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The tectonometamorphic evolution of the marbles in the Lądek-Śnieżnik Metamorphic Unit, West Sudetes

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Abstract Together with the adjacent rocks, the marbles of the Lądek-Śnieżnik Metamorphic Unit (LSMU), West Sudetes, SW Poland underwent a polyphase structural evolution that occurred in metamorphic conditions changing from medium-grade to low-grade and in deformation regimes changing from ductile to semi-brittle. The structural evolution of the marbles began with E–W subhorizontal shortening resulting in the tilting of the Cal-Dol layering (which had generally originated as a pre-tectonic and pre-metamorphic feature) and its transposition to a steeply dipping metamorphic S1 foliation. The subsequent vertical flattening occurred at the temperature peak of regional metamorphism and produced the N–S trending tight, recumbent F2 folds. This event is also documented by the subhorizontal S2 axial-plane carbonate grain shape fabric and the parallel alignment of Phl-Ms ± Tr ± Czo in the marbles, and the S2 axial-plane schistosity in the adjacent mica schists. The temperature increase was associated with the progressive mineral sequence Phl → Tr → Di in the dolomite-bearing marbles, which probably initially equilibrated at low to moderate X(CO_2). Under peak temperatures, the observed arrangement of the metamorphic zonation of the Stronie formation developed, overprinting the folded planes. Subsequently, under retrogressive conditions, younger deformations were localised in the dynamically recrystallised shear zones that mostly reactivated the S2 planes and were associated with a late top-to-the-N (NE) directed tectonic transport. The D3 mylonitisation was associated with the elongation and size reduction of carbonate grains within the S-C' or S-C mylonites. It produced the S3 planes and the N–S trending L3 stretching lineation. Both groups of the tectonic structures and D2-established mineral isograds (Tr-in and Di-in) were together reoriented during the late compressional stages D4 and D5, related respectively to the SW–NE (WSW–ENE) and NW–SE (NNW–SSE) directed tectonic shortenings. This is visible in the large scale F4 folds, the diversity of the D2-and D3-related mineral assemblages, and the temperature estimations related to both tectonic stages, which indicate decreasing metamorphic conditions from ≥ 600°C in the SE to ≥ 490°C in the NE of the LSMU during D2, and from ca. 510°C to 430°C for the respective domains during D3. The incomplete pattern of the Di-in and Tr-in isograds, which still refers to the geometry of gneiss-schist boundary, confirms that the macrostructures of the LSMU mainly developed in tectonic event(s) following the temperature peak of metamorphism.

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INTRODUCTION

Upper Proterozoic to Lower Palaeozoic mica schists with subordinate intercalations of marbles, quartzites, acid-metavolcanites and metabasites form the Stronie formation – a supracrustal sequence in the Lądek-Śnieżnik Metamorphic Unit (LSMU), the West Sudetes. During the tectonometamorphic evolution of the LSMU, the rocks of the Stronie formation were intensively deformed (e.g. Don *et al.*, 1990) and underwent regional metamorphism (e.g. Smulikowski, 1979) terminated by the emplacement of Variscan granitoids.

Thanks to the well-exposed interlayers of marbles, quartzites and metavolcanites within the mica schists, all with preserved deformation structures, the rocks of the Stronie formation have been the focus of numerous investigations into their structural and metamorphic record. However, the interpretations led to different, and therefore possibly in part erroneous conclusions. Controversies regarding the origin and tectonic significance of N–S trending folds and lineations, the question of a polyphase versus single-phase structural evolution, and kinematics of the tectonic movements and their relationships to metamorphism have been widely discussed, but further studies are still needed.

This paper provides a reconstruction of the tectonometamorphic evolution of the marbles in the Lądek-Śnieżnik Metamorphic Unit. Thanks to their rheological

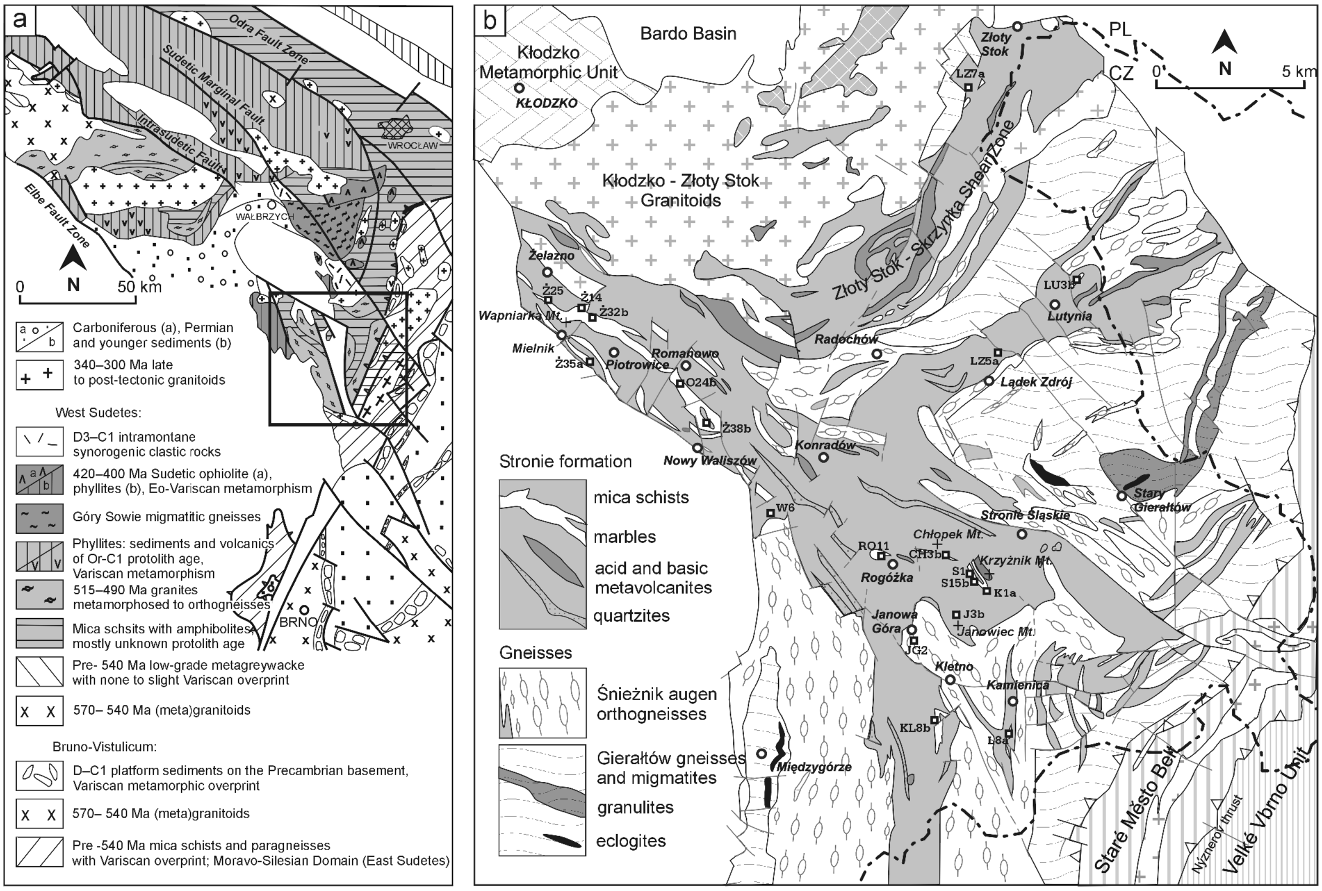

Fig. 1. a. The position of the Orlica-Śnieżnik Dome in the West Sudetes (map modified after Żelaźniewicz *et al.*, 2004). **b.** Geological map showing the distribution of the Stronie formation rocks and the gneiss formations in the Lądek-Śnieżnik Metamorphic Unit (modified after Sawicki, 1995). The squares mark the locations of the samples selected for microprobe analyses.

properties, the marbles allow for a good distinction between the tectonic features developed during consecutive tectonometamorphic stages. Although numerous detailed petrographic and structural studies have already been performed on these rocks, they did not consider relationships between metamorphism and deformation. This paper relates the meso- and microstructures to the metamorphic evolution inferred from the changing mineral assemblages and thermobarometric calculations. The results of this study contribute to the recognition of the origin of the tectonic fabrics, the cause of the progressive changes in metamorphic and kinematic conditions, and differences in the metamorphic record throughout the Stronie formation. Accordingly, this paper provides new verifiable data required for understanding the structure and geodynamic development of the borderland of the West Sudetes continental domain.

GEOLOGICAL SETTING

The Lądek-Śnieżnik Metamorphic Unit forms the eastern part of the Orlica-Śnieżnik Dome (Don *et al.*, 1990), which is the easternmost tectonostratigraphic unit of the West Sudetes (Fig. 1). The West Sudetes are considered to be either a single Lugian continental domain referred to as an orogenic root (Schulmann & Gayer, 2000) or a mosaic of several separate terranes correlated with large-scale units of the Bohemian Massif. Published terrane models place the Orlica-Śnieżnik Dome in either the SE part of the Saxothuringian terrane (Franke & Żelaźniewicz, 2000) or the NE part of the Moldanubian terrane (e.g. Cymerman *et al.*, 1997; Aleksandrowski & Mazur, 2002). The LSMU is composed of the metamorphosed volcano-sedimentary Młynowiec and Stronie formations, and gneisses subdivided into the Śnieżnik augen-orthogneisses and the fine-grained, often migmatitic Gierałtów gneisses (according to Fischer's terminology, 1936). The NW part of the LSMU is a blastomylonitic zone called the Złoty Stok-Skrzynka Shear Zone. In the east, the NNE-trending Staré Mesto Belt divides the LSMU from the Moravo-Silesian domain, which formed an accretionary wedge over the Bruno-Vistulian (Brunia) microcontinent during its Carboniferous oblique convergence with the West Sudetes domain (Schulmann & Gayer, 2000). In the north, the Kłodzko-Złoty Stok Granitoids separate the LSMU from the phyllites of the Kłodzko-Metamorphic Unit, conceivably an equivalent of the Teplá-Barrandian (Bohemicum) terrane (e.g. Aleksandrowski & Mazur 2002; Cymerman *et al.*, 1997).

The structural relationship between the rocks of the Stronie formation and the gneisses of the LSMU remains a subject of major debate. Following Fischer (1936), the Stronie formation is considered to be the structurally higher part of the LSMU (e.g. by Don *et al.*, 2003). The lower part consists of gneisses enclosing several eclogite and granulite bodies. According to this view, the rocks of the Stronie formation occupy polyphase synclinorial macrostructures, whereas the gneisses are exposed in the axial parts of anticlinoria. Conversely, the gneiss domain in the Złote Mts. is regarded as positioned in the core of a synform (e.g. Oberc, 1972). In the most recent interpretation, the gneiss domains are considered to be separate tectonic slices forming a nappe pile with the rocks of the Stronie formation (Cymerman, 1997).

The Stronie formation is considered to be an Upper Proterozic to Lower Palaeozoic volcano-sedimentary sequence, with the light quartzites at the base, mica schists and graphite quartzites in the main part of sequence and metavolcanic rocks and marbles at its top (e.g. Don *et al.*, 2003). The metabasites of the Stronie formation are attributed to an ensialic rift (Floyd *et al.*, 1996), but their geochemical signatures vary from WPB to MORB (Nowak & Żelaźniewicz, 2002). The microfossils preserved in the marbles (e.g. Gunia, 1984b) and quartzites (Gunia, 1984a) indicate Late Proterozoic to Early Cambrian sedimentation. The relics of fauna skeletons indicate a Palaeozoic age for the marbles (Koszela, 1997). New U-Pb SHRIMP zircon dating of the acid metavolcanic intercalations representing the synsedimantary volcanism in the Stronie formation yields an age of ~500 Ma (Murtezi & Fanning, 2005).

The augen to flaser Śnieżnik orthogneisses are deformed and regionally metamorphosed porphyritic granites. Magmas resulting from the melting of Neoproterozoic crust (Turniak *et al.*, 2000) intruded into the rocks of the Stronie formation (e.g. Don, 1964; Borkowska *et al.*, 1990) during a widespread magmatic event ~500 Ma (e.g. Oliver *et al.*, 1993; Turniak *et al.*, 2000; Kröner *et al.*, 2001). The fine-grained partly migmatitic Gierałtów gneisses encompass a lens-shaped, 12-km long, granulite body (extending from Stary Gierałtów towards the NE) (Fig. 1) and several dispersed eclogite and post-eclogite amphibolite lenses (Międzygórze, Wójtówka, Mt. Sowia Kopa, Nowa Morawa). The geochemical and age similarities ascertained for the protoliths of both gneisses suggest their close affinity (e.g. Borkowska *et al.*, 1990; Turniak *et al.*, 2000); however, their mutual age relationships are still debatable. In the Międzygórze area, fine-grained, migmatitic gneisses occurring within the augen Śnieżnik gneisses have been considered either enclaves (e.g. Grześkowiak & Żelaźniewicz, 2002) or a more deformed and migmatitzed form of the Śnieżnik gneisses (Don in Don *et al.*, 1990; Turniak *et al.*, 2000).

