagrams (Fig. 20d, e) show a distinct tendency to scatter along two small circles around the poles to foliation. Quartz <c> axis analysis indicates that total strain of the mica schists from the vicinity of Stolec involved two main components: simple shear and coaxial strain ranging between pure shear and general flattening. Both components are superimposed in various proportions. Some diagrams (Fig. 20a, b) show patterns representative for a strain very close to a simple shear, whereas others (e.g. Fig. 20e) demonstrate almost symmetric scatter typical of pure shear. An inclination of single girdles with respect to the foliation, indicates a top-to-SW sense of simple shear. Therefore, quartz fabric in mica schists from the vicinity of Stolec presumably developed due to superposition of the D_2 coaxial and the D_3 non-coaxial deformations.

Most samples from all varieties of mica schists yielded quartz <c> axis patterns characterised by maxima located near the centre of diagram. Such patterns are usually interpreted to be indicative of deformation under the conditions

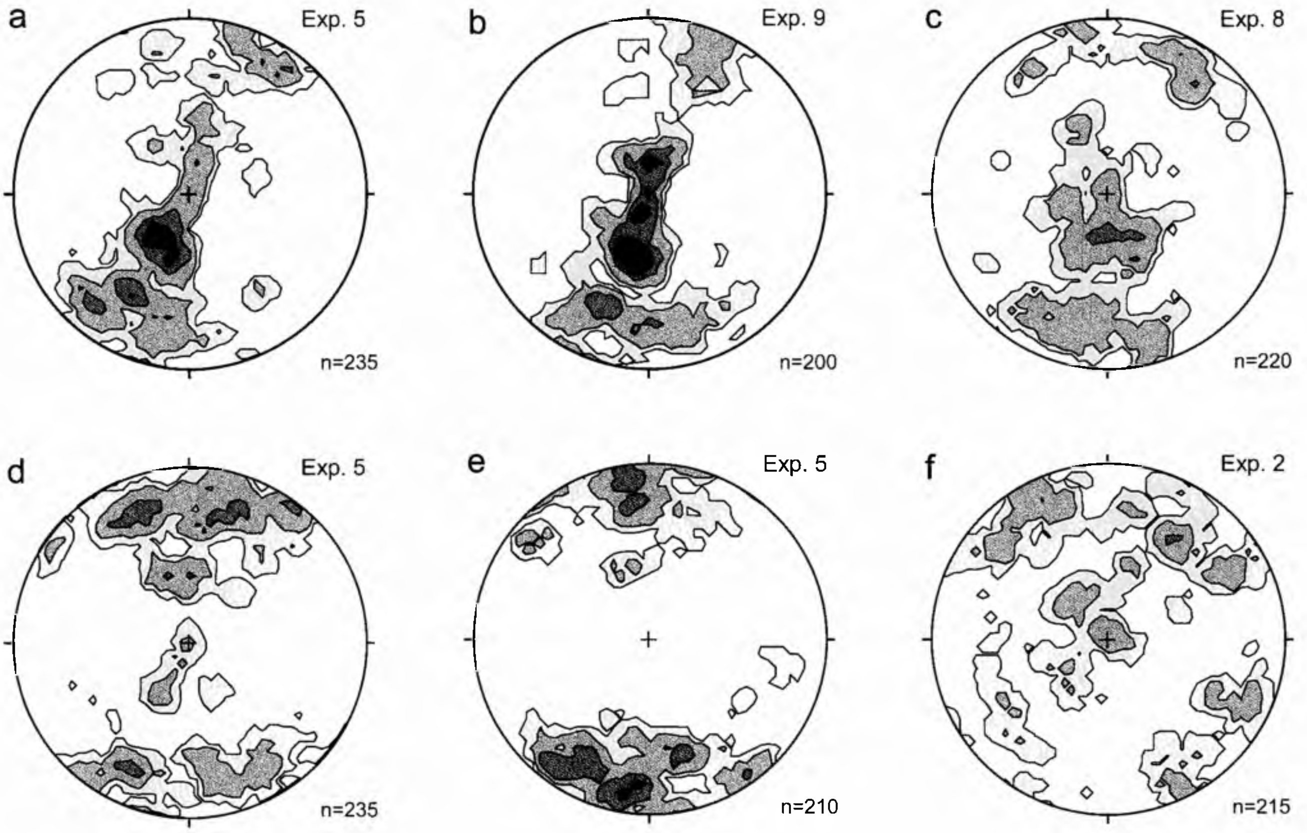


Fig. 18. Representative examples of quartz c-axis patterns in coarse-grained mica schists from vicinities of Kamieniec Ząbkowicki. Equal-area net, lower hemisphere. Density contours at 2% intervals. Projection plane is XZ plane of strain ellipsoid. Attitude of foliation corresponds to a plane perpendicular to the figure. Lineation (parallel to X axis of strain ellipsoid) trends parallel to the figure. **a, d, e** – exposure 5; **b** – exposure 9; **c** – exposure 8; **f** – exposure 2

of the upper greenschist or amphibolite facies (Schmid & Casey, 1986). This corollary is confirmed by composition of mineral assemblages which are in the mica schists synkinematic with D_1–D_3 events.

DISCUSSION

The effects of the deformation D_1 are preserved in the coarse-grained mica schists. The foliation S_1 represents the main planar structures in these rocks, whereas the lineation L_1 is almost entirely obliterated by younger lineation L_2. Kinematic indicators suggest that the foliation S_1 was produced by non-coaxial shearing. A restoration of the original direction of shear is difficult due to reorientation of the stretching lineation L_1 on limbs of F_2 folds (Fig. 5c). Assuming that the foliation S_1 had been subhorizontal before the D_2 event, the incipient orientation of L_1 was E–W. If this reasoning is correct, the kinematic indicators recorded a top-to-E sense of shear during the D_1 deformation.

The chemical composition of minerals that define the foliation S_1 in the coarse-grained mica schists, together with the composition of synkinematic garnet porphyroblasts in these rocks, indicate that the deformation D_1 took place under upper amphibolite facies conditions (Józefiak, 1996). The temperatures calculated by Józefiak using garnet-biotite geothermometer (Ferry & Spear, 1978; Hodges & Spear, 1982; Ganguly & Saxena, 1984) are within the range of 570–640°C (Józefiak, 1996). Pressure estimated for the D_1 event using GASP (Hodges & Crowley, 1986; Koziol & Newton, 1988) and GMBP (Hoisch, 1990) geobarometers ranges between 8 and 13 kbars. High magnitude of pressure calculated by Józefiak for the coarse-grained mica schists, which included intercalations of eclogites (Achramowicz *et al.*, 1997), indicated a continuous transition from eclogite to amphibolite facies at the onset of the D_1.

The foliation S_1 was deformed during the D_2 event by F_2 folds of the NW asymmetry (Fig. 10). Folds facing the dip direction of the main foliation suggest that the whole rock series in the vicinities of Kamieniec Ząbkowicki and Stolec represents the overturned limb of a F_2 megafold. The same is indicated by the cleavage S_2 of shallower attitude than that of foliation S_1 on the steeper, longer limbs of F_2 folds. Kinematic indicators show that the development of the F_2 folds together with their axial cleavage S_2 was accompanied by coaxial deformation. Quartz <c> axis patterns recorded strain in the field of general flattening or close to pure shear. The lineation L_2 was formed due to coaxial stretching and by intersection of the S_1 foliation and the S_2 cleavage. It parallels axes of F_2 folds which trend NE–SW or ENE–WSW.

A transition from the coarse- to fine-grained mica schists is related to the conversion of cleavage S_2 into the main foliation of the rock. The new foliation S_2 is defined