The rocks of the Stronie formation underwent a complex tectonic evolution spanning up to 7 stages of deformation (e.g. Don *et al.*, 1990) and regional metamorphism (e.g. Smulikowski, 1979) preceding the intrusions of Variscan granitoids. The LSMU rocks recorded Upper Devonian (Klemd & Bröcker, 1999; Szczepański *et al.*, 2004; Lange *et al.*, 2005) and/or Lower Carboniferous metamorphism (Borkowska *et al.*, 1990; Brueckner *et al.*, 1991; Steltenpohl *et al.*, 1993; Maluski *et al.*, 1995; Turniak *et al.*, 2000; Lange *et al.*, 2002; Marheine *et al.*, 2003; Štípská *et al.*, 2004). It has also been suggested that the polyphase metamorphic evolution of the LSMU started in the Early Caledonian phase (Don in Don *et al.*, 1990; Olivier *et al.*, 1993; Grześkowiak *et al.*, 2005). In this latter view, the first deformational event in the rocks of the Stronie formation could be connected with the Sardinian orogenic phase, terminated by the intrusions of porphyritic granites – the protholih of the Śnieżnik gneisses (e.g. Fischer, 1936; Don in Don *et al.*, 1990). According to Don (e.g. in Don *et al.*, 1990), the succeeding deformational event, connected with the E-directed thrusting, led to the formation of N–S trending, tight folds in the metapelites and a meridionally trending rodding lineation in the Śnieżnik orthogneisses. The ultimate arrangement of six anticlinoria and five synclinoria resulted from the obliteration of the N–S trending folds by NW–SE ones during a subsequent oblique folding (Don *et al.*, 1990). The axes of these macrostructures compose a fan-like pattern (termed the Lądek virgation by Teisseyre, 1956) and converge, plunging towards the NW in the area of the Krowiarki Mts. (Don, 1964). Dumicz (1979, Dumicz in Don *et al.*, 1990) remarked that the LSMU recorded two Variscan tectonic cycles. During the first, as a result of the horizontal shortening, an intensive folding leading to the crustal thickening took place. The consequent isostatic uplift was associated with the formation of tight recumbent folds and originally horizontal metamorphic axial planes. During the Late-Variscan cycle, an obliterated shearing and a large-scale folding of the earlier structures took place (Dumicz, 1979).

The regional elongation along the N–S trending rodding lineation in the LSMU orthogneisses could be the result of either coincidental strain due to a N–S tectonic escape induced by the E–W shortening (Żelaźniewicz, 1988) or NE–SW strike slip in a transpressional regime (Cymerman, 1997). Żelaźniewicz (1991) connects the development of the N–S stretching lineation with the early tectonic stage of the tectonic evolution, whereas Cymerman (1997) assumes that all the tectonic features developed during one deformational event.

The geothermobarometric calculations indicate that all the studied domains of the Stronie formation underwent medium grade Barrovian metamorphism. Published data reveals that the mica schists experienced progressive metamorphism reaching temperatures of 520–650°C and pressures of 7–9 kbar (e.g. Józefiak, 2000; Romanová & Štípská, 2001; Murtezi, 2003; Žačková & Štípská, 2004). The maximum temperatures obtained for the LSMU marbles yield ~500–565°C (e.g. Koszela, 1997; Jastrzębski, 2003). The P-T estimations calculated for the metabasites concur with those mentioned above, yielding 530–669°C and 8–9 kbar (Nowak & Żelaźniewicz, 2002). By contrast to these values, the dispersed granulite and eclogite bodies underwent either high pressure (HP) (Štípská *et al.*, 2004) or even ultra-high pressure (UHP)/ultra-high temperature (UHT) conditions (Bakun-Czubarow, 1992; Bröcker & Klemd, 1996; Kryza *et al.*, 1996; Szczepański *et al.*, 2004). The P-T estimations for the Śnieżnik and Gierałtów gneisses are more difficult to calculate because of the poorer mineral assemblages. The thermobarometric calculations performed in the gneisses of the LSMU show that they underwent metamorphism under upper-amhibolite facies conditions (Grześkowiak & Żelaźniewicz, 2002; Stawikowski, 2002; Začková & Štípská, 2004). The high grossular content (XCa: 0.3–0.5) in the garnets from the gneisses adjacent to the eclogites suggests that the garnet-bearing gneisses experienced (U)HP conditions (Borkowska *et al.*, 1990; Bröcker & Klemd, 1996). However, new, detailed investigations show that the unusual garnet composition did not result from the high pressures. It is more likely that it was either produced by a diffusional modification of the inherited grains (Grześkowiak, 2004) or resulted from a migration of Ca ions from the adjoining metabasites during garnet growth at the migmatisation stage (Stawikowski, 2005) under medium pressure conditions.

PREVIOUS STUDIES ON MARBLES

The marbles of the Lądek-Śnieżnik Metamorphic Unit have been the object of numerous studies focusing on various aspects of their geology, e.g. their economical use (e.g. Kuźniar, 1960; Witek, 1976), preserved microfossils (e.g. Gunia, 1996; Koszela, 1997), and the environment of their sedimentation, and their position in the lithostratigraphic column of the Stronie formation (Karwacki, 1990; Koszela, 1997). Detailed petrographic descriptions of the LSMU marbles have been presented by many authors, including Kuźniar (1960), Butkiewicz (1968), Witek (1976), Smulikowski (1979), Karwacki (1990), and most recently by Koszela (1997). Due to the good exposure of the marble interlayers within the mica schists and the well-preserved deformation structures, the marbles have also been the focus of numerous structural investigations. In this section, special emphasis has been put on earlier mapping and existing structural and petrologic studies of these rocks.

The marbles of the Stronie formation occur within the mica schists mostly as elongated interlayers several meters up to 400 meters thick and tens of meters to a few kilometres long (Fig. 1). They are distributed irregularly throughout the LSMU and concentrate in the NW part of the Krowiarki Range, while there are only several isolated inserts in the S and E parts of the LSMU (Fig. 1b). These marble bodies are generally preserved the original position of the sedimentary interbeds within the adjacent metavolanic and metapelitic rocks (Koszela, 1997). Detailed petrographic investigations revealed the variability of the calcite/dolomite ratio of individual marble layers in the outcrop profiles (e.g. Witek, 1976; Karwacki, 1990). However, in general, the marble bodies occupying the NW part of the Krowiarki Mts. are mainly a dolomite-rich variety, whereas the intercalations in the SW part of the LSMU are mainly calcite marbles (Cwojdziński, 1979a, 1979b, 1983). The latter were assigned by Koszela (1997) to the lower part of the metavolcanic association of the Stronie formation. In his opinion, the impure, mainly dolomite marbles might represent the upper parts of the litostratigraphic profile.

The distinct lithological contacts with the adjacent rocks allow the survey of large, map-scale tectonic structures within the LSMU (e.g. Kuźniar, 1960; Don, 1964, 1976, 1988; Karwacki 1990). Despite variations in the chemical composition in the NW part of the Krowiarki Range, Kuźniar (1960) considered four NW-trending, elongated marble outcrops to be synformal parts of a single ~150-m thick marble layer, deformed into slightly inclined, SW-vergent and NW-plunging macrofolds. Contrarily, the outcrops in the Krowiarki Mts could represent two layers folded into a syncline, the hinge zone of which is exposed near Nowy Waliszów (Don, 1964). The SW-vergent geometry of the deformed marble interbeds has been confirmed in the Krowiarki Mts and recognised in its SE part in Rogóżka (Karwacki, 1990).

On the western slope of Mt. Krzyżnik, 1 km southwest of Stronie Ślaskie, the marbles are exposed in two layers; the western layer is traditionally termed Biała Marianna, and the eastern Zielona Marianna. They are both ca. 40 meters thick (Fig. 4), and are considered to be two limbs of a single marble body deformed in the form of a N–S trending tight synform (Oberc, 1966; Don, 1976; Cwojdziński, 1983). However, these layers have also been considered separate, independent bodies (Karwacki, 1990). He assumes that the two layers are pinched out within the mica schists, remarking also their different lithology: the Zielona Marianna contains more metapelitic inserts. In Kletno, four several tens of meters wide marble outcrops occur (Kasza, 1964; Frąckiewicz & Teisseyere, 1973). They could be the exposures of an intensively folded marble layer, which probably extends towards the south where it also exposes in the Morava valley (Don, 1982). Outcropped dispersed marble bodies also occur in the vicinity of Radochów (Cwojdziński, 1979b), Lutynia and Lądek Zdrój (Gierwelaniec, 1971), Złoty Stok (Cwojdziński, 1976), Janowa Góra (e.g. Don, 1988), and Kamienica (e.g. Teisseyre, 1959; Don, 1982). The conditions of occurrence and the locations of the LSMU marbles are described in detail by Karwacki (1990), among others.

The marbles of the Stronie formation affected the regional metamorphism (Teisseyre, 1959), possibly associated with a fluid flow resulting in changes in a bulk-rock composition (Banaś, 1962). An observed irregular distribution of feldspars, epidote, Ca-amphibole and Ca-pyroxene in the marble bodies that are in contact with the granitoids and gneisses in the Orlica-Śnieżnik Dome suggests a higher metamorphic grade for the marbles near Stronie Śląskie than for those exposed near Żelazno (Karwacki, 1990). Accordingly, the maximum values of the Mg-content in the calcites, corresponding with temperatures of ~500°C, were noted in the marbles in the vicinity of Kletno and Stronie Śląskie (Koszela, 1997; Jastrzębski, 2003).

ANALYTICAL METHODS

In order to establish the tectonometamorphic evolution of the marbles and possible differences in their tectonic and metamorphic record, integrated field and laboratory structural and petrological studies were carried out on marble occurrences throughout the Polish part of the LSMU (Fig. 1). During the fieldwork, tectonic structures in the marbles and adjacent rocks were identified and classified. The geometric relationships between folds and planar and linear structures were taken into account in order to recognise the deformational sequence of the marbles. The order of the observed mesofolds and the orientation of the macrofold envelope were tested to determine the position of planar structures from before their reorientation during successive tectonic events. In order to establish the regime of the tectonic movements, the kinematic indicators, i.e. asymmetry of higher-order folds, asymmetry of δ- and σ-type porphyroclasts (Passchier & Trouw, 1995) and the geometry of S-C- and S-C'-type mylonites (Blenikshop & Treolar, 1995) were considered.

Polished thin sections were examined in order to correlate the changing mineral assemblages with successive tectonic fabrics. The major elements and chemical zonation of the minerals forming successive tectonic fabrics in the marbles were analysed using a JEOL JSM 840A electron microprobe combined with a ThermoNoran microanalysis system of the Laboratory of Institute of Geological Sciences of Polish Academy of Sciences in Warsaw, Poland. Additional analyses were collected using a CAMECA-CAMEBAX SX 1002 in the Electron Microprobe Laboratory Inter-Institute Analytical Complex for Minerals and Synthetic Substances in Warsaw, Poland. Spot analyses were collected under conditions of accelerating voltage of 15kV with a beam current of 10nA. The Mg-Kα intensity mapping and traverse analyses for several calcite grains were carried out in order to recognise the origin of their chemical zonation, required for the conscious application of the carbonate geothermometer (e.g. Essene, 1983). The temperature of each sample was calculated by taking the average of the highest Mg analyses from the cores of several different calcites devoid of retrogressed dolomite exsolutions but coexisting with dolomite in the matrix. These conditions were calculated using the Cal-Dol geothermometer, with a correction for the effect of Fe, as per Anovitz & Essene (1987). Due to the nearly Fe-free composition of the minerals, an isobaric T-X(CO_2) diagram showing the phase equilibria of D2-related mineral reactions was constructed for the simplified system K_2O-Al_2O_3-CaO-MgO-SiO_2-CO_2-H_2O using the THERMOCALC 3.1 software containing an internally consistent thermodynamic database (Holland & Powell, 1998). The diagram was constructed for a pressure of 7 kbar, and this average of the peak conditions of regional metamorphism (e.g. Murtezi, 2003; Žačková & Štípská, 2004) was found to correlate with the tectonic stage D2. The mineral abbreviations used in this paper are after Kretz (1983).