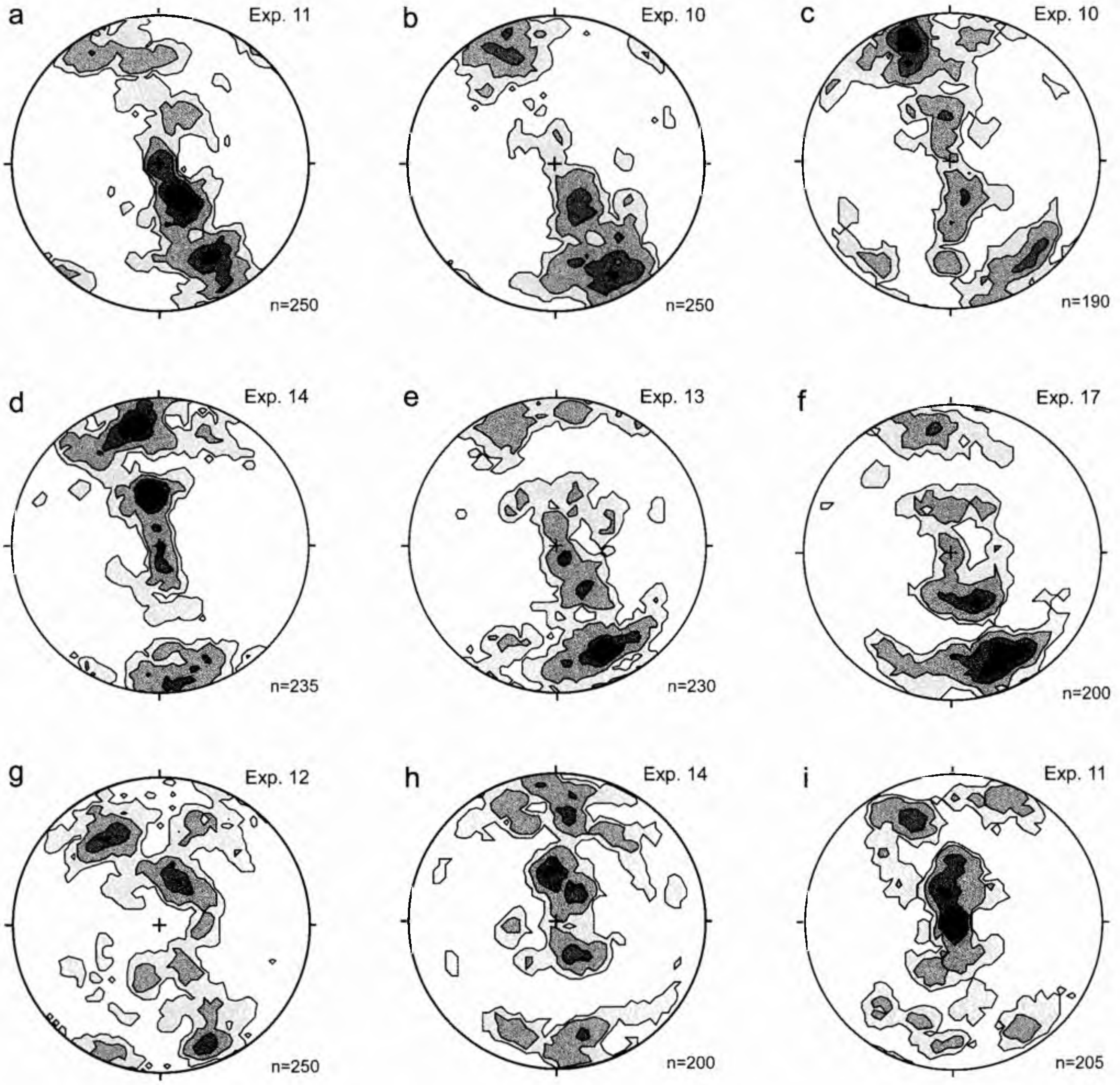


Fig. 19. Representative examples of quartz c-axis patterns in fine-grained mica schists from vicinities of Kamieniec Ząbkowicki. Equal-area net, lower hemisphere. Density contours at 2% intervals. Projection plane is XZ plane of strain ellipsoid. Attitude of foliation corresponds to a plane perpendicular to the figure. Lineation (parallel to X axis of strain ellipsoid) trends parallel to the figure. **a, i** – exposure 11; **b, c** – exposure 10; **d, h** – exposure 14; **e** – exposure 13; **f** – exposure 17; **g** – exposure 12

by mica and quartz-mica layers developed due to increasing strain. Therefore, the coarse-grained mica schists must represent a less strained zone of the rock sequence which is characterised by the D_1 fabric not obliterated by the D_2 structures. On the contrary, the fine-grained schists were subjected to a relatively higher strain during the D_2 event. Consequently, the differentiation of mica schists into the coarse- and fine-grained varieties reflects variable intensity of the D_2 strain within the same complex. Increasing strain resulted in a more uniform attitude of the foliation S_2 in comparison to that of the S_2 crenulation cleavage.

The chemical composition of minerals synkinematic with reference to the D_2 event, suggests a deformation under lower amphibolite facies conditions (Józefiak, 1996). The temperatures calculated using the garnet-biotite geothermometer (Ferry & Spear, 1978; Hodges & Spear, 1982; Ganguly & Saxena, 1984) are in the range of 510–540°C, whereas the pressure estimated on the basis of GASP (Hodges & Crowley, 1986; Koziol & Newton, 1988) and GMBP (Hoisch, 1990) geobarometers ranges between 7 to 8.5 kbar (Józefiak, 1996). The chemical zonation of garnet porphyroblasts in the fine-grained schists, except for the albite-bearing schists, indicates an increase in temperature during the D_2 event.

The deformation D_3 is confined mainly to shear zones, developed in the fine-grained mica schists. These zones are

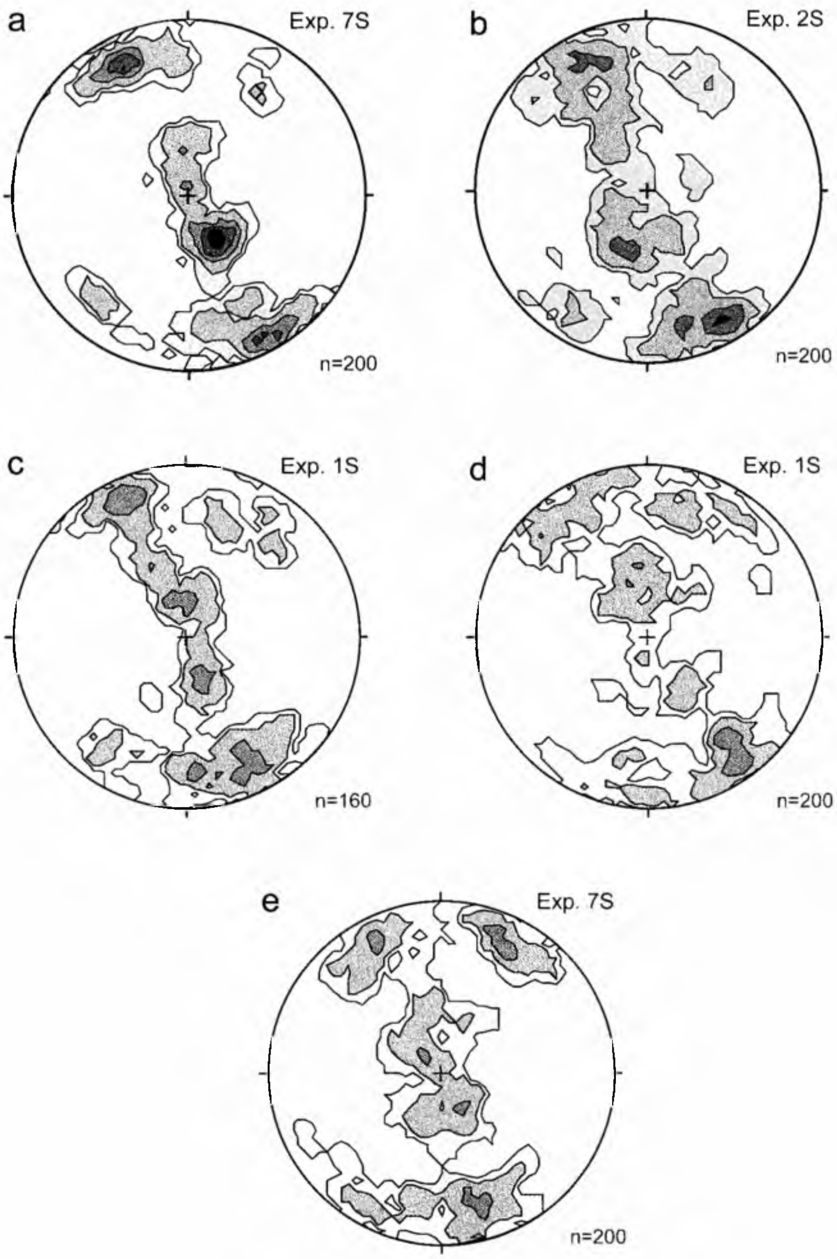


Fig. 20. Representative examples of quartz c-axis patterns in mica schists from vicinities of Stolec. Equal-area net, lower hemisphere. Density contours at 2% intrvals. Projection plane is XZ plane of strain ellipsoid. Attitude of foliation corresponds to a plane perpendicular to the figure. Lineation (parallel to X axis of strain ellipsoid) trends parallel to the figure. **a, e** – exposure 7S; **b** – exposure 2S; **c, d** – exposure 1S

characterised by a top-to-WSW sense of shear. Deformation D_3 was accompanied by significant decrease of pressure. The occurrence of andalusite indicates decompression from 7–8 kbar during the D_2 to 2–4 kbar during the D_3 deformation. The latter event took place under still relatively high temperature, exceeding 500°C. This suggests very rapid exhumation of the whole rock complex. Only local synkinematic chlorite documents temperature retrogression during the late phase of the D_3 event.

There is a distinct contrast of mineral composition between (1) the coarse- and fine-grained mica schists with staurolite and garnet porphyroblasts and (2) the albite-bearing mica schists. This difference partly reflects the contrast in bulk chemical composition of both rock types (Tab. 2) since the albite-bearing schists are less oversaturated in alumina. On the other hand, the observed difference in mineral composition points to a lower metamorphic grade of albite-bearing schists. During the D_1 event they were metamorphosed under conditions transitional between those of greenschist and amphibolite facies, as indicated by large amount of spessartine component (Spe_{27}) in scarce garnet porphyroclasts. The contrast of metamorphic grades between the two varieties of mica schists, apparent during the D_1 deformation, is less evident during the D_2 and D_3 events. The crystallization of albite porphyroblasts in the plagioclase-rich mica schists during the D_2 deformation could have taken place under the conditions comparable to those calculated for the fine-grained mica schists with staurolite and abundant garnet (510–540°C). The development of albite was possible under temperatures exceeding 500°C, since the relatively high pressure of about 8 kbars enlarged a stability field of this mineral phase. Rapid decompression during the D_3 event probably resulted in the growth of small oligoclase grains (20–24% An) which accompanied albite porphyroblasts in the albite-bearing schists. The presence of oligoclase suggests the temperatures still exceeding 500°C during the D_3 deformation, similarly to the temperatures recorded from other varieties of mica schists.

Two large tectonic units were distinguished in the study area, based on the contrasts in metamorphic grade and lithology difference: the Kamieniec unit (higher grade) and the Byczeń unit (lower grade). The boundary between the two units is located to the west of Byczeń (Fig. 2) and continues northward into the vicinity of Stolec (Fig. 3), west of the Wapienna Hill. This boundary is not directly visible in the field, but exposures of mica schists showing contrasting metamorphic grades occur not further apart from each other than a few tens of metres. Therefore, a tectonic character of the contact is inferred for the distinguished units. The results of preliminary investigations (Leszczyński, 1995) suggest that both the Kamieniec and Byczeń units continue northward to the vicinities of Niemcza (Fig. 1). The majority of rocks of the northern segment of the Kamieniec Metamorphic Complex probably belongs to the Byczeń unit.

The Kamieniec unit crops out to the west of the Byczeń unit, between Kamieniec Ząbkowicki and Byczeń (Fig. 2). The foliation dips generally to the west there (Fig. 14), so

Table 2

Representative chemical analyses of mica schists containing staurolite and andalusite and mica schist having albite porphyroblasts

Sample	A1166	F1202	F1208	F1209	F1217	F1243	A1167	F1204	F1221	F1232	F1241	F1247	F1224	L1328	L1333	L1357
	c.g.	c.g.	c.g.	c.g.	c.g.	c.g.	f.g.	f.g.	f.g.	f.g.	f.g.	f.g.	a.f.g.	a.f.g.	a.f.g.	a.f.g.
SiO_2	69.20	61.63	65.23	56.60	68.23	63.21	62.33	60.96	65.78	65.64	67.02	68.34	65.12	66.63	66.82	68.16
TiO_2	0.73	0.80	0.60	1.04	0.76	0.89	1.02	0.97	0.71	0.75	0.91	0.68	0.70	0.49	0.54	0.48
Al_2O_3	14.71	21.52	15.90	22.59	16.44	18.21	19.05	21.07	17.96	17.33	14.51	14.90	15.47	16.26	16.36	15.72
Fe_2O_3	0.03	0.28	1.40	1.83	0.68	1.39	3.87	2.22	0.05	1.71	1.81	3.07	3.84	0.61	0.05	0.67
FeO	2.54	4.68	7.01	5.34	3.77	4.32	2.32	4.10	5.65	4.24	4.06	3.95	2.37	4.28	4.40	3.99
MnO	0.07	0.11	0.22	0.24	0.14	0.09	0.26	0.26	0.34	0.13	0.31	0.40	0.08	0.04	0.04	0.04
MgO	3.78	1.56	1.75	2.08	1.31	1.96	1.67	1.84	1.56	1.43	2.06	1.75	1.64	2.03	1.90	1.82
CaO	1.14	1.11	1.25	0.92	1.24	0.95	0.97	0.78	1.01	0.83	0.80	0.78	1.46	1.62	2.08	1.40
Na_2O	2.95	0.94	1.16	1.42	1.51	1.25	0.76	0.85	1.20	1.54	1.49	0.95	3.09	2.67	3.49	2.65
K_2O	2.89	4.22	3.44	4.67	3.52	4.25	3.80	3.82	3.33	4.15	3.74	3.01	3.09	2.94	2.90	3.54
P_2O_5	0.15	0.18	0.10	0.10	0.16	0.09	0.09	0.08	0.14	0.11	0.17	0.13	0.17	0.12	0.14	0.11
H_2O	1.39	2.73	1.59	2.89	1.98	2.57	3.40	2.80	2.04	1.99	3.31	2.32	3.20	2.06	1.08	1.23
total	99.77	99.76	99.65	99.72	99.74	99.18	99.73	99.75	99.77	99.85	100.19	100.28	100.23	99.75	99.80	99.81
Q	32.29	33.51	35.95	23.21	40.28	33.61	40.60	36.22	38.38	35.52	38.65	46.35	31.09	30.75	25.28	31.10
Or	17.41	25.73	20.75	28.53	21.30	26.02	23.38	23.31	20.16	25.09	22.84	18.18	18.84	17.42	17.18	20.97
Ab	25.40	8.19	10.00	12.40	13.06	10.94	6.68	7.41	10.38	13.30	13.00	8.20	26.92	22.65	29.59	22.47
An	4.77	4.47	5.66	4.04	5.23	4.27	4.40	3.46	4.20	3.48	2.96	3.09	6.33	7.27	9.42	6.24
C	5.10	14.23	8.38	14.20	8.45	10.38	12.61	14.75	11.12	9.24	7.18	9.15	4.93	6.04	4.04	5.26
Hy	13.25	11.48	15.80	12.61	8.83	10.74	4.34	9.46	14.00	9.14	10.50	8.89	4.40	11.71	11.99	10.61
en	9.63	4.02	4.46	15.37	3.35	5.07	4.34	4.75	3.99	3.65	5.32	4.47	4.23	5.07	4.74	4.54
fs	3.62	7.46	11.34	7.24	5.48	5.66	0.00	4.71	10.01	5.48	5.19	4.42	0.17	6.64	7.25	6.06
Mt	0.04	0.42	2.07	2.74	1.01	2.09	5.58	3.32	0.07	2.53	2.71	4.54	5.74	0.89	0.07	0.97
Il	1.41	1.57	1.16	2.04	1.48	1.75	2.02	1.90	1.38	1.46	1.79	1.32	1.37	0.93	1.03	0.91
Ap	0.33	0.41	0.22	0.23	0.36	0.20	0.20	0.18	0.31	0.25	0.38	0.29	0.38	0.28	0.32	0.26

Mica schists containing staurolite and andalusite: c.g. – coarse-grained, f.g. – fine-grained, a.f.g. – albite-bearing fine-grained mica schist. Samples L1328, L1333 and L1357 were collected north of Niemcza in the vicinities of Księgienice Wielkie (presented after Leszczyński, 1995).

that the Kamieniec unit probably overlies the Byczeń unit in that area. An opposite situation is encountered in the vicinity of Stolec, where the Byczeń unit is interpreted to overlie the Kamieniec unit, exposed more to the east (Fig. 3). In general, the Kamieniec unit recorded an increase of temperature (D_2 event) and a higher metamorphic grade during the D_2 and D_3 deformations and, thus, probably underlies the Byczeń unit. Such a tectonic sequence, actually observed in the vicinity of Stolec, is interpreted here, as a result of the F_2 folding. On the other hand, the outcrop pattern between Kamieniec Ząbkowicki and Stolec may represent an intersection effect caused by (1) N–S trending brittle normal fault dipping steeply to the east (Behr, 1926; Baraniecki, 1956) or (2) low-angle normal shear-zone dipping to WSW. The latter interpretation, preferred by the present authors, is in agreement with the observed increase in the intensity of D_3 simple shear deformation towards the contact of the Kamieniec and Byczeń units. The simple shear strain is related to the development of ductile D_3 shear zone occurring at the boundary of both units (Fig. 21). This shear zone is parallel to the foliation S_{2+3}, which dips to the WSW at an angle of 20°. A normal-slip top-to-WSW sense of shear, along the L_3 lineation, is defined by numerous kinematic indicators.

A ductile shear zone which represents the boundary of the Kamieniec and Byczeń units to the west of Byczeń, is less inclined than the primary tectonic contact of these both units formed during the D_1 event (Fig. 21c). Therefore, a fragment of the Kamieniec unit is inferred to have been displaced to the WSW on the hanging wall of the normal-slip D_3 shear zone, above the Byczeń unit (Fig. 21b). The horizontal amplitude of this translation inferred from a geological map, probably exceeds 5 km. A later erosional exhumation resulted in exposing the Kamieniec unit on the hanging wall of the D_3 shear zone to the west of Byczeń (Fig. 21b). The primary contact of the Kamieniec and Byczeń units within its foot wall is now hidden under Cenozoic sediments east of Byczeń (Fig. 21c). The same contact is exposed within the hanging wall more to the north in the vicinities of Stolec (Fig. 21a).

The results of our investigations allow us to update the preliminary interpretation by Mazur & Puziewicz (1995a, b) and by Mazur *et al.* (1995), who considered the L2 lineation in the mica schists of the Kamieniec Ząbkowicki Metamorphic Complex as a structure produced exclusively by non-coaxial shearing. On the other hand, the present study confirms earlier data of several authors, according to which the D3 deformation concentrated in low-angle shear zones characterised by a normal top-to-WSW or to-SW sense of shear. Results of our study are in agreement with earlier observations by Dziedzicowa (1985, 1987), who proved that the oldest S1 foliation in the Kamieniec Metamorphic Complex is very steep and involved into F2 folds with subhorizontal axial planes. Axial cleavage S2 of these folds obliterates, in places, the older foliation S1 and contributes to the formation of the L2 lineation due to intersection of S1 and S2 planes (Dziedzicowa, 1985, 1987). The existence, in the study area, of normal-slip shear zones with a top-to-WSW kinematics and of east-vergent thrusts is confirmed by the work of Achramowicz *et al.* (1997), in spite of different interpretation presented in that paper. Our investigations do not comply, however, with data by Cymerman and Piasecki (1994) who postulated the dominant role of the NE-directed thrusting in the eastern part of the Fore-Sudetic block.