The entire documentation of this study (oriented marble samples, thin sections, mineral analyses) is stored in the Institute of Geological Sciences of the Polish Academy of Sciences, Department of Geology of the Sudetes, Podwale 75, Wrocław, Poland.

PETROGRAPHY AND MINERALOGY

The modal content of the carbonates in most of the marbles of the Lądek-Śnieżnik Metamorphic Unit varies form 92 to 99% with pure marbles having a content above 95%, as per the classification of Rosen *et al.*, 2004. The major minerals are calcite and dolomite. They are usually concentrated in monomineralic laminae or lenses. The minor metamorphic minerals are white micas, Mg-biotite, Mg-chlorite, K-feldspar, plagioclase, Ca-amphibole, Ca-clinopyroxene and epidote-clinozoisite. The diverse mineral habits, volume proportions and spatial arrangements all resulted from the different chemical compositions of the protoliths, metamorphic conditions and intensity of dynamic recrystallisation, and define specific structures of the marbles: planar or non-planar, homeoblastic or heteroblastic, grano- or lepidoblastic. The condensed petrographic description of the LSMU marbles is presented in Table 3. In this paper, on the basis of the Cal-Dol ratio, the marbles are subdivided into four groups: (i) calcite marbles, (ii) calcite-dolomite marbles, (iii) dolomite-calcite marbles and (iv) dolomite marbles (Tab. 3).

Calcite

The wide range of volume proportions of calcite and dolomite in the marbles means that calcite is present in various amounts of rock volume (Tab. 3). The calcite blasts form anhedral crystals with a slight anisomertic habit, ca. 1 mm in diameter on average with maximum diameters up to ca. 6 mm. The calcite boundaries with silicate minerals are straight, whereas those with the surrounding carbonates are irregular, indicating their recrystallisation by the grain boundary migration (Schmid *et al.*, 1980). The less frequent straight boundaries and polygonal shapes of calcite aggregates indicate the decrease in total free surface energy by grain boundary area reduction (as in Passchier &

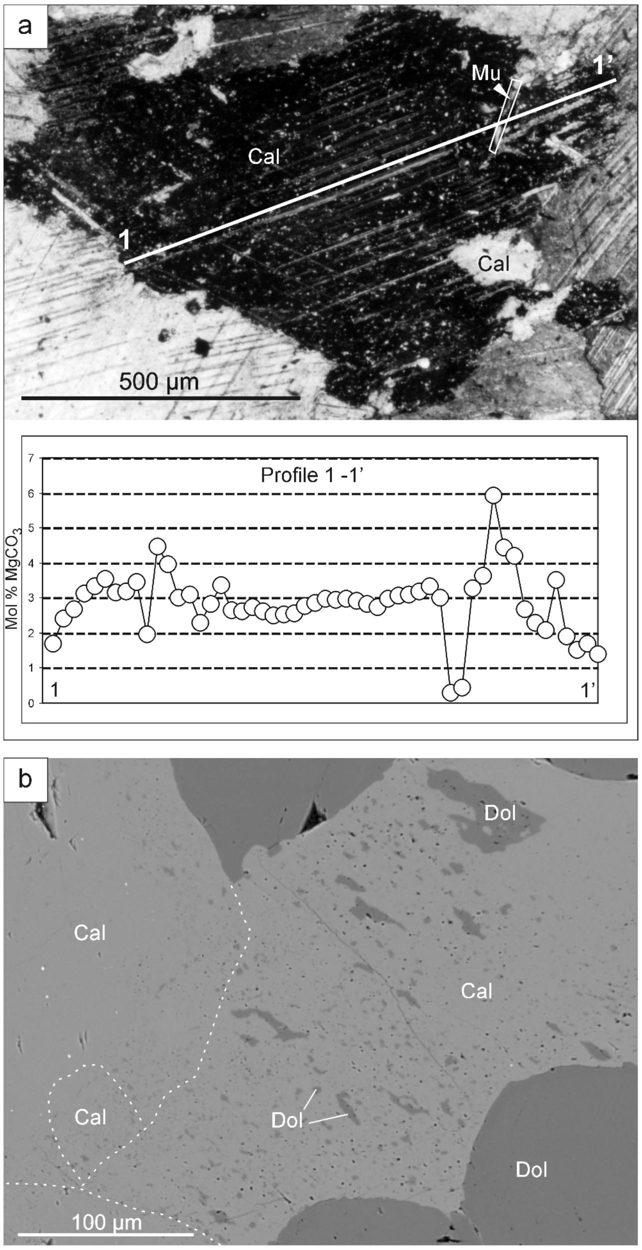

Fig. 2. a. A representative traverse analysis through a D2-related calcite blast. The profile displays a nearly constant Mg-concentration in the inner calcite part and a decreasing trend with an irregular Mg-content towards the calcite rim. This shows the presence of submicroscopic-scale dolomite exsolutions synchronous with the Mg-depletion of the calcite edges. **b.** Back-scattered electron image showing dolomite exsolutions developed both near the calcite edges and within its core, resulting from the chemical reequilibration during retrogression.

Trouw, 1998), which partially overprinted a pre-existing fabric during periods of static recrystallisation. In the dolomite-bearing marbles, calcite mainly forms millimetre- to centimeter-scale laminae. Occasionally, it is interstitial between dolomite grains or forms veins of varying size (from 1 mm to a few decimetres across), cross-cutting the rock lamination. The Mg-content in the calcites of the dolomite-bearing marbles varies from 2.0 to 6.9 Mol% $MgCO_3$, and it is heterogeneous within a single grain. Moreover, the average Mg-content of single calcites can differ in a wide range, even in adjoining grains. The inner parts of the calcites are characterised by a constant Mg-concentration with differences not exceeding 0.3 Mol% $MgCO_3$, whereas traverses across the rims reveal a distinctly irregular pattern with an Mg-decreasing trend towards the grain boundaries (Fig. 2a). Accordingly, the back-scattered electron images and Mg-Kα intensity mapping of several retrogressed magnesian calcites revealed dolomite exsolution mainly gathering within the rims of the calcites and along the grain boundaries. In some cases, the dolomite exsolutions locate within a whole grain (Fig. 2b). The disturbance in the decreasing trend of the Mg content for calcite rims towards their edges may suggest that dolomite exsloution also occurred on a submicroscopic scale. By contrast, the chemical analyses of calcites from the calcite marbles show a very low Mg-content (up to 0.3 Mol% $MgCO_3$). The Fe-content in the calcites varies from 0 to 1.8 Mol % $FeCO_3$ and is generally higher in more Mg-rich blasts.

Dolomite

Dolomite blasts tend to be more anisometric and finer-grained than calcites (Fig. 5b, 5d) (ca. 0.3 mm in diameter). The dolomite blasts form mainly anhedral grains with irregular, curved boundaries or, occasionally, subhedral rhomboidal grains. Elongated or flattened blasts are orientated parallel to the rock lamination. The size diversity of the two carbonate minerals led to the development of the lamination recognised on the mesoscale in the marbles, even with a deficiency of micas.

Biotite

Biotite is present in nearly half of the studied marble outcrops (Fig. 8). Its content is up to 5% of the rock volume. Depending on the volume, it is distributed as single flakes in a carbonate matrix or it is concentrated in Bt-Ms ± Chl ± Ep(Czo) laminae. In most cases, the biotite flakes are orientated parallel to the main rock lamination. Their size ranges from tens of micrometers to ca. 1.5 mm across. Most of the analysed biotites plot in phlogopite quarter and give an X_{Mg} = (Mg/Mg + Fe) = 0.86–0.99 (Tab. 2). In the dolomite-absent marbles, the biotites are considerably more Fe-rich (X_{Mg} = 0.52). Alternate Mg-rich chlorite and quartz occur along the cleavage planes and near the flake margins (Fig. 3f).

White micas

White micas are locally present within laminae composed of phyllosilicate minerals (Figs 5b, 6e) or as sparse single flakes (Fig. 5d). Forming up to 2.0-cm long flakes, they are mainly oriented parallel to the main rock lamination. On the basis of the Si-content, the white micas can be divided into two groups with ca. 6.12 and ca. 6.35 Si per formula unit.

Ca-amphibole

Ca-amphibole has been noted as a minor component of the dolomite laminae in a few occurrences, i.e. Nowy Waliszów, Lutynia, Kletno, Mt. Janowiec, and quarries in the Mt. Krzyżnik area (Zielona and Biała Marianna layers)

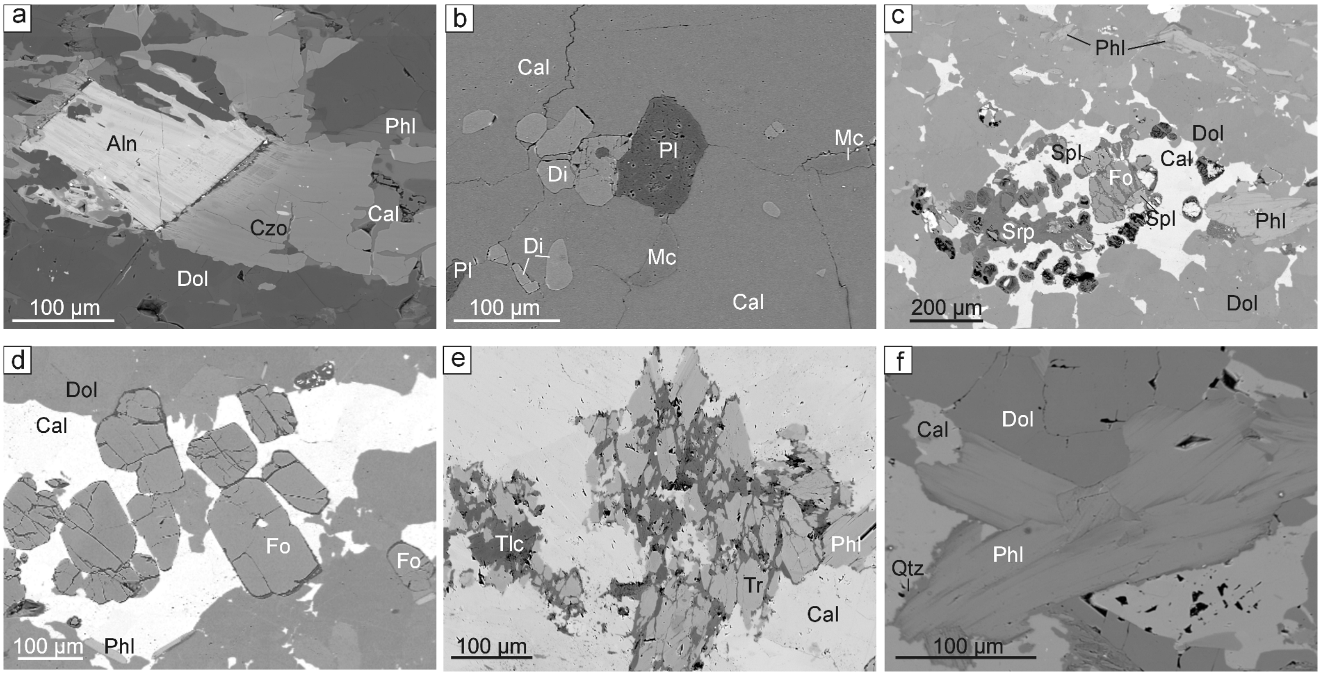

Fig. 3. **a.** Allanite and clinozoisite in the calcite-dolomite marbles from the Krzyżnik quarry. **b.** Ca-pyroxene, phlogopite and K-feldspar in calcite marbles from Lutynia. **c.** Lenses composed of calcite, serpentinized Mg-olivine and spinel within the martix consisting of dolomite and phlogopite. From Złoty Stok. **d.** Mg-olivine in dolomite-calcite marbles from Złoty Stok. **e.** Ca-amphibole partially replaced by talc accumulated near the edges and along the cleavage planes in calcite-dolomite marbles from the Stronie Śląskie quarry. **f.** Mg-biotite with alternate chlorite in the calcite-dolomite marbles from the Janowiec Mt.