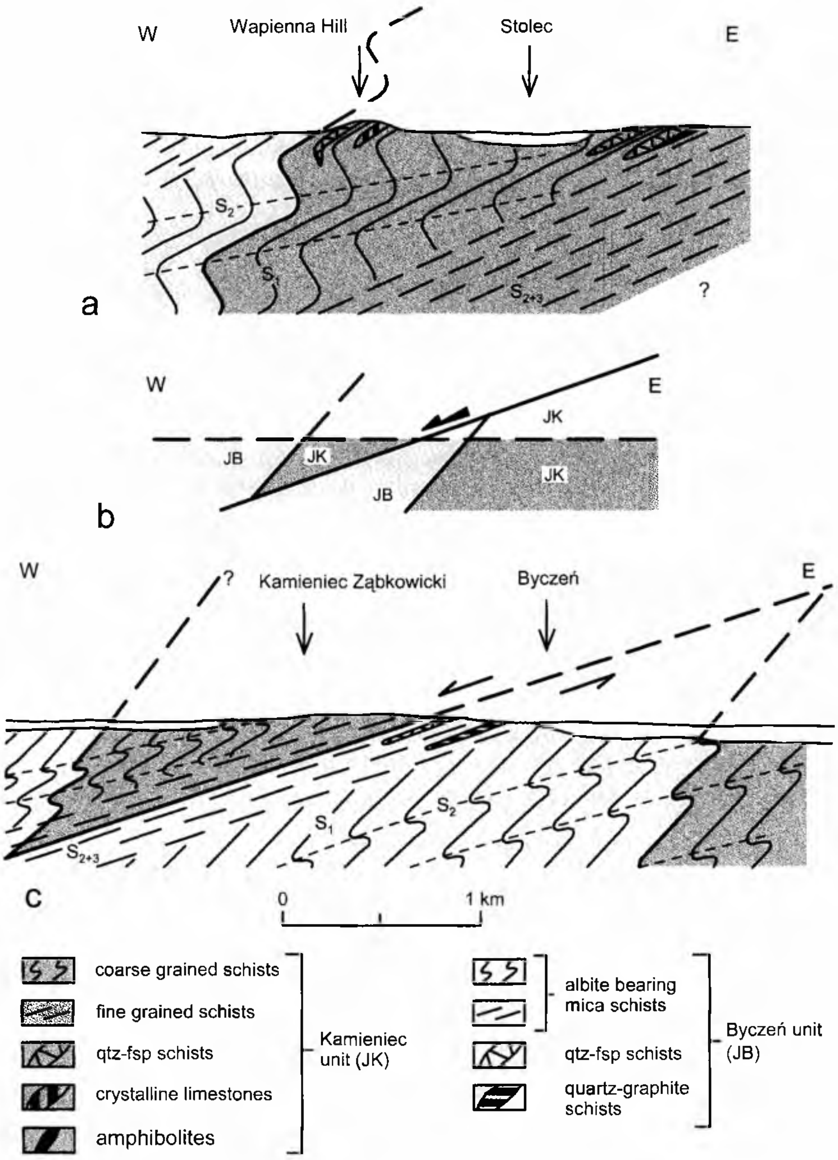


Fig. 21. Generalized sections across the contact zone between Kamieniec (JK) and Byczeń (JB) units. **a** – cross-section through the vicinity of Stolec, **b** – schematic diagram explaining the outcrop map-pattern between Kamieniec Ząbkowicki and Byczeń, **c** – cross-section in the vicinity of Kamieniec Ząbkowicki

TECTONIC EVOLUTION OF METAMORPHIC SERIES BETWEEN THE GÓRY SOWIE AND NIEDŹWIEDŹ MASSIFS

The observations from southern part of the Kamieniec Ząbkowicki Metamorphic Complex, complete earlier data from the Niemcza Zone and the Doboszowice Metamorphic Complex (Mazur & Puziewicz, 1995a, b; Mazur *et al.*, 1995; Mazur *et al.*, 1997; Puziewicz & Rudolf, 1998; Puziewicz *et al.*, 1998). They allow us to formulate the preliminary hypothesis explaining the structure and evolution of the metamorphic series between the Góry Sowie Massif and Niedźwiedź Massif (Fig. 22). The deformation D1, whose effects are preserved in the coarse-grained mica schists, is equivalent to the deformation described as D1 by Mazur & Puziewicz (1995b) in the Chałupki paragneiss (Fig. 22). The D1 deformation in both areas took place under retrogression of metamorphism from the upper to lower amphibolite facies and was probably related to a top-to-E shearing. On the other hand, the coaxial D2 deformation of mica schists is equivalent to the deformation recorded by the Doboszowice orthogneiss (Fig. 22). This granite intrusion, recently dated at ca. 380 Ma (A. Kröner – pers. com.), was transformed into an orthogneiss due to deformation comprising mainly a coaxial component. The significance of non-rotational strain is additionally documented by lately published quartz <c> axis analyses (Czapliński *et al.*, 1996; Bartz, 1997). The deformation of the Doboszowice orthogneiss included as well, a component of a top-to-NE simple shear (Mazur & Puziewicz, 1995b). In contrast, no effect of this non-coaxial D2 shear is recorded in mica schists from vicinities of Kamieniec Ząbkowicki. Apart from fine-grained mica schists, the results of the D_3 event are also recorded by the Lipniki late tectonic granite. The Lipniki intrusion was deformed in a low-angle normal shear zone characterised by a top-to-WSW sense of shear (Mazur *et al.*, 1997). The D_3 event involved, as well, the development of the Niemcza Zone which represented a sinistral strike-slip shear zone of regional scale (Mazur & Puziewicz, 1995a, b). A sinistral shear along the subvertical Niemcza Zone was accompanied, according to Mazur and Puziewicz (1995a, b), by a top-to-WSW or top-to-SW normal shear on the shallow dipping S_{2+3} foliation in the mica schists from southern part of the Kamieniec Ząbkowicki Complex.

Our data indicate that the mica schists of the Kamieniec Ząbkowicki Metamorphic Complex are exposed on the shorter limb of an asymmetric F_2 megafold. On the other hand, the Chałupki paragneiss is exposed on the longer limb of the same fold (Fig. 23). The mesofolds in the paragneiss show SE asymmetry, i. e. opposite to the asymmetry of mesofolds in the mica schists. Their axial cleavage, S_2, is steeper than the foliation S_1 (Mazur & Puziewicz, 1995b; Mazur *et al.*, 1995). Both limbs of the F_2 megafold define an asymmetric synform, overturned to the SE, with a NE–SW trending subhorizontal axis (Fig. 23). In the hinge of this synform there occur the Doboszowice orthogneiss, preliminary interpreted as a syntectonic intrusion (Mazur & Puziewicz, 1995b). In the west, the strike-slip Niemcza Zone separates the overturned limb of the F_2 megafold from the Góry Sowie Massif (Fig. 23).

The reconstruction of the F_2 synform allows the structural position to be determined for the three tectonic units exposed in the study area (Fig. 22). From bottom to top, these are: (1) Byczeń unit, (2) Kamieniec unit and (3) Chałupki unit (paragneisses and amphibolites). They represent a pre-D_2 stack of thrust sheets characterised by tectonic inversion of metamorphic grade. The two upper thrust sheets (Kamieniec and Chałupki units) represent a higher metamorphic grade (upper amphibolite facies) than the lowermost, Byczeń, unit (lower amphibolite facies). On the other hand, the Kamieniec and Chałupki units differ in the maximum values of temperatures recorded during the early phase of metamorphism. The uppermost, Chałupki unit comprises granulites metamorphosed under the temperature reaching up to 920°C (Achramowicz *et al.*, 1995), whereas the lower, Kamieniec unit contains eclogites metamorphosed under temperature of 575 °C (Achramowicz *et al.*, 1997). At the base of the distinguished thrust sequence the main thrust (Paczków thrust) occurs, which separates it from the underlying metabasites of the Niedźwiedź massif (Fig. 23).

The development of the described nappe pile during the D_1 event was coeval with the thrusting of the West Sudetes over the East Sudetes. The direction of tectonic transport

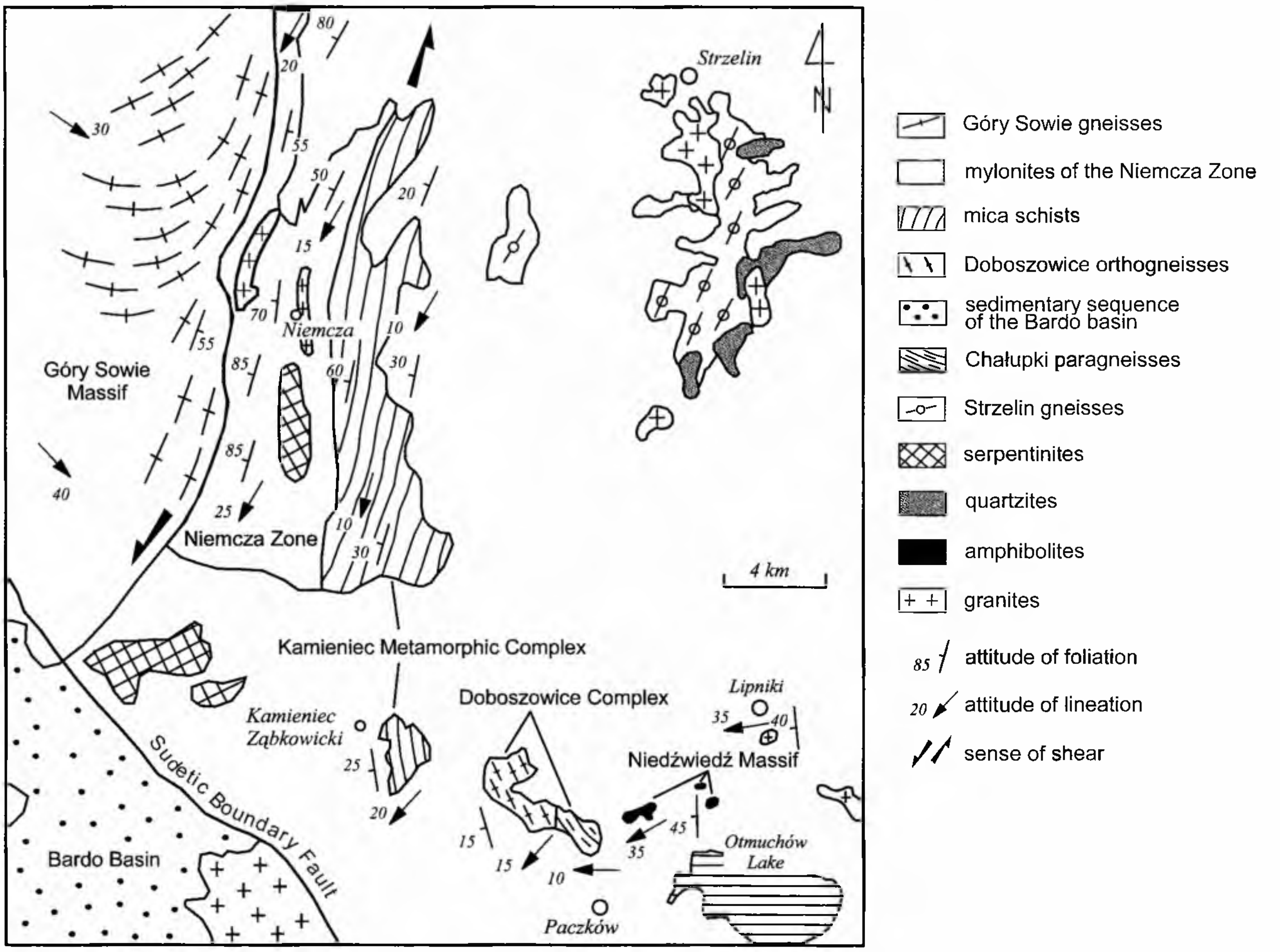


Fig. 22. Simplified tectonic map of metamorphic complexes cropping out between the Góry Sowie Massif and the Niedźwiedź Massif

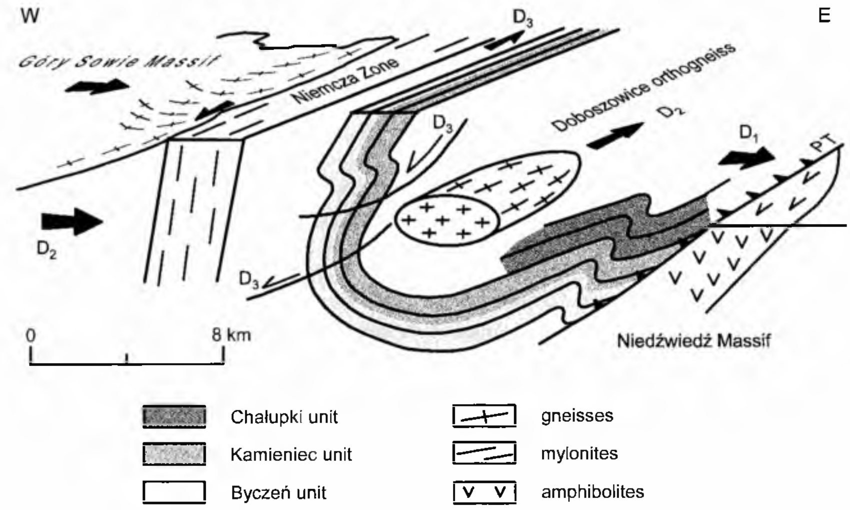


Fig. 23. Schematic block diagram showing the structural geometry of metamorphic complexes between the Góry Sowie Massif and the Niedźwiedź Massif. Chałupki, Kamieniec and Byczeń units are separated by overthrusts (here omitted for sake of simplicity). PT – Paczków overthrust

was probably towards the east, in agreement with the classical interpretation of Suess (1912). An eastward direction of the overthrusting is indicated by E–W orientation of the stretching lineation L_1 and by consistent east-verging asymmetry of kinematic indicators in both normal and inverted limbs of the NE–SW trending megasynform F_2. The kinematic indicators both in the Chałupki paragneiss (Mazur & Puziewicz, 1995b; Puziewicz *et al.*, 1998) and in the coarse-grained mica schists of the Kamieniec unit suggest a persistent top-to-E sense of shear. This implies that the direction of tectonic transport during the D_1 event was probably oblique at high angle or perpendicular to the axis of the later F_2 synform.

The folding and coaxial shortening during the D_2 event probably represented a continuation of E–W-directed contraction, which had previously given rise to the nappe stacking. The highest strain was imposed, during the D_2 event, on a shorter limb of the F_2 synform. It was subjected to progressive coaxial shortening which produced the crenulation cleavage and foliation S_2. High strain concentrated, as well, in the syn-tectonic Doboszowice intrusion due to its low competence. The Doboszowice granite was transformed into the orthogneiss as a result of deformation comprising coaxial NW–SE shortening and a top-to-NE non-coaxial shearing. The significance of the latter component cannot be estimated in the study area.

The deformation D_3 was related to WSW-directed extensional collapse of a regional extent. A similar deformation has been recently described in the Jesenik Massif (Cymerman, 1993; Chab *et al.*, 1994; Schulmann *et al.*, 1995). The extensional collapse was accompanied by the development of the subvertical strike-slip Niemcza Shear Zone along the eastern margin of the Góry Sowie Massif (Mazur & Puziewicz, 1995). Low-angle normal-slip D_3 shear zones developed in the rocks subjected to the high strain during the D_2 event (fine-grained mica schists) or in low-competence rocks (late tectonic Lipniki granite). The transition from coaxial shortening to non-coaxial WSW-directed extensional collapse reflects, in our opinion, a response of the rocks to increasing deformation in high strained zones.

The extensional collapse resulted in rapid decompression which was recorded by andalusite growth. In the D_3 shear zones the andalusite is synkinematic, whereas in rocks subjected only to coaxial strain it is postkinematic. This indicates that rock volumes in which the deformation had ceased after the D_2 coaxial flattening subsequently underwent only passive displacement along the D_3 shear zones.

Timing the main deformation events is still poorly constrained. The approximate age of the deformation D_2 probably represents the age of the Doboszowice orthogneiss considered to be a syntectonic intrusion (Mazur & Puziewicz, 1995; Puziewicz & Rudolf, 1995). The magmatic protolith of the Doboszowice gneiss has been recently dated at 379 ±1 Ma (A. Kröner – pers. com.), using U-Pb evaporation method on single zircons. The deformation D_1 must have predated the emplacement the Doboszowice intrusion so that it was probably Middle Devonian in age. On the other hand, the age of the extensional collapse D_3 is constrained in a wide time interval by the age of the D_2 event (ca. 380 Ma) and the age of the late- to post-tectonic granite from the Niemcza Zone dated at ca. 340 Ma (Oliver *et al.*, 1993).

CONCLUSIONS

The metamorphic complexes exposed between the Góry Sowie Massif and the Niedźwiedź Massif display a nappe structure. Three tectonic units (Chałupki, Kamieniec and Byczeń units) of different metamorphic history were subjected to ductile overthrust towards the east during the D_1 event. A penetrative foliation S_1 was formed parallel to thrust planes and a stretching lineation L_1 developed parallel to the thrust direction. Subsequent folding and coaxial shortening during the D_2 event produced lineation L_2 trending NE–SW, that represented a dominant linear structure in the area. At the same time subhorizontal axial cleavage of F_2 folds was transposed, in places, into a new penetrative foliation S_2 overprinting the older foliation S_1. The deformation D_2 was presumably accompanied by a syntectonic granite intrusion, subsequently transformed into the Doboszowice orthogneiss. The eventual tectonic event D_3 involved WSW-directed extensional collapse recorded by the development of low-angle normal-slip shear zones. The sinistral strike-slip Niemcza Shear Zone formed along the eastern margin of the Góry Sowie Massif during the same D_3 event.

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Streszczenie

DEFORMACJA W ŁUPKACH ŁYSZCZYKOWYCH Z OKOLIC KAMIEŃCA ZĄBKOWICKIEGO NA BLOKU PRZEDSUDECKIM: WARYSCYJSKA TEKTONIKA PŁASZCZOWINOWA I KOLAPS EKSTENSYJNY

Stanisław Mazur & Dariusz Józefiak

WSTĘP

Charakter i następstwo deformacji we wschodniej części bloku przedsudeckiego wciąż pozostają przedmiotem wzajemnie sprzecznych interpretacji (Dziedzicowa, 1985, 1987; Cymerman & Jerzmański, 1987; Cymerman & Piasecki, 1994; Achramowicz, 1994; Mazur & Puziewicz, 1995a; Nowak, 1995). Z myślą o dostarczeniu nowych danych na temat historii deformacji wschodniej części bloku przedsudeckiego prowadziliśmy badania w łupkach łyszczykowych z okolic Kamieńca Ząbkowickiego (Fig. 1). Nowe informacje uzyskane w efekcie przeprowadzonych badań pozwoliły sformułować wstępną hipotezę objaśniającą ewolucję tektoniczną serii krystalicznych pomiędzy blokiem sowiogórskim a masywem amfibolitowym Niedźwiedzia (Fig. 1).