Table 1

Selected chemical analyses of calcites from the marbles of the Lądek-Śnieżnik Metamorphic Unit

	Di-in			*Tr-in*		*Tr-out, Phl-in*				*Tr-in*		Tr-out, *Phl-in*			
	S and E of the OSD			SE of the Krowiarki		mid. of the Krowiarki		NW of the Krowiarki		SE of the Krowiarki		mid. od the Krowiarki		NW of the Krowiarki	
Sample	L8a	Lu3b	JG2	S1m	S1m	Ro11	Ro11	Ż14	Ż14	K1a	K1a	Ż35	Ż35	Ż25	Ż25
Analysis	Cal21	2b17	2f05	Cal21	Cal21b	4d05	4d06	4e05	4e06	Cal1	Cal1b	Cal2ś	Cal2b	Cal2ś	Cal2b
Mineral	Cal	Cal	Cal	Cal core	Cal rim	Cal core	Cal rim	Cal core	Cal rim	Cal core	Cal rim	Cal core	Cal rim	Cal core	Cal rim
Structural position	S2	S2	S2	S2	S2	S2	S2	S2	S2	L3/S3	L3/S3	L3/S3	L3/S3	L3/S3	L3/S3
Wt%															
FeO	0.14	0.03	0.17	0.24	0.52	0.14	0.14	0.02	0.04	0.64	0.31	0.04	0.06	0.05	0.00
MnO	0.00	0.00	0.93	0.06	0.00	0.05	0.00	0.12	0.18	0.03	0.00	0.00	0.00	0.06	0.06
MgO	0.11	0.34	0.16	2.35	1.26	1.91	1.29	1.41	1.13	1.78	1.35	0.96	0.33	1.07	0.80
CaO	53.16	56.19	53.98	51.09	53.44	55.33	53.92	56.04	56.80	52.75	53.38	54.95	54.87	53.01	52.69
Total	53.41	56.56	55.24	53.74	55.22	57.43	55.35	57.59	58.15	55.20	55.04	55.95	55.26	54.19	53.55
Fe^{2+}	0.004	0.001	0.005	0.007	0.015	0.004	0.004	0.001	0.001	0.018	0.009	0.001	0.002	0.001	0.000
Mn	0.000	0.000	0.027	0.002	0.000	0.001	0.000	0.003	0.005	0.001	0.000	0.000	0.000	0.002	0.002
Mg	0.006	0.017	0.008	0.120	0.063	0.091	0.064	0.067	0.054	0.089	0.068	0.047	0.017	0.055	0.041
Ca	1.990	1.982	1.960	1.872	1.922	1.903	1.932	1.929	1.940	1.892	1.924	1.951	1.982	1.942	1.957
Total	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
$CaCO_3$	99.5	99.1	98.0	93.6	96.1	95.2	96.6	96.4	97.0	94.6	96.2	97.6	99.1	97.1	97.8
$MgCO_3$	0.29	0.83	0.4	5.99	3.15	4.57	3.21	3.37	2.68	4.44	3.38	2.37	0.83	2.73	2.07
$FeCO_3$	0.2	0.04	0.24	0.34	0.73	0.19	0.2	0.03	0.05	0.9	0.44	0.06	0.08	0.07	0
$MnCO_3$	0	0	1.34	0.09	0	0.07	0	0.16	0.24	0.04	0	0	0	0.09	0.09
T °C *				565	450	512	445	470	409	513	458	385		413	357

The calcites are normalized to 2 cations per formula unit. The low Mg-content in the calcite rims resulted from their chemical re-equilibration. The low Mg-content in the calcites of the samples from Kamienica (L8a), Lutynia (Lu3b) and Janowa Góra (JG2) (Fig. 1) is due to the low Mg-saturation in the dolomite-absent calcite marbles. Nd. – not determined. (*) Temperatures calculated according to the calibration of Annovitz and Essene (1987).

Table 2

Selected chemical analyses of index minerals from the marbles

	Tr-out		*Tr-in*						*Di-in*							
Sample	Kl8b	Kl8b	J3b	J3b	J3b	J3b	S1	S1	Lu3b	Lu3b	L8a	L8a	Lu3b	Lu3b	ZS7a	ZS7a
Analysis	Bt 06	Bt 07	Bt1 śr	Bt1 brz	amf1	amf2	Amf 1 śr	Amf 1 brz	amf 1 sr	amf 1 br	Di 1c	Di 1r	Di 1c	Di 1r	Fo 12	Spl 17
Mineral	Bt core	Bt rim	Bt core	Bt rim	Amp core	Amp rim	Amp core	Amp rim	Amp core	Amp rim	Di core	Di rim	Di core	Di rim	Fo	Spl
	Wt%															
SiO_2	40.34	38.35	40.62	39.59	57.55	57.08	55.77	55.42	56.28	55.65	53.97	53.87	54.66	54.29	42.15	0.03
TiO_2	1.45	1.21	0.53	0.05	0.05	0.09	0.21	0.08	0.12	0.00	0.00	0.00	0.23	0.10	0.00	0.02
Al_2O_3	17.17	17.33	18.54	18.86	1.85	2.42	2.93	3.70	2.48	2.10	0.95	0.39	0.92	0.90	0.00	69.10
FeO*	4.7	3.95	1.54	1.41	0.96	1.04	2.40	3.68	2.71	3.55	5.20	5.79	0.90	1.36	1.54	1.37
MnO	0.00	0.05	0.05	0.05	0.00	0.07	0.00	0.13	0.07	0.00	0.34	0.31	0.11	0.00	0.08	0.09
MgO	20.68	20.8	23.64	23.48	22.64	22.80	21.83	20.86	19.80	18.88	14.23	14.08	16.89	17.40	54.97	25.02
CaO	0.33	0.37	0.00	0.11	13.51	13.29	13.51	12.95	14.76	14.85	24.52	24.48	25.08	25.12	0.16	0.06
Na_2O	0.22	0.11	0.17	0.14	0.22	0.28	0.33	0.34	0.24	0.19	0.43	0.29	0.37	0.33	N.d.	N.d
K_2O	10.10	9.13	10.00	9.46	0.07	0.04	0.03	0.07	0.23	0.00	0.00	0.05	0.00	0.00	N.d.	N.d
ZnO	N.d.	N.d.	N.d.	N.d.	N.d.	N.d.	N.d.	N.d.	N.d.	N.d.	N.d.	N.d.	N.d.	N.d.	N.d.	3.04
Total	94.99	91.30	95.09	93.15	96.85	97.11	97.01	97.23	96.69	95.22	99.64	99.26	99.16	99.50	98.90	98.73
Si	5.726	5.631	5.659	5.615	7.932	7.818	7.718	7.654	8.028	8.107	1.997	2.007	1.993	1.979	1.005	0.006
Ti	0.155	0.134	0.056	0.005	0.005	0.009	0.022	0.008	0.013	0.000	0.000	0.000	0.006	0.003	0.000	0.003
Al	2.873	2.999	3.043	3.153	0.300	0.391	0.478	0.602	0.417	0.361	0.042	0.017	0.040	0.039	0.000	15.983
Fe	0.558	0.485	0.179	0.167	0.111	0.119	0.278	0.425	0.323	0.432	0.161	0.180	0.027	0.041	0.031	0.225
Mn	0.000	0.006	0.006	0.006	0.000	0.008	0.000	0.015	0.008	0.000	0.011	0.010	0.003	0.000	0.002	0.015
Mg	4.376	4.553	4.910	4.965	4.652	4.655	4.504	4.295	4.211	4.100	0.785	0.782	0.918	0.945	1.953	7.316
Ca	0.050	0.058	0.000	0.017	1.995	1.950	2.003	1.916	2.256	2.318	0.972	0.977	0.980	0.981	0.004	0.013
Na	0.061	0.031	0.046	0.038	0.059	0.074	0.089	0.091	0.066	0.054	0.031	0.021	0.026	0.023	-	-
K	1.829	1.710	1.777	1.712	0.012	0.007	0.005	0.012	0.042	0.000	0.000	0.002	0.000	0.000	-	-
Zn	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.440
Total	15.627	15.607	15.675	15.678	15.066	15.031	15.097	15.019	15.364	15.371	3.998	3.996	3.994	4.011	2.995	24.000
Mg/(Mg+Fe)	0.88	0.90	0.96	0.97	0.98	0.98	0.94	0.94	0.93	0.90	0.83	0.81	0.97	0.96	0.98	0.97

Mg-biotite is normalized to 22 oxygens. Ca-amphibole is normalized to 13 cations+Na+K+Ca. Ca-pyroxene is normalized to 6 oxygens. Mg-olivine is normalized to 4 oxygens. Spinel is normalized to 32 oxygens. (*) Total iron as FeO.

(Fig. 5d). It occurs as elongate prisms up to 1 mm in diameter, with either diamond or needle cross sections (Fig. 3e). Ca-amphibole exhibits the composition of tremolite and shows slight zoning from core (X_{Mg} = (Mg)/(Fe^{2+}+Mg) = 0.90) to rim (X_{Mg} = 0.94) or forms nearly pure tremolite (X_{Mg} > 99) (Tab. 2). It is partially replaced by talc accumulated near the edges and along cleavage planes (Fig. 3e).

Ca-pyroxene

Ca-pyroxene is limited to the calcite marbles occurring near Lutynia, Janowa Góra and Kamienica, in close adjacency to the Śnieżnik orthogneisses. It constitutes up to 6% of the rock volume and forms small rounded grains up to 300 µm in diameter (Fig. 3b). The chemical analyses do not reveal any zonation in the Mg/Fe ratio in any of the examined blasts. Their Ca/Mg/Fe proportions situate the analysed Ca-pyroxenes in the diopside field. Their X_{Mg} varies from 0.78 to 0.99. Ca-pyroxene regularly coexists with K-feldspar and plagioclase, occasionally, with vesuvianite (Kamienica) and phlogopite (Lutynia).

Plagioclase

Plagioclase is noted sporadically in calcite or calcite-dolomite marbles. It occurs as isolated small rounded grains up to 400 µm in diameter, or lens-shaped aggregates up to 1 mm long. It usually lacks twinning. Chemical analyses of plagioclase can generally be divided into two groups: Ab = ~99 and Ab = 79–86.

Epidote/clinozoisite group

Epidote/clinozoisite minerals form elongate to short prismatic subhedral grains, regularly ca. 500 µm long, max. 2.5 mm long. The greenish core and colourless rim reveal their compositional zoning, characterised by a decrease in the pistacite member from core (Fe/(Fe+Al) = 0.30–0.31) to rim (Fe/(Fe+Al) = 0.20–0.24). The brownish epidote cores in the calcite-dolomite marbles from the quarry on Mt. Krzyżnik contain a considerable REE content –

Table 3

Petrographic characteristics of representative marble samples

Classification	Mesoscopic character	Avg. mineral composition	Petrography	Localisation	Mineral composition	Accessory minerals
Calcite marbles- Dol 0-5%	White, with subordinate pink or grey bands or lenses	Cal - 90-99% Dol - 0-5% Kfs - 0-3% Di - 0-3% Ms - 0-2% Tr - 0-2% Czo - 0-2% Qtz - 0-2%	Medium-grained homeoblastic marble with granoblastic fabric defined by nearly isometric calcite, microcline and Ca-pyroxene blasts. Occasionally, the presence of platy orientated plate- or needle-shaped minor silicates causes either weak foliation or mineral lineation	Janowa Góra	Cal, Di, Kfs, Pl, Ep, Fl	Zrn, Ttn
				Kamienica	Cal, Di, Kfs, Pl, Vsv	
				Lutynia	Cal, Di, Kfs, Phl, Tr, Ms, Qtz	Ilm, Rt, Ttn, Mag
				Lądek Zdrój	Cal, Qtz, Ms, Bt	Chl
				Ołdrzychowice	Cal, Qtz, Ms	
				Krzyżnik Mt.	Cal, Tr, Czo, Ms, Dol	
				Radochów	Cal, Qtz, Pl, Kfs, Ms	
Calcite-dolomite marbles- Dol < Cal < 95%	Greyish-white, occasionally striped by the white and coloured constituent minerals	Cal - 75-90% Dol - 5-25% Phl - 0-3% Tr - 0-2% Czo - 0-2% Ms - 0-2% Qtz - 0-2%	1-5 mm scale mineral banding composed of alternating laminae of calcite, dolomite and sporadically quartz. Heteroblastic (fine-grained dolomite, medium-grained calcite) marbles with grano- or lepidoblastic fabric defined by flattened dolomite and plate- or needle-shaped minor silicates. The size diversity of both carbonate minerals causes this lamination also seen in mesoscale, even with a deficiency of micas. At contacts with metapelites, Cal-Dol lamination is nearly parallel to rock boundaries	Chłopek Mt.	Cal, Qtz, Dol, Phl, Ms	
				Janowiec Mt.	Cal, Dol, Qtz, Phl, Tr	Chl
				Krzyżnik Mt.	Cal, Dol, Qtz, Phl, Ms, Pl, Czo, Aln	
				Stronie Śląskie	Cal, Dol, Qtz, Tr, Ms, Phl, Czo	Tlc, Chl
				Kletno	Cal, Dol, Phl, Qtz, Chl	
				Rogóżka	Cal, Dol, Phl, Qtz, Ms	Rt, Py
				Żelazno	Cal, Dol, Qtz, Ms, Phl	
Dolomite-calcite marbles- Dol > Cal > 5%	White, yellowish- or greyish-white	Dol - 70-90% Cal - 5-30% Qtz - 0-3% Ms - 0-2% Phl - 0-2% Chl - 0-2%	Fine- or medium-grained marbles. Calcite laminae or lenses. Grano- or lepidoblastic fabric marked by anisometric dolomite and flakes of phlogopite and white micas scattered in matrix or accumulated along thin laminae, considerably emphasising planar structure	Piotrowice	Dol, Cal, Ms	Qtz
				Ołdrzychowice	Dol, Cal, Ms	Qtz
				Nowy Waliszów	Dol, Cal, Ms, Qtz, Tr	Tlc, Tur
				Żelazno	Dol, Cal, Chl, Ms, Qtz	Rt
				Mielnik	Dol, Cal, Ms, Qtz	Rt
				Złoty Stok	Dol, Cal, Fo, Sp, Phl, Srp	Ap, Py, Sp
Dolomite marbles- Dol > 95%	Yellowish- or greyish-white, often veined	Dol - 95-99% Phl - 0-3% Chl - 0-2% Ms - 0-2%	Fine-grained rock with grano- or lepidoblastic fabric (often mylonitic) defined by platy orientation of Mg-chlorite, white micas as well as elongated quartz lenses	Żelazno	Dol, Chl, Ms, Cal	
				Romanowo	Dol, Chl, Ms	

$Ca/(Ca+Ce+Nd+Y+La) = 0.75$. Sparse analysed epidotes from Janowa Góra are characterised by a high Mn content ($Fe/Fe+Mn = 0.16$).