Na wschód od strefy Niemczy i bloku gnejsowego Gór Sowich łupki łyszczykowe tworzą południkowo wydłużoną wychodnię (Fig. 1). Jest ona określana w tej pracy mianem metamorfiku Kamieńca Ząbkowickiego. Północna część metamorfiku przylega bezpośrednio od wschodu do strefy Niemczy, podczas gdy część południowa tworzy izolowaną wychodnię w okolicach Kamieńca Ząbkowickiego. Łupki łyszczykowe zawierają wkładki łupków kwarcowo-skaleniowych i marmurów oraz, występujące podrzędnie, soczewki łupków kwarcowo-grafitowych, łupków amfibolowych i eklogitów (Fig. 2, 3).

Penetratywna foliacja w metamorfiku Kamieńca zapada pod zmiennym kątem ku SW, W i NW. Upad foliacji zwiększa się ku zachodowi w strefie kontaktu północnej części metamorfiku ze strefą Niemczy (Mazur & Puziewicz, 1995b). Główna lineacja ma w przybliżeniu stałą orientację, zanurzając się pod niewielkim kątem ku SW i SSW.

Mazur i Puziewicz (1995a, b) oraz Mazur *et al.* (1995) opisują trzy etapy deformacji D_1, D_2 i D_3 w seriach skalnych położonych na wschód od bloku sowiogórskiego. Etapy D_1 i D_2 są ich zdaniem związane z nasuwaniem płaszczowin, odpowiednio, ku E i NE w warunkach facji amfibolitowej. Odpowiadają one głównym deformacjom kontrakcyjnym w obrębie wschodniej strefy krawędziowej masywu czeskiego związanym z nasuwaniem Sudetów zachodnich na Sudety wschodnie. Etap D_3 był natomiast efektem regionalnej ekstensji zaznaczającej się po fazie tworzenia nasunięć. Struktury powstałe w etapie D_3 wskazują na ścinanie o zwrocie lewoskrętno-przesuwczym, w strefach o stromej foliacji, lub o zwrocie "strop-ku-SW" w obszarach o foliacji subhoryzontalnej (Mazur & Puziewicz, 1995a, b; Mazur *et al.*, 1995).

LITOLOGIA I PETROGRAFIA

Łupki łyszczykowe z okolic Kamieńca Ząbkowickiego (Fig. 2: odsł. 1–14) są łupkami kwarcowo-muskowitowymi z biotytem, granatem, oligoklazem, andaluzytem, staurolitem i chlorytem. Do minerałów akcesorycznych należą turmalin, apatyt, cyrkon, allanit, rutyl i ilmenit. Wśród łupków występuje zróżnicowane na dwie odmiany strukturalne: grubo- i drobnoblastyczną (Józefiak, 1995).

Łupki drobnoblastyczne (odsł. 10–14) charakteryzują się występowaniem naprzemianległych lamin kwarcowo-muskowitowych i muskowitowo-biotytowych, podczas gdy w łupkach gruboblastycznych (odsł. 1–9) nieregularne, wydłużone soczewki kwarcowe, z nielicznymi blaszkami muskowitu są opływane przez smugi i laminy muskowitowo-biotytowe. Laminy łyszczykowe w obu odmianach łupków zawierają liczne porfiroblasty granatu. W łupkach gruboblastycznych osiągają one rozmiary 4–10 mm, a w łupkach drobnoblastycznych nie przekraczają 3 mm średnicy.

W okolicach Byczenia odsłaniają się drobnoblastyczne łupki łyszczykowe z albitem (Fig. 2). W odróżnieniu od opisanych powyżej łupków drobnoblastycznych zawierają liczne porfiroblasty albitu (Fig. 4), natomiast brak w nich staurolitu oraz porfiroblastów andaluzytu. Łupki z albitem składają się z drobnoblastycznego tła złożonego z kwarcu, biotytu, chlorytu, muskowitu i plagioklazu oraz z soczewek i lamin kwarcowych bądź muskowitowo-biotytowych. Zarówno w tle skalnym jak i laminach łyszczykowych mogą występować nieliczne relikty granatów lub bardzo małe (poniżej 0,05 mm) blasty tego minerału.

Łupki łyszczykowe z okolic miejscowości Stolec (Fig. 3) charakteryzują się dużą zmiennością struktury i składu mineralnego. Na zachód od wspomnianej wsi (odsłonięcia 1S, 2S) występują łupki łyszczykowe o ubogim składzie mineralnym i drobnoblastycznej strukturze. Zbudowane są głównie z kwarcu, muskowitu, biotytu i plagioklazu. W niektórych partiach łupków łyszczykowych duże porfiroblasty (do 3 mm) tworzy albit. Na wschód i północ od Stolca łupki łyszczykowe mają bogatszy skład mineralny i są średnioziarniste (odsłonięcia 6S, 7S). Poza kwarcem, muskowitem, biotytem i plagioklazem, w dużej ilości występuje w nich granat, staurolit i chloryt, a w nieco mniejszej andaluzyt i sylimanit.

METAMORFIZM

Badania Józefiaka (1994, 1996) w okolicach Kamieńca Ząbkowickiego sugerują, że na obszarze tym można wyróżnić dwie odmiany strukturalne łupków łyszczykowych: grubo- i drobnoblastyczną. Obie odmiany łupków łyszczykowych zachowały zapis odmiennych warunków metamorfizmu. Łupki gruboblastyczne osiągnęły maksimum metamorfizmu w temperaturze 570–640°C, przy ciśnieniu 8,0–13 kbar, podczas gdy łupki drobnoblastyczne zarejestrowały metamorfizm w temperaturze 510–540°C przy ciśnieniu 7,0–8,5 kbar. Końcowy etap metamorfizmu w obu odmianach łupków reprezentuje parageneza Ms+Bt+Grt+Pl+And± Sil±St. Ciśnienia i temperatury w jego trakcie obrazuje współwystępowanie andaluzytu i lokalnie zastępującego go sylimanitu (poniżej 4 kbar i powyżej 530°C).

STRUKTURY DEFORMACYJNE

W łupkach łyszczykowych z okolic Kamieńca Ząbkowickiego wyróżniliśmy trzy podstawowe zespoły struktur deformacyjnych odpowiadające co najmniej trzem głównym etapom deformacji D_1, D_2 i D_3 o znaczeniu regionalnym. Do zespołu struktur deformacyjnych powstałych w etapie D_1 zaliczamy foliację S_1 i lineację L_1. Z etapem D_2 wiążemy natomiast powstanie fałdów F_2, kliważu krenulacyjnego i foliacji S_2 oraz lineacji L_2. W ostatnim etapie D_3 rozwinęła się lineacja L_3 występująca na powierzchniach foliacji S_3 równoległych do foliacji S_2.

Obserwacje strukturalne wykazały, że w okolicach Kamieńca Ząbkowickiego foliacja S_1 i lineacja L_1 są wykształcone penetratywnie w łupkach, które charakteryzują się grubym lub bardzo grubym ziarnem. Drobniejsze ziarno mają natomiast łupki, w których powierzchnie S_1 zostały zatarte przez młodszą, penetratywną foliację S_{2+3}. W badanym terenie łupki gruboblastyczne występują w bezpośrednim sąsiedztwie Kamieńca Ząkowickiego, podczas gdy łupki drobnoblastyczne odsłaniają się w okolicach Byczenia (Fig. 2). Dalej ku północy w rejonie Stolca (Fig. 3) ekwiwalentem łupków gruboblastycznych są skały występujące na wzgórzu Wapienna i na północ od niego (Fig. 3 – odsłonięcia 3S i 6S). W pozostałych odsłonięciach położonych w pobliżu wsi Stolec dominują łupki drobnoblastyczne.

Foliację łupków gruboblastycznych (S_1) wyznacza równoległe ułożenie blaszek łyszczyków oraz orientacja naprzemianległych warstewek kwarcowych i łyszczykowych. W rejonie Kamieńca Ząbkowickiego (Fig. 2) foliacja S_1 wykazuje zróżnicowaną orientację (Fig. 7). Najczęściej ma ona upad ku NW pod dużym lub umiarkowanym kątem (odsłonięcia 1, 2, 3), miejscami też zanurza się łagodnie ku SE (odsłonięcia 6 i 7). Zmienna orientacja foliacji jest wynikiem występowania fałdów F_2, które na diagramach strukturalnych (Fig. 5) wywołują rozrzut pomiarów powierzchni S_1 wzdłuż pasa o osi NE–SW. W odsłonięciach położonych blisko granicy łupków drobnoblastycznych (odsłonięcia 5, 8, 9) foliacja S_1 ma jednolity upad ku W pod niewielkim kątem (Fig. 6). W okolicach Stolca (odsłonięcia 3S i 6S) struktury S_1 wykazują wyraźny rozrzut wzdłuż pasa o osi zorientowanej NE–SW (Fig. 8). Na powierzchniach foliacji łupków gruboblastycznych lineacja intersekcyjna L_2 zaciera starszą lineację z rozciągania L_1. Ta ostatnia jest lineacją mineralną łyszczyków, którą podkreśla miejscami wydłużenie wrzecionowatych agregatów kwarcowych. Generalnie, ma ona orientację W–E lub WNW–ESE (Fig. 5, 7).

W łupkach gruboblastycznych licznie występują duże ziarna granatu. Mają one cechy synkinematycznych porfiroblastów powstałych w trakcie deformacji D_1. Świadczą o tym sigmoidalne smugi wrostków (Fig. 9), obecne w wielu kryształach. Porfiroblastom granatu towarzyszą cienie ciśnienia, których asymetria wskazuje na niekoaksjalne ścinanie o zwrocie "strop-ku-E" lub "strop-ku-ESE" po powierzchniach subhoryzontalnej foliacji.

Foliację S_1 deformują fałdy mezoskopowe F_2 o amplitudzie sięgającej od kilkunastu centymetrów do kilku metrów. Ich osie mają w przybliżeniu orientację NE–SW, taką jak lineacja L_2, a powierzchnie osiowe zapadają łagodnie ku NW lub SE. W odsłonięciach położonych na zachód od Kamieńca Ząbkowickiego i w okolicach Stolca fałdy F_2 są średniopromienne. Ich dłuższe skrzydła zapadają stromo ku NW, podczas gdy krótsze skrzydła są łagodnie nachylone ku SE (Fig. 10). Fałdom F_2 towarzyszy kliważ krenulacyjny S_2 będący ich kliważem osiowym. Dwa maksima widoczne na diagramie strukturalnym (Fig. 11) pokazują zmienną orientację kliważu na przeciwległych skrzydłach fałdów F_2.

W badanych skałach można prześledzić kolejne etapy rozwoju powierzchni S_2 od kliważu krenulacyjnego po penetratywną foliację (Fig. 12). W łupkach gruboblastycznych foliacja S_1 pozostaje główną strukturą planarną skały. Jest ona zdeformowana przez symetryczne fałdki, których powierzchnie osiowe wyznaczają kliważ krenulacyjny. W łupkach drobnoblastycznych powierzchnie S_2 stanowią główną foliację tych skał, podkreśloną przez naprzemianległe warstewki łyszczykowe oraz łyszczykowo-kwarcowe. Starsza foliacja S_1 jest zachowana w mikrolitonach kwarcowo-łyszczykowych jako przeguby krenulacji (Fig. 12). W niektórych partiach łupków foliacja S_2 niemal całkowicie zaciera starszą foliację S_1. Jej relikty spotyka się jedynie w postaci smug wrostków w porfiroblastach oraz jako przeguby fałdów śródfoliacyjnych F_2 (Fig. 13). Foliacja S_2 w łupkach drobnoblastycznych ma w badanym terenie jednolitą orientację. Wykazuje ona konsekwentnie upad ku WNW pod niewielkim kątem (Fig. 8, 14).

Przecięcie powierzchni kliważu S_2 z foliacją S_1 łupków gruboblastycznych tworzy lineację intersekcyjną L_2, równoległą do przegubów fałdów F_2. Jednocześnie na foliacji S_2 łupków drobnoblastycznych lineacja L_2 jest lineacją mineralną z rozciągania wyznaczoną przez równoległe ułożenie ziarn łyszczyków. Orientacja lineacji L_2 jest dość jednolita w skali całego obszaru. Przebiega ona NE–SW lub ENE–WSW, zanurzając się łagodnie ku SW lub WSW (Fig. 7, 8, 14).

W łupkach drobnoblastycznych występują liczne porfiroblasty granatu, z których przynajmniej część powstała w trakcie deformacji D_2 (Fig. 9, 15). Porfiroblastom towarzyszą dobrze wykształcone cienie ciśnienia. Ich symetryczny kształt dowodzi, że niektóre partie łupków drobnoblastycznych zarejestrowały jedynie efekty odkształcenia koaksjalnego.

Łupki drobnoblastyczne z albitem odsłonięte w okolicach Byczenia i na zachód od Stolca (Fig. 2, 3) nie różnią się pod względem strukturalnym od pozostałych łupków określanych w tej pracy jako drobnoblastyczne. Istotnie różny jest natomiast w tych skałach synkinematyczny zespół mineralny związany z etapem D_2. Najważniejszym składnikiem tego zespołu są liczne porfiroblasty albitu (Fig. 4).

Przeważająca część łupków drobnoblastycznych zarejestrowała efekty niekoaksjalnego ścinania wzdłuż powierzchni S_3 równoległych do foliacji S_2. Liczne wskaźniki kinematyczne (Fig. 16) dokumentują konsekwentnie zwrot ścinania "strop-ku-SW" lub "ku-WSW" po łagodnie nachylonej foliacji. Kierunek ścinania wyznacza lineacja z rozciągania L_3 rozwinięta na powierzchniach foliacji S_{2+3}, równolegle do lineacji L_2. Ma ona charakter lineacji mineralnej łyszczyku i zanurza się konsekwentnie ku WSW (Fig. 8, 14). Niekoaksjalne ścinanie w etapie D_3 przebudowuje starszą więźbę łupków drobnoblastycznych powstałą w wyniku koaksjalnego odkształcenia tych skał podczas etapu D_2 (Fig. 15). Generalnie udział deformacji D_3 w całkowitym odkształceniu łupków drobnoblastycznych, wyrażony przez rosnącą asymetrię ich więźby, zwiększa się z zachodu na wschód w kierunku granicy oddzielającej łupki z granatem i staurolitem od łupków z albitem. W tych ostatnich zaznacza się podobna tendencja – wzrost asymetrii więźby (w tym przypadku ku zachodowi) w stronę kontaktu obu odmian łupków drobnoblastycznych.

Charakterystycznym składnikiem łupków łyszczykowych są porfiroblasty andaluzytu (Fig. 17). Brak ich jedynie w łupkach drobnoblastycznych z albitem. W łupkach gruboblastycznych oraz w łupkach drobnoblastycznych o symetrycznej więźbie andaluzyt tworzy zawsze porfiroblasty postkinematyczne. Natomiast w łupkach mających więźbę asymetryczną występują synkinematyczne blasty tego minerału powstałe w trakcie deformacji D_3 (Fig. 17c).

ORIENTACJA OSI <c> KWARCU

W łupkach gruboblastycznych występują trzy podstawowe rodzaje rozrzutu osi <c>: (1) wzdłuż pojedynczego pasa rozrzutu nachylonego do foliacji, (2) wzdłuż krzyżujących się pasów rozrzutu (I typ krzyżujących się pasów rozrzutu wg: Schmid & Casey, 1986) lub dwóch kół małych wokół normalnej do foliacji i (3) rozrzut izotropowy. Pojedynczy pas rozrzutu nachylony pod dużym kątem do foliacji (Fig. 18a, b) uznaje się za efekt deformacji niekoaksjalnej zbliżonej do prostego ścinania (Schmid & Casey, 1986). Nachylenie pasa rozrzutu wskazuje na ścinanie o zwrocie "strop-ku-E" charakterystyczne dla deformacji D_1. Rozrzut wzdłuż krzyżujących się pasów (Fig. 18c, d) lub wzdłuż dwóch kół małych wokół normalnej do foliacji (Fig. 18e) jest rezultatem deformacji koaksjalnej (Schmid & Casey, 1986), odpowiednio, czystego ścinania i ogólnego spłaszczenia. Koaksjalną deformację łupków gruboblastycznych, zarejestrowaną przez więźbę kwarcu, należy wiązać z rozwojem kliważu krenulacyjnego w etapie D_2. Izotropowy rozrzut osi <c> kwarcu na diagramach (Fig. 18f) można natomiast wytłumaczyć jako rezultat statycznej rekrystalizacji kwarcu po zakończeniu podatnej deformacji.

W łupkach drobnoblastycznych (Fig. 19) stwierdziliśmy występowanie dwóch podstawowych typów rozrzutu osi <c> kwarcu: (1) wzdłuż pojedynczego pasa nachylonego do foliacji (Fig. 19a – d) oraz (2) wzdłuż krzyżujących się pasów rozrzutu (I typ krzyżujących się pasów rozrzutu) prostopadłych do foliacji (Fig. 19g – i). Pierwszy z wymienionych rodzajów rozrzutu wskazuje na deformację niekoaksjalną, zbliżoną do prostego ścinania, podczas gdy drugi jest przypuszczalnie efektem deformacji koaksjalnej o charakterze czystego ścinania (Schmid & Casey, 1986). Nachylenie pasa rozrzutu na diagramach reprezentujących deformację niekoaksjalną wskazuje konsekwentnie na ścinanie o zwrocie strop-ku-SW. W nawiązaniu do obserwacji strukturalnych, powstanie rozrzutu osi <c> kwarcu wzdłuż dwóch krzyżujących się pasów uznajemy za efekt deformacji D_2, natomiast rozrzut wzdłuż pojedynczego pasa wiążemy z deformacją D_3.

Rozrzuty osi <c> kwarcu uzyskane na diagramach z łupków łyszczykowych odsłoniętych w pobliżu Stolca (Fig. 20) reprezentują niemal pełną gamę przejść od pojedynczego pasa nachylonego do foliacji (Fig. 20a, b) do I typu krzyżujących się pasów (Fig. 20e). Otrzymane diagramy rozrzutu osi <c> kwarcu sugerują, że całkowite odkształcenie łupków łyszczykowych z okolic Stolca było wypadkową składowej prostego ścinania oraz składowej koaksjalnej mieszczącej się w zakresie od czystego ścinania po ogólne spłaszczanie. Podobnie jak w okolicach Kamieńca Ząbkowickiego rozrzut osi <c> kwarcu w łupkach z otoczenia wsi Stolec interpretujemy jako efekt superpozycji deformacji D_2 i D_3.