Mg-olivine

Mg-olivine forms euhedral or anhedral grains up to 200 μm in diameter. They regularly contain irregular cracks partially replaced by alternate serpentine (Fig. 3d). It has a homogenous chemical composition of Mg-rich forsterite ($Mg/Mg+Fe = 0.98$). Its occurrence is restricted to marble bodies located 2 km southwest of Złoty Stok.

Spinel

Spinel usually forms colourless isometric grains with maximum diameters of 150 μm and a mean near 50 μm. It is characterised by a low Fe content ($Mg/Mg+Fe = 0.97–0.98$). It occurs in up to 3-mm long calcite lenses in the dolomite-calcite marbles near Złoty Stok, where it coexists with Mg-olivine (Fig. 3c, d).

MESO- AND MICROSTRUCTURAL CHARACTERISTICS

Structural record

Numerous tectonic structures representing ductile, medium-grade metamorphic conditions and continuing to more brittle, low-grade ones were preserved in the marbles of the Lądek-Śnieżnik Metamorphic Unit. Scarce, small-scale intrafolial, rootless folds are the deformation structures recognisable in the mineral layering of Cal and Dol

(Fig. 5a). They are characterised by non-cylindrical up to sheath geometry with thickened, disharmonic hinges. Their axial plane fabric usually formed parallel to the folded bedding planes.

Tight, often similar, strongly inclined to recumbent folds developed in an early metamorphic fabric composed of well-developed quartz laminae alternating with the Cal-Dol segregation (Fig. 5c, d). The orientation of the axes of these tight folds scatters slightly from the N–S direction and has a maximum of 348/20 (Fig. 4a). The tight folds are non-penetrative over the study area. Their abundance is characteristic for the Zielona Marianna layer, on the western slopes of Mt. Krzyżnik, where they form a set of parasitic mesofolds associated with a higher-order synform. The axial planes of the tight folds are defined by the shape-preferred orientation of the carbonates (Cal-Dol) and parallel alignment of plate- and needle-shaped silicates (Phl-Ms±Tr±Czo) (Fig. 5d). In the impure calcite-dolomite marbles, because of the tight interlimbs, the grain shape axial fabric generally mimics or intersects the Cal-Dol-silicate layering at low angles. In the hinge zones of the tight folds, the preferred orientation of the scattered phyllosilicates is oblique to the relics of folded early quartz laminae, but parallel to the axial planes of these folds. The folds are less penetrative than the foliation; however, this microstructural evidence indicates that the penetrative grain shape fabric in the LSMU marbles is related to the tight folds striking generally in the N–S (NNW–SSE) direction.

The spatial orientations of the axial plane foliation to the tight folds differ over the LSMU area, considerably varying even in the neighbouring areas (Fig. 4d). In the Krowiarki range, the penetrative Cal-Dol-Phl-Ms±Tr foliation generally dips towards the NE, N or NW, usually at low and rarely at high angles. Near Stronie Śląskie, it mainly dips toward the NE. By contrast, it assumes a subvertical to vertical dip and N–S strikes near Złoty Stok. On the stereographic projections, the poles to the main foliation in the NW parts of Lądek-Snieżnik occasionally form a girdle of great circles with common girdle axes near 330/15 (Fig. 4d). The poles to the planes, the orientations of which were measured in the Krzyżnik, Janowiec and Chłopek Mts., locally form a belt with girdle axes near 40/40 (Fig. 4d). A weakly visible E–W trending mineral lineation on the folded planes and better-preserved intersection lineation due to the intersection of the folded planes and the axial planes are observed. On the folded planes, the intersection lineation manifests as frequently arranged thin trails of axial grain shape fabric. On the exposed axial planes of the tight folds, the intersection lineation occurs as differently thickened and shaded bands, depending on the thickness and colour of the folded beds (Fig. 5f).

Zonally, a reworking of the fabric into a planar-linear or linear one is characterised by a sequence of deformed marbles from protomylonies to S-C or S-C' mylonites. The calcite protomylonites are characterised by the presence of large elongated porpyroclasts enclosed within the matrix of small-scale slightly elongated calcite grains (Fig. 6c). In the calcite and dolomite mylonites, the porphyroclasts are absent, and calcite and dolomite blasts were recrystallized. (Fig. 6d, e). The elongated carbonate grains are accompanied by linearly accumulated carbonates in the pressure shadows of less ductile domains, e.g. boudinaged Czo porphyroclasts (Fig. 6a, d). The elongated fabric elements form a stretching lineation plunging towards the N, NNE or NW at moderate angles, overlying the penetrative foliation (Fig. 4b). Sporadically, in the originally non-foliated, granoblastic marbles, the mylonitic planes evince the variable orientation, but still parallel to the meridional, stretching lineation. Additionally, asymmetric microstructures, i.e. s-porphyroclasts of Czo with asymmetric pressure shadows composed of Cal-Phl, and S-C- and more frequent S-C'-type mylonites, were found in thin sections cut parallel to the mineral lineation (Fig. 6d, e). The S-cleavage of the S-C' structures is mainly parallel to the preferred alignment of carbonate and silicate minerals forming the penetrative foliation (Ms-Phl laminae), whereas the C'-cleavage occurs as microfaults intersecting the S-planes at angles of 20–30° (Fig. 6e).

Within the interlayers banded by the penetrative foliations, non-penetrative concentric folds deforming the penetrative foliation occur (Fig. 6b). Their longer limbs are oriented nearly parallel to the penetrative grain shape fabric. They are characterised by prominent N-asymmetry corresponding to the shear zones. In the Biała Marianna marble layer, they are associated with up to 3-m long lenses of boudinaged amphibolite and quartz-bearing mica schists within less viscous marbles. The E–W or NE–SW trending boudinage mesostructures are best preserved in marble outcrops from Mielnik and Ołdrzychowice. The asymmetric and symmetric fabric elements (foliation, stretching lineation, boudinage, S-, C- and C'-cleavages, concentric folds), localized in shear zones differing widely in their width from tens of meters to centimeter-scale narrow bands, appeared locally across the study area and zonally within individual outcrops. They were best preserved in the Krowiarki range and the Złoty Stok-Skrzynka Shear Zone.

Parallel concentric or kink folds, ranging in amplitude from several meters down to the microcrenulation scale, form the crenulation lineation in the adjoining mica schists (Fig. 6g). Their axes plunge towards the NW (N). The mesofolds are mainly vertical, but the largest concentric folds recognised in Romanowo quarry are W-inclined. The orientations of the fold axes and the crenulation lineation exhibit a maximum of 330/10, which concurs with the orientation of the girdle axes of the belt of poles to the penetrative foliation in the stereographic projections for the Krowiarki range (Fig. 4c, d).

The NW-plunging folds dominating in the NW part of the area disappear towards the E and S in favour of NE-plunging ones (compare Fig 2c and 2d). The axes of these open, vertical, concentric or kink folds plunge towards the NE at moderate angles. Their axial planes developed as complementary surfaces – 330/60 and 120/70.

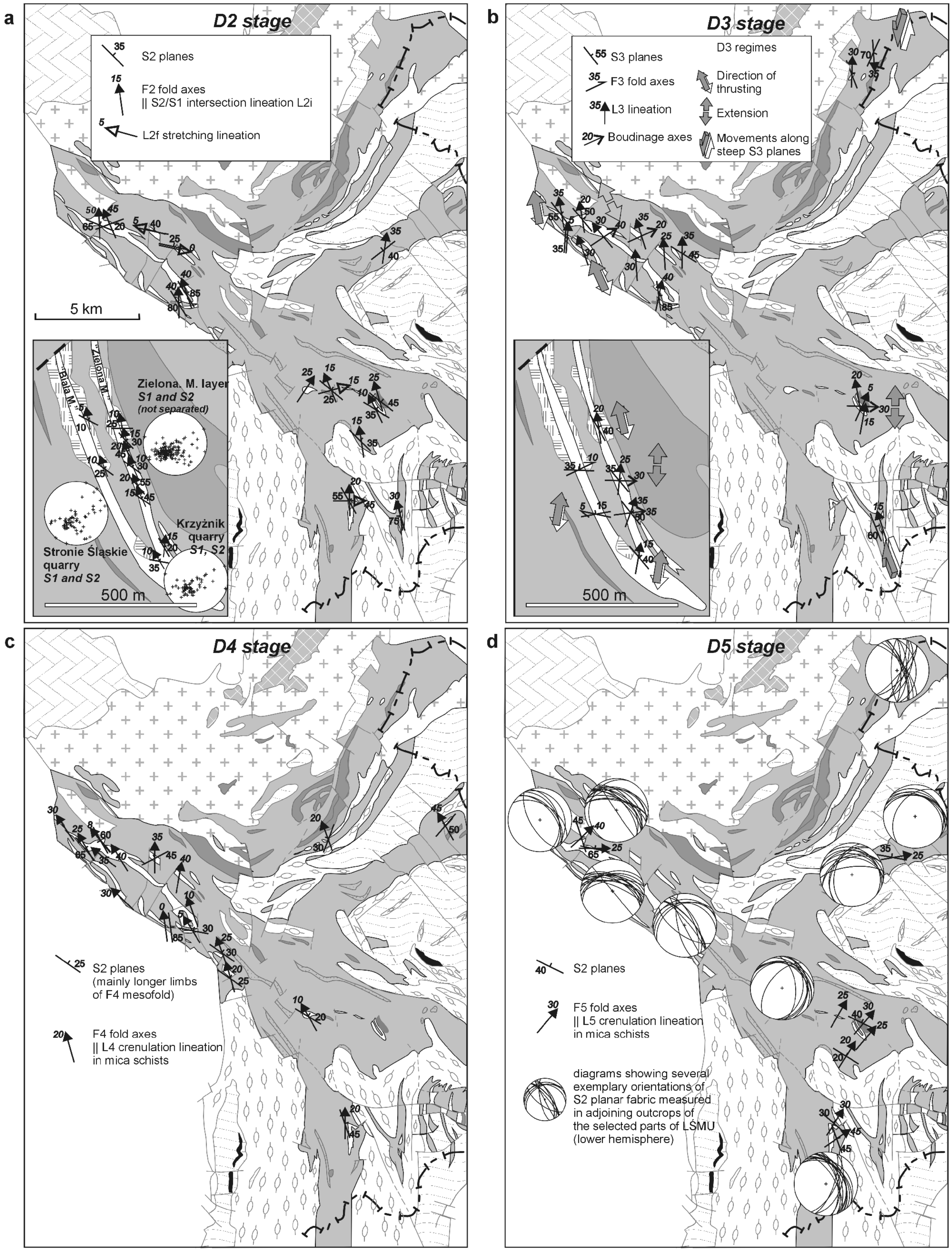

Fig. 4. Tectonic maps showing the orientation and distribution of the deformational structures correlated with consecutive tectonic stages on the geological map of the LSMU (modified after Sawicki, 1995) and the geological map of the Krzyżnik Mt. region (Cwojdziński, 1983)