DYSKUSJA

Efekty najstarszej deformacji (D_1) są zachowane w łupkach gruboblastycznych. Foliacja S_1 stanowi tam główną powierzchnię anizotropii, podczas gdy lineacja L_1 została niemal całkowicie zatarta przez młodszą lineację L_2. Wskaźniki kinematyczne sugerują, że foliacja S_1 rozwinęła się w wyniku niekoaksjalnego ścinania. Ustalenie kierunku ścinania w etapie D_1 utrudnia rozrzut lineacji L_1 na skrzydłach młodszych fałdów F_2 (Fig. 5). Lineacja L_1 miała przebieg w przybliżeniu E–W przy założeniu, że pierwotna (przed D_2) orientacja foliacji S_1 była subhoryzontalna. W takim przypadku wskaźniki kinematyczne zarejestrowały w etapie D_1 ścinanie o zwrocie "strop-ku-E". Skład minerałów wyznaczających foliację S_1 w łupkach gruboblastycznych, a także skład występujących w nich porfiroblastów granatu sugeruje, że deformacja tych skał w etapie D_1 zachodziła w warunkach górnej facji amfibolitowej (Józefiak, 1996).

Foliacja S_1 łupków gruboblastycznych została zreorientowana w etapie D_2 na skrzydłach fałdów F_2. Północno-zachodnia asymetria wspomnianych fałdów (Fig. 10) sugeruje, że cała seria skalna odsłonięta w okolicach Kamieńca Ząbkowickiego i Stolca stanowi strome skrzydło asymetrycznego makrofałdu F_2. Wniosek ten potwierdza orientacja kliważu krenulacyjnego S_2, który na dłuższych, bardziej stromych skrzydłach fałdów F_2 ma nachylenie mniejsze niż foliacja. Powstaniu fałdów F_2 wraz z ich kliważem osiowym S_2 towarzyszyła koaksjalna deformacja łupków gruboblastycznych. Lineacja L_2 o orientacji NE–SW lub ENE–WSW powstała w wyniku koaksjalnego rozciągania oraz z przecięcia foliacji S_1 i kliważu S_2.

Przejście od łupków grubo- do drobnoblastycznych jest związane z przekształceniem kliważu krenulacyjnego S_2 w główną foliację skały. Przemiana ta nastąpiła w wyniku zróżnicowania skały na naprzemianległe warstewki kwarcowe i łyszczykowe równoległe do kliważu S_2. Przypuszczamy, że dyferencjacja łupku na warstewki o różnym składzie miała związek ze wzrostem wielkości odkształcenia w trakcie deformacji D_2.

Skład minerałów wyznaczających foliację S_2 łupków drobnoblastycznych, a także skład powstałych równocześnie porfiroblastów granatu sugeruje, że deformacja D_2 zachodziła w warunkach dolnej facji amfibolitowej (Józefiak, 1996). Zonalność składu chemicznego granatu w łupkach drobnoblastycznych (z granatem i staurolitem) wskazuje na wzrost temperatury w trakcie etapu D_2.

Deformacja D_3 była związana z niekoaksjalnym ścinaniem o zwrocie "strop-ku-WSW", które zachodziło w warunkach znacznego spadku ciśnienia. Wskazuje na to występowanie andaluzytu zarówno w grubo- jak i drobnoblastycznej odmianach łupków. Obecność tego minerału sugeruje spadek ciśnienia od 7–8 kbar w etapie D_2 do 2–4 kbar w etapie D_3 przy wciąż stosunkowo wysokiej temperaturze, przekraczającej 500°C.

Wyraźny kontrast w stopniu metamorfizmu różni łupki grubo- i drobnoblastyczne ze staurolitem i porfiroblastami granatu od łupków drobnoblastycznych z albitem. W oparciu o różnice stopnia metamorfizmu i składu litologicznego wydzieliliśmy w badanym terenie dwie jednostki tektoniczne: jednostkę Kamieńca (wyższy metamorfizm) i jednostkę Byczenia (niższy metamorfizm). Granica obu wyróżnionych jednostek przebiega na zachód od Byczenia (Fig. 2) i kontynuuje się w okolicach Stolca na zachód od szczytu wzgórza Wapienna (Fig. 3).

W okolicach Stolca wychodnia łupków z albitem przebiega na zachód od wychodni łupków ze staurolitem i granatem (Fig. 3). Sytuacja taka jest wynikiem fałdowania w etapie D_2. Jednocześnie w okolicach Kamieńca Ząbkowickiego i Byczenia łupki ze staurolitem i granatem odsłaniają się na zachód od łupków z albitem (Fig. 2). Takie położenie wychodni obu jednostek tektonicznych jest tam efektem przemieszczeń wzdłuż niskokątowej strefy podatnego ścinania o upadzie ku WSW i o zrzuconym skrzydle zachodnim (Fig. 21). Strefa ta jest równoległa do foliacji S_{2+3}, która w okolicach Byczenia zapada konsekwentnie ku WSW pod kątem około 20°. Jednocześnie liczne wskaźniki kinematyczne jednoznacznie określają zrzutowo-normalny (strop-ku-WSW) zwrot ścinania w tej strefie.

Deformacja D_1, której zapis zachował się w łupkach gruboblastycznych stanowi naszym zdaniem odpowiednik deformacji opisanej jako D_1 (Mazur & Puziewicz, 1995b) w paragnejsach z Chałupek (Fig. 22). W obu obszarach deformacja ta zachodziła w warunkach retrogresji metamorfizmu od górnej do dolnej facji amfibolitowej i wiązała się przypuszczalnie ze ścinaniem o zwrocie "strop-ku-E". Koaksjalna deformacja łupków łyszczykowych znajduje natomiast swój odpowiednik w deformacji ortognejsów z Doboszowic (Fig. 22). Ortognejsy, zinterpretowane jako syntektoniczna intruzja (Mazur & Puziewicz, 1995), uległy odkształceniu o znaczącej składowej koaksjalnej. Deformacja ortognejsów w etapie D_2 obejmowała także składową prostego ścinania o zwrocie "strop-ku-NE" (Mazur & Puziewicz 1995b). Efekty deformacji D_3, zapisanej w łupkach drobnoblastycznych, zarejestrowały także późnotektoniczne granity z Lipnik (Mazur *et al.*, 1997). Deformacja ta wiązała się w obu przypadkach z rozwojem niskokątowych, zrzutowo-normalnych stref ścinania, o zwrocie "strop-ku-WSW".

W świetle zebranych obserwacji łupki metamorfiku Kamieńca występują na krótszym skrzydle makrofałdu F_2 o stromym upadzie ku NW. Jednocześnie paragnejsy z Chałupek (Fig. 23) znajdują się na przeciwnym, dłuższym skrzydle, łagodnie nachylonym ku WNW. Oba skrzydła makrofałdu F_2 połączyć można w asymetryczną synformę obaloną ku SE, której oś przebiega NE–SW.

Rekonstrukcja makrosynformy F_2 pozwala na ustalenie wzajemnego położenia trzech dużych jednostek tektonicznych występujących w badanym terenie. Od góry do dołu są to: (1) jednostka Chałupek (paragnejsy i amfibolity), (2) jednostka Kamieńca oraz (3) jednostka Byczenia. Jednostki te reprezentują naszym zdaniem trzy płaszczowiny, które przed etapem D_2 zalegały płasko na sobie. Sekwencja wyróżnionych jednostek wykazuje, typową dla budowy płaszczowinowej, tektoniczną inwersję stopnia metamorfizmu. Dwie górne płaszczowiny (Chałupek i Kamieńca) mają wyższy stopień metamorfizmu (górna facja amfibolitowa) od płaszczowiny Byczenia (dolna facja amfibolitowa lub pogranicze facji zieleńcowej i amfibolitowej) położonej najniżej. Jednostki Chałupek i Kamieńca różni natomiast od siebie maksymalny zakres temperatury, jaki zapisał się w nich podczas wczesnych faz metamorfizmu. Najwyżej położona jednostka Chałupek zawiera soczewki granulitów zmetamorfizowanych w temperaturze do 920°C (Achramowicz *et al.*, 1995), podczas gdy w niżejległej jednostce Kamieńca występują eklogity rejestrujące temperaturę 575°C (Achramowicz *et al.*, 1997).

PODSUMOWANIE I WNIOSKI

Serie skalne odsłonięte pomiędzy blokiem sowiogórskim a masywem Niedźwiedzia wykazują budowę płaszczowinową. Trzy jednostki tektoniczne (Chałupek, Kamieńca i Byczenia) o odrębnej historii metamorfizmu są nasunięte na siebie ku wschodowi w rezultacie deformacji D_1. Lineacja o przebiegu NE–SW, dominująca w badanym terenie, jest efektem fałdowania i koaksjalnej kontrakcji wzdłuż kierunku NW–SE, podczas deformacji D_2. Kliważ osiowy fałdów F_2 rozwinął się miejscami w penetratywną foliację S_2 zacierającą starszą foliację S_1. Deformacji D_2 towarzyszyła przypuszczalnie syntektoniczna intruzja przekształcona w ortognejsy z Doboszowic. Ewolucję obszaru zakończył kolaps ekstensyjny ku WSW, związany z rozwojem niskokątowych, zrzutowo-normalnych stref podatnego ścinania.