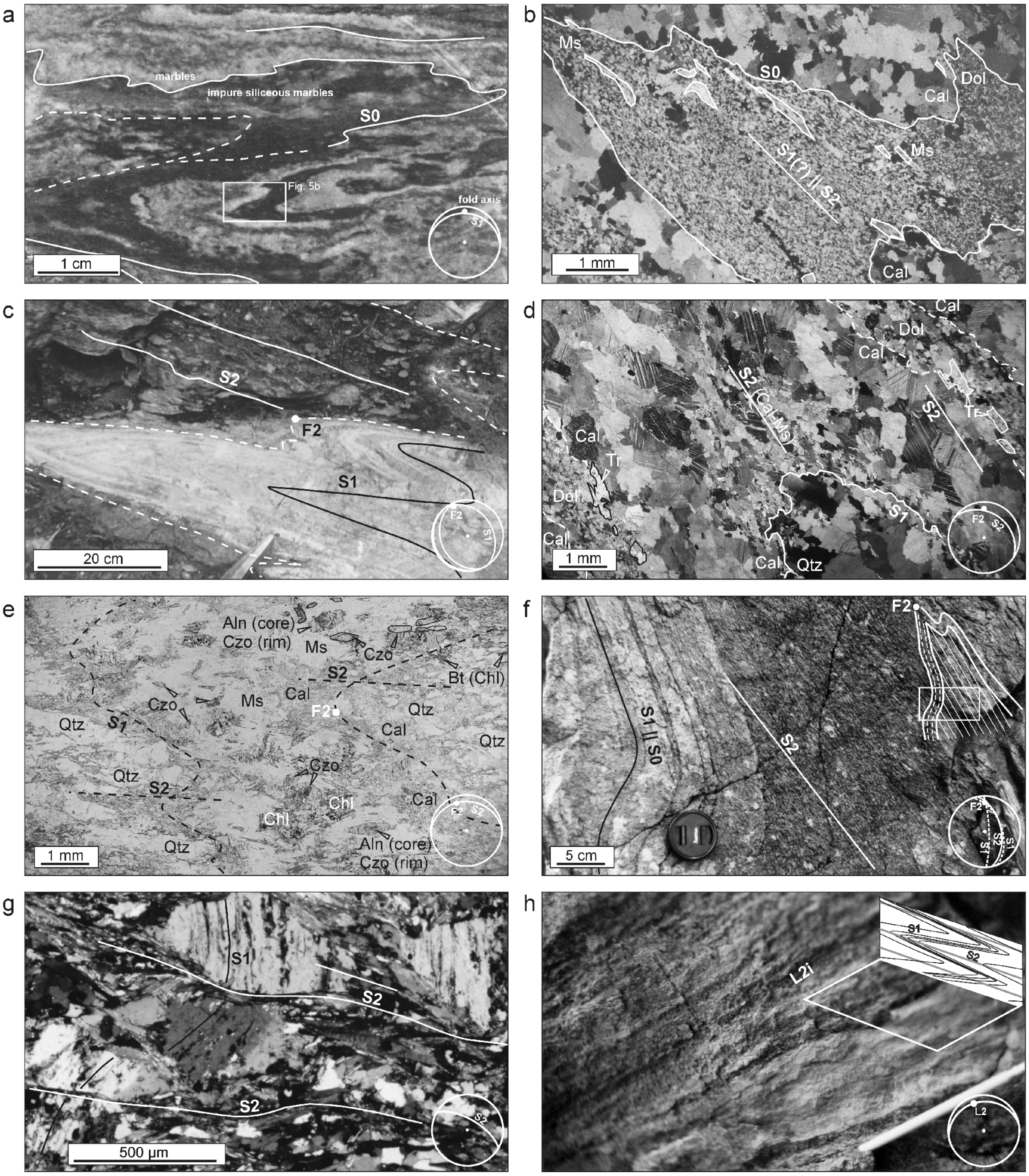

Fig. 5. Meso- and microstructures associated with D1 and D2, in the marbles and adjacent rocks of the Stronie formation. **a.** A small-scale intrafolial disharmonic fold developed in the mineral layering. From the Krzyżnik quarry. The bracket shows the area of Fig. 5b. **b.** Segregation of the phyllosilicate minerals into individual laminae in the hinge zone of the microfold. Due to its intrafolial geometry, its axial planar fabric overlays the S2 planes. **c.** 3rd order and parasitic 4th order F2 folds developed in contacting marbles and mica schists, connected with the large-scale synform in the Krzyżnik Mt. region. The F2 folds are more evident within the calcite-dolomite marbles than in the surrounding fine-grained metapelites, where the mainly quartz-biotite axial schistosity appeared as a predominant tectonic feature. **d.** The development of the S2 axial planar foliation in the marbles marked by the grain shape fabric of the carbonates and the parallel arrangement of tremolite and phyllosilicates. Stronie Śląskie quarry. **e.** An F2 microfold in the calc-silicate rock. The development of the S2 axial planar fabric was associated with the transposition of white micas and biotite flakes and the growth of the Czo porphyroblasts. The boundaries of some Czo blasts have been outlined in the upper-right corner of the photograph. From the Stronie Śląskie quarry. **f.** The relationship between the S1 || S0 layering and the S2 foliation, which developed parallel to the axial planes of the F2 mesofolds in the mica schists. From Kletno. The S1 planes were preferably preserved in the coarse-grained quartz-bearing mica schists, while the S2 schistosity is more common in the fine-grained micaeous varieties. **g.** Relics of S1 planes preserved in plagioclase cores and the external S2 axial schistosity. Within the plagioclase cores, traces of the internal fabric define the geometry of the superposed F2 folds, while the plagioclase pressure shadows include the minerals of the matrix. From Mielnik. **h.** The L2i intersection lineation, occurring as differently thickened and shaded bands on the exposed S2 surface in calcite-dolomite marbles. From natural outcrops on the western slopes of the Krzyżnik Mt.

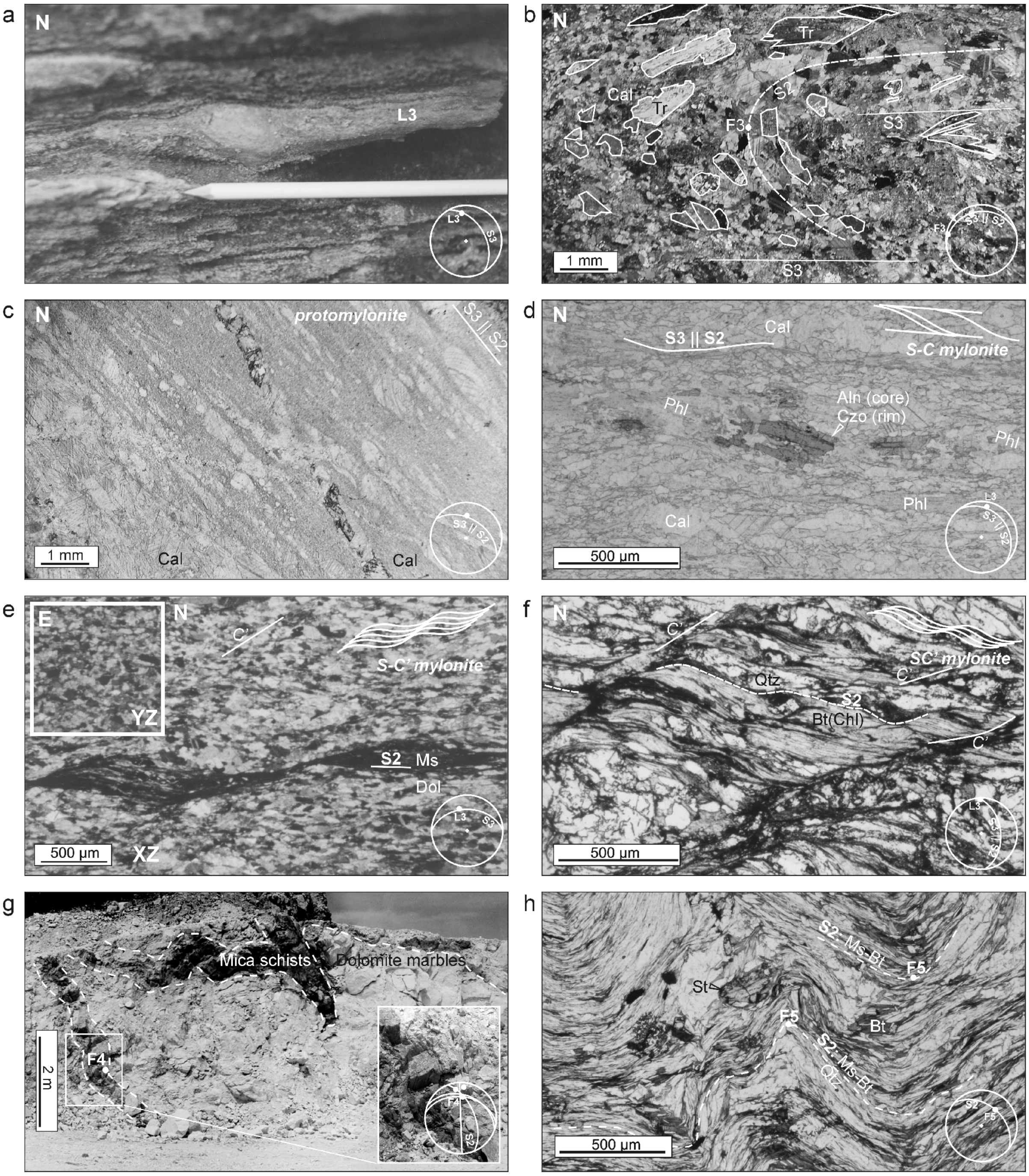

Fig. 6. Meso- and microstructures associated with D3, D4, and D5. **a.** An asymmetric ó-type calcite porphyroclast within the impure marbles, indicating the top-to-the-N sense of shear. Its deformation and the accumulation of new calcite in its pressure shadows took place under ductile conditions of deformation. **b.** F3 folds deforming the S2 structural planes mainly defined by a parallel alignment of Tr porphyroclasts in the calcite marbles from the Stronie Śląskie quarry. **c.** The structural reworking during D3 in the calcite marbles from Ołrzychowice, from outcrops close to a railway trench. **d.** Separated Aln-Czo porpryroclasts along the L3 lineation, within an S-C-type fabric in the calcite-dolomite marbles from the Krzyżnik quarry. **e.** Contrasting grain shape fabric in XZ (parallel to L3) and YZ (perpendicular to L3) sections in S-C' mylonite. The angular relationships between the S and C' cleavage planes (e.g. Blenkinsop & Treloar, 1995) indicate the shearing component orientated nearly parallel to the S2 planes. From the dolomite marbles from the Wapniarka Mt. **f.** The development of C'-type planes intersecting the S2 fabric in the mica schists. From Mielnik. **g.** Concentric large-scale F4 folds, associated with small-scale crenulations in the mica schists. From the Romanowo quarry. **h.** F5 microfolds deforming S2 planes composed of a Qtz-Ms-Bt-St assemblage. On the S2, the microfold axes form the L5 crenulation lineation. From Mt. Janowiec.

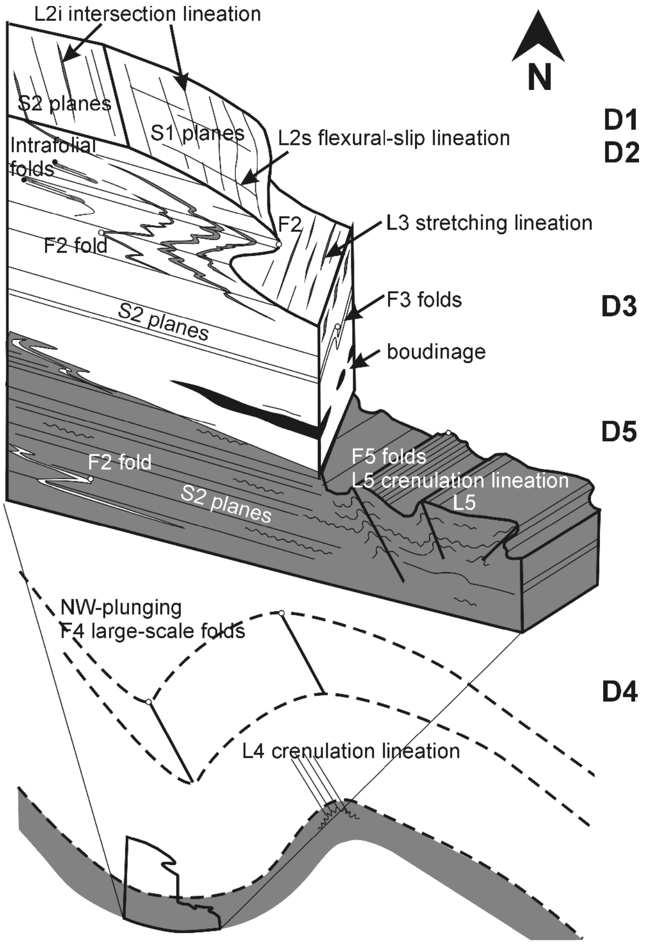

Fig. 7. Blockdiagrams showing the sequence of deformational events in the marbles and adjacent rocks of the Stronie formation in the area of the Krowiarki Mts

Sequence of deformational events

Due to the geometric relationships between the foremost tectonic structures, the folded quartz laminae with the Cal-Dol mineral layering parallel to them are labelled as the S1 planes (Fig. 5d), whereas the tight N–S trending folds deforming them as the F2 folds. The structures related to the F2 folds are accordingly labelled: the axial planes as S2, the N–S trending intersection lineation as L2i (Fig. 5h), the E–W trending stretching lineation as L2s. Their geometry indicates a ductile character of deformation within those highly incompetent layers. The mesoscopic equivalents of the S1 planes could be the small-scale intrafolial folds with the axial plane foliation preserved parallel to the folded bedding planes. However, because of the intrafolial geometry (within the S2 planes), it is not possible to definitively separate the structural and mineral record of the D1 stage from the following D2 (Fig. 5b). It is also possible that some such folds represent deformations assigned to sedimentary flows.

The asymmetrical structures (S-C-, S-C'-type fabrics, σ-clasts, asymmetrical folds) and symmetrical elements of the fabric (boudinage) are superimposed on the S2 fabric (Fig. 6a, b, c, d, e). In Mt. Krzyżnik area, in the XZ sections of the finite strain ellipsoid, the shear sense indicators on the S2 planes invariably show top-to-the-N (NNE) kinematics, and this applies to both limbs of the major synform F2 (Fig. 4b). In addition, the S2-related fabric elements are folded around E–W trending fold axes of N-asymmetry, and boudinaged along the mylonitic fabric. Therefore, the shear zones in which these mylonitic structures occur are assigned to the subsequent tectonic stage – D3. Consequently, the mylonitic structures that were formed in still ductile conditions are labelled as the S3 planes, the stretching lineation as L3 and the folds as F3. The mylonitisation took place under still ductile conditions of deformation.

The geometric relationships between both the NW-plunging and NE-plunging vertical mesofolds and the stretching lineation show that not only the S2 planes but also the mylonitic fabric is deformed by both fold types. The more ductile conditions of deformation and higher temperature conditions of the D3 shearing also confirm its overprinting by the late folding stages occurring under apparently more brittle conditions. However, this could require further confirmation, i.e. the kinematic criteria related to the D3 shearing should evince an opposite sense of shear on the overturned, steep limbs of the NW-plunging macrofolds in the Krowiarki Mts (shown by stereographic analysis of the density of the poles to S2) regarded as the succeeding tectonic features.

NW-plunging and NE-plunging folds rarely occur in one outcrop, so there is not much evidence of their mutual relationship (Fig. 4c, d). The similar geometry of the F4 and F5 folds indicates a comparable low-ductile character of late deformation in marbles. Nevertheless, the extension fractures related to the shorter limbs of the NE-plunging folds reveal somewhat less ductile conditions of deformation, and might be related to the closely following D5.

Structural development in the adjacent rocks

The contrasting rheological properties between the marbles and adjacent rocks induce differences in the constitution of the deformational structures of the various tectonic stages (Tab. 4, Fig. 7). In the mica schists, the equivalent of the isoclinal, disharmonic folds could be the small-scale, rootless, intrafolial folds developed in the relics of quartz horizons. These folds occasionally developed in the distinct marble-mica schist boundaries, showing that the two rocks together experienced the earliest deformational stages. The S1 planes were only preserved within the quartz-bearing mica schists (Fig. 5f). In the common fine-grained micaeous varieties, the dominating schistosity (alternating laminae composed of quartz and phyllosilicates) situates parallel to the transposed S2 planes developed parallel to the axial planes of the F2 folds (Fig. 5f). Therefore, the relics of the S1 planes with the tight F2 folds developed on the S1 foliation are notably less penetrative in the mica schists than in the marbles. In microscale, the planar S1 fabric is observed within the cores of the plagioclase porphyroblasts, where traces of this internal fabric define the geometry of the superposed F2 folds (Fig. 5g). In the calc-

Table 4

A comparison of the deformational structures of the marbles and mica schists related to the consecutive tectonic stages

Stage	Marbles	Adjacent metapelites	Conditions and regime of deformation	Metamorphism
D1	Foliation S1, intrafolial folds (?)	S1 inclusion trails in plagioclase blasts, intrafolial folds (?)	Ductile, E-W compression	Progression
D2	Tight, often similar F2 foldsGrain shape axial planar fabric S2E-W trending, L2f mineral lineation (on S1)N-S trending, L2i intersection lineation (on S1 and S2)	Tight F2 folds S2 axial planar schistosity L2i intersection lineation	Ductile,Vertical flattening	Temperature peak conditions 500–600°C
D3	Shear zones: S-C and S-C' mylonites L3 stretching mineral lineation (on S3||S2)N-asymmetric concentric intrafolial F3 folds Boudinage, Czo σ- and δ-clasts	Shear zones: S-C' mylonites	Ductile, top-to-the-N shearing	Retrogression 400–500°C
D4	Parallel F4 concentric or kink folds	F4 concentric, kink folds L4 crenulation lineation (on S2, S3)	Low-ductile,NE(ENE)-SW(WSW) compression.	Retrogression
D5	Parallel F5 concentric or kink folds	F5 concentric, kink folds L5 crenulation lineation (on S2, S3)S5 crenulation cleavage	Low-ductile, NW(NNW)-SE(SSE) compression	Retrogression

silicate rocks, the development of the S2 axial planar fabric was associated with transposition of the white micas and biotite flakes and growth of the Czo porphyroblasts (Fig. 5e).

As in the case of the S2 fabric in the marbles, the S2 planes in the mica schists were locally reactivated as a result of the subsequent shearing with top to-the-N kinematics, which is evidenced by the development of a C'- cleavage intersecting the main S2 schistosity (Fig. 6f). However, due to the plate mineral composition of the majority of mica schists, the shearing stage manifests much more poorly than in the marbles, which can evince a wide range of microstructures.

In the mica schists, parallel to the axes of the F4 and F5 concentric and kink folds, a crenulation lineation, which is very rare in pure marbles, developed as a penetrative tectonic feature (Fig. 6g, Fig. 7). The axial planes of the NE-plunging F5 folds (330/60, 120/70) occasionally form a new and distinct crenulation cleavage.

METAMORPHISM

Microstructural and petrographic studies on the relationships between the development of the metamorphic mineral assemblages and the deformational structures partially allow the reconstruction of the metamorphic evolution of the marbles. A simple chemical system of carbonate rocks constrains the chance of determining the pressures during successive tectonic events in the marbles. Temperature estimations for the calcite marbles are also difficult to calculate because their poor mineral assemblages, such as Cal-Qtz, are stable at a wide range of temperatures (Fig. 9). The marbles more predisposed to preserve mineralogical evidence of the metamorphic evolution are the magnesium- and potassium-bearing impure dolomite or dolomite-calcite marbles. In that case, during thermal progression, mixed-volatile dolomite-consuming and Mg-silicate-producing reactions occurred. The presence of index minerals (Tlc, Phl, Tr, Di, Fo) involved in the reactions display the metamorphic grade. These reactions are mainly dependent on temperature conditions, but they are also strongly determined by the X(CO_2) of the metamorphic fluid phase (Fig. 9). Nevertheless, in the dolomite-bearing marbles, it was possible to establish the temperatures of metamorphism (during both D2 and D3) by applying the Mg-solvus, Cal-Dol geothermometer.

Mineral assemblages

As presented in the structural section, the S1 planes can be distinguished from the S2 planes only in the hinge zones of the F2 folds as the Qtz lamination parallel to the Cal-Dol layering. The mineral assemblages which marked the S2 axial planar foliation overprint the folded lamination.

In the studied samples of the LSMU marbles, the simple equilibrium peak mineral assemblages correlated with D2 show a compositional diversity throughout the area: Cal-Di-Phl-Kfs-Qtz (Lutynia), Cal-Di-Qtz (Janowa Góra), Cal-Dol-Phl±Tr±Czo±Ms (Stronie Śląskie), Dol-Cal-Tr-Qtz (Nowy Waliszów), Dol-Cal-Phl±Qtz±Pl (Kletno, Rogóżka, Trzebieszowice and in the N part of the Krowiarki range) (Fig. 8, Tab. 5). This diversity indicates differ-

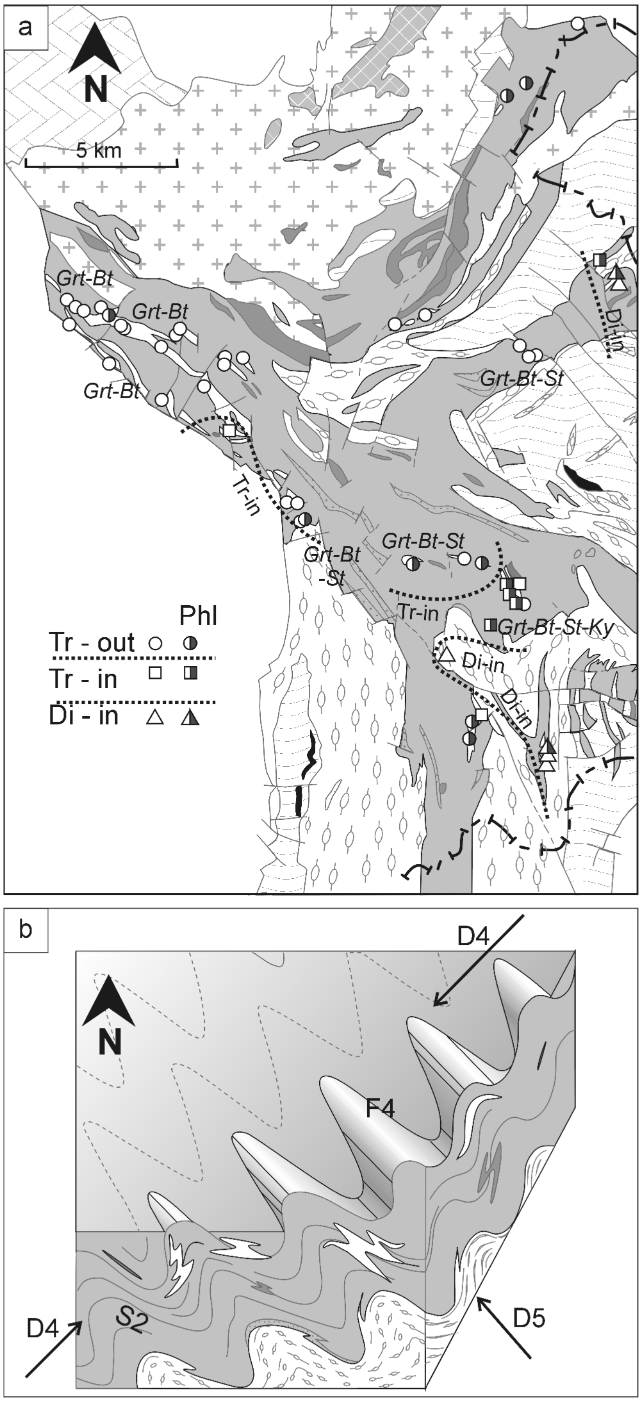

Fig. 8. **a.** The distribution of the peak temperature mineral assemblages in the marbles and adjacent mica schists. Peak mineral assemblages noted in mica schists, adjacent to marble outcrops, are *italicized*. **b.** The differences in the mineral assemblages and the course of the marble isograds could be explained by the disturbance of the metamorphic surfaces during D4 and D5.

ences in the chemical composition of the marble protoliths and suggests different metamorphic conditions associated with their development.

As K-feldspar is the most common source of potassium in the carbonate sediments (e.g. Bucher & Frey, 2002), the first appearance of phlogopite in the LSMU marbles could be relevant to the reaction:

$3Dol + Mc + H_2O = Phl + 3Cal + 3CO_2$ (Fig. 9),

Tremolite occurring as the accessory mineral in the dolomitic domains (Fig. 5d) could possibly appear as a result of the progressive dolomite- and quartz-consuming reaction:

$5Dol + 8Qtz + H_2O = Tr + 3Cal + 7CO_2$.

In potassium-absent marbles, as in the case of the sample from Janowa Góra, the diopside formation could probably form through the reaction:

$2Otz + Dol = Di + 2CO_2$.

Additionally, coexistence with K-feldspar, and the lack of dolomite and tremolite in the diopside-bearing marbles in Lutynia and Kamienica suggests that the Di-Mc mineral assemblage was probably produced by the reaction:

$Phl + 3Cal + 6Qtz = 3Di + Mc + 3CO_2 + H_2O$.

The S2 fabric, marked by minerals of the peak mineral assemblages, was deformed during D3 resulting in F3 folds (Fig. 6b) and the L3 stretching lineation (Fig. 6d). The poor mineral assemblage composed of Phl-Cal that formed in the pressure shadows or between boudinaged fragments of the stretched Ep-Czo blasts at the time of the top-to-the-N shearing was recognised in the Mt. Krzyznik area. In the Krowiarki range, the D3-related mineral assemblage mainly contains Chl-Ms.

The presence of chloritized phlogopite in the dolomitic matrix suggests that the exceptionally found assemblage composed of serpentinized forsterite and spinel in calcite lenses in the dolomite marbles of Złoty Stok was probably formed by the reaction:

$2Dol + Chl = 2Cal + 3Fo + Spl + 2CO_2 + 4H_2O$.

The relationship between the metamorphic and structural development

D1-D2, progression

The foremost-recognised mineral record of the regional metamorphism is represented by the allanite and epidote-rich cores of S2-related clinozoisite porphyroblasts (Fig. 6d). Their structural position indicates that their formation took place at the early stages of the regional metamorphism. The progressive regional metamorphism led to the development of a sequence of index minerals: Phl, Tr and Di. The end-member phase equilibria for the reaction involving tremolite requires temperatures reaching up to 615°C. The maximum temperature of ca. 515°C calculated for the calcites marking the S2 planes in the sample of the tremolite-bearing marble from the Nowy Waliszów shows that the probable tremolite-forming reaction occurred at low $X(CO_2) = \sim 0.1$. In another case, the temperature of ca. 570–600°C for the Tr-in, Di-out samples from the Janowiec and Krzyżnik Mts. indicates the mineral equilibrium for the reaction at $X(CO_2) = \sim 0.4$. A trend of increasing $X(CO_2)$ values at rising temperatures predicts the occurrence of an internal buffering with a low level of fluid flow. Consequently, the first appearance of diopside should require temperatures of > 615°C, at which the invariant point of the Di-Tr-Dol assemblage is attained. However, the absence of dolomite in the diopside-bearing samples does not allow the Cal-Dol geothermometer to be

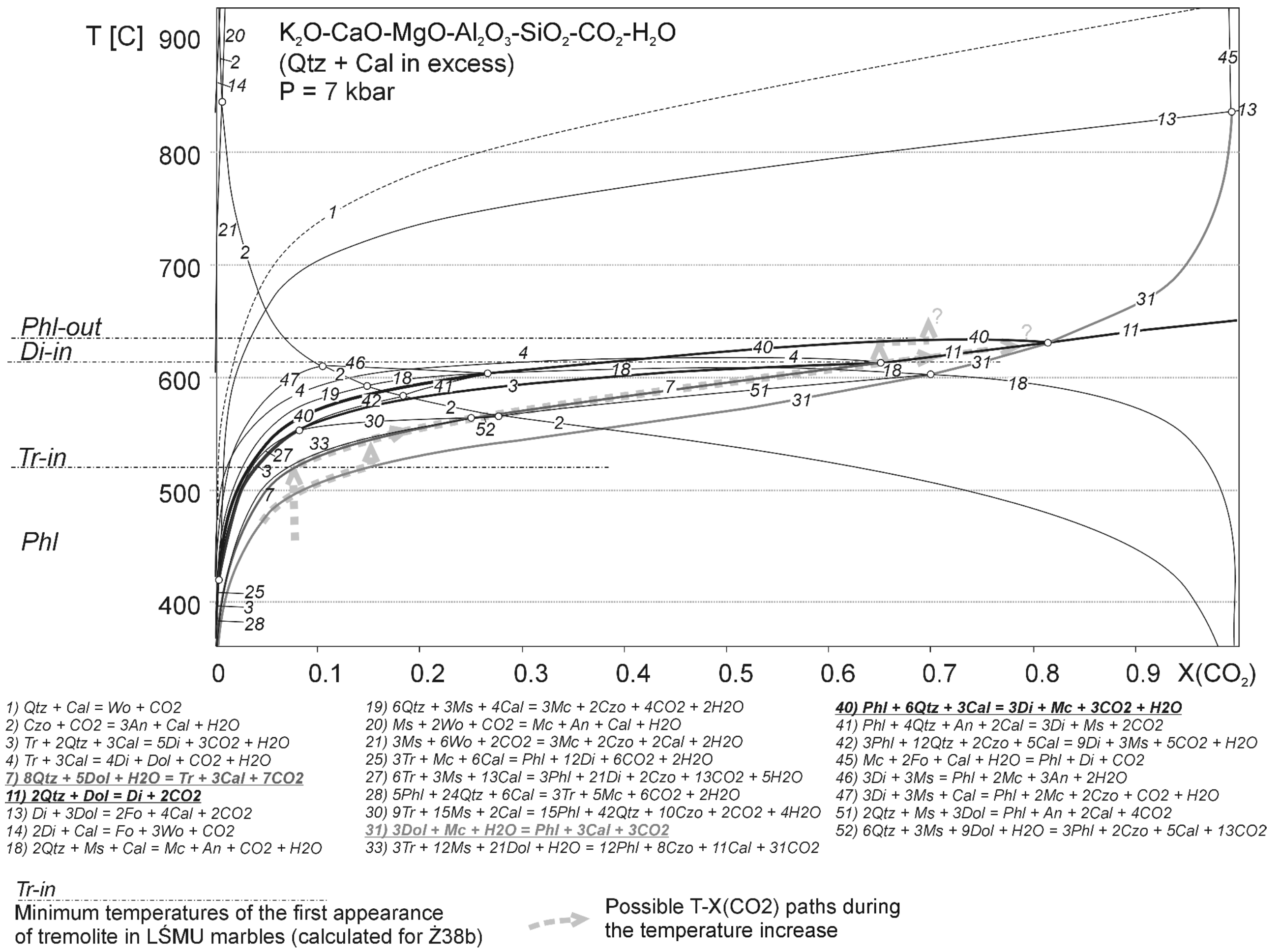

Fig. 9. Isobaric T-X(CO_2) equilibrium curves for the metamorphic reactions related to D2 in the marbles. The curves of possible reactions involving the index minerals Phl, Tr and Di are thickened; the invariant points are indicated by open circles. The grey dashed lines represent possible reaction paths during the temperature increase.

used to support this suggestion. In conclusion, the development of the D2-related mineral assemblages from reaction 3Dol + Mc + H_2O = Phl + 3Cal + $3CO_2$, followed by reactions 5Dol + 8Qtz + H_2O = Tr + 3Cal + $7CO_2$, and 2Otz + Dol = Di + $2CO_2$ or Phl + 3Cal + 6Qtz = 3Di + Mc + $3CO_2$ + H_2O, is considered to be the mineral sequence in the dolomite-bearing marbles, which were initially equilibrated at low to moderate X(CO_2) (Fig. 9).

The distribution of the peak mineral assemblages correlated with D2 allows the mineral zones to be in part drawn separated by two mineral isograds (Tr-in and Di-in). Diopside occurs in marble bodies outcropping in close proximity to the gneisses in Lutynia or in Kamienica and Janowa Góra within intercalations of the Stronie formation considered as small-scale synforms of the Stronie formation within the Śnieżnik orthogneisses (the Kamienica syncline according to Don, 1982, and the Janowa Góra syncline according to Don, 1988). For that reason, in the geological map, the Di-in isograd roughly refers to the contour of the gneiss-schist boundary. Similarly, the tremolite occurrences are restricted to the marble bodies localised in the area limited to several kilometres from the gneiss/schist boundary; therefore, the Tr-in isograd assumes a similar shape to that of the Międzygórze anticlinorium (defined by Don, 1964) and the fan-type Kletno anticlinorium (Don, 1991). The general decreasing trend of mineral zonation towards the NE is coherent with the geothermometric calculations showing different maximum temperatures ranging from ca. 500 to 540°C for the Tr-out marbles and ca. 515 to 600°C for the Tr-in marbles (Tab. 5). Consequently, the difference in the S2 mineral assemblages refers to the different temperature conditions currently observed at the surface levels of the Stronie formation. The evidence of partial re-equilibration, which is commonly observed as a depletion of the Mg-content in the calcite rims accompanied by the submicroscopic dolomite exsolutions suggests that the calculated temperatures could be somewhat understated in relation to the true temperatures of the D2-related metamorphism. The valuations of the maximum temperatures associated with D2 are presented in Table 4.

D3, D4 and D5, retrogression

The Cal-Dol geothermometry applied for the recrystallised elongated calcite grains defining the L3 stretching lineation gave temperatures ca. 100°C lower than those obtained for the S2 fabric in the related areas. The obtained

Table 5

The temperatures of development of the mineral assemblages in dolomite-bearing marble samples based on the Mg (*) or Mg and Fe (**) contents in Mg-rich calcite cores

	Sample	Outcrop location	Mineral assemblage	Analysis	X(MgCO$_3$)	X(FeCO$_3$)	X(MnCO$_3$)	X(CaCO$_3$)	T[°C] *	T[°C] **
			S2							
SE ↓ NW	S1	Stronie Śląskie quarry	Cal-Dol-Ms-Phl-Tr-Czo (Tr-in)	Cal 6	5.96	0.74	0.08	93.21	563	567
				Cal 21	5.98	0.35	0.08	93.59	563	565
				Cal 12	5.67	0.85	0.14	93.34	552	558
	J3b	Janowiec Mt.	Cal-Dol-Phl-Tr (Tr-in)	p4	6.85	0.05	N.d.	93.10	591	592
				p3	6.30	0.03	N.d.	93.68	574	574
				p9	5.65	0.10	N.d.	94.25	552	552
	KL8b	Kletno I quarry	Cal-Dol-Phl	Cal 6	4.94	0.11	0.01	94.94	525	526
				Cal 10 śr	5.17	0.10	0.20	94.53	534	535
				Cal 8 śr	5.07	0.36	0.21	94.36	530	533
	CH3b	Chłopek Mt.	Cal-Dol-Phl-Ms	5pr 188	4.59	0.17	N.d.	95.24	511	512
				4pr 70	4.47	0.06	N.d.	95.47	505	506
				5 pr 202	4.41	0.32	N.d.	95.27	503	506
	RO11	Rogóżka	Cal-Dol-Phl-Ms	4d11	4.68	0.36	0.07	94.89	514	518
				4d05	4.57	0.19	0.07	95.17	510	512
				4d17	4.15	0.47	0.26	95.12	491	496
	W6	Nowy Waliszów-Modrzeńce Mt.	Dol-Cal	Cal 5 śr	5.29	0.57	0.00	94.14	539	543
				Cal 5'	4.28	0.33	0.06	95.33	497	501
				Cal 7	4.14	0.04	0.27	95.55	491	491
	Ż38b	Nowy Waliszów	Dol-Cal-Tr (Tr-in)	Cal 3	4.70	0.00	0.00	95.30	515	515
				Cal 2 śr	4.53	0.10	0.20	95.17	508	509
				Cal 6	4.28	0.09	0.01	95.62	497	498
	Ż32b	Żelazno	Dol-Cal-Ms	Cal 3 śr	4.62	0.14	0.00	95.24	512	513
				Cal 2 śr	4.35	0.17	0.38	95.10	500	502
				Cal 4	3.49	0.63	0.08	95.80	458	467
	Ż14	Żelazno,Wapniarka Mt.	Cal-Dol-Ms-Phl	4e08	4.27	0.12	0.00	95.61	497	498
				4e12	3.68	0.79	0.00	95.53	468	479
				4e10	3.70	0.59	0.00	95.71	469	477
			S3/L3							
SE ↓ NW	K1a	Krzyżnik quarry	Cal-Dol-Phl	Cal 1	4.44	0.89	0.04	94.63	504	513
				Cal 1 śr	4.39	0.55	0.14	94.92	502	508
				Cal 2 śr	3.20	0.41	0.00	96.39	441	448
	O24b	Romanowo	Dol-Cal-Ms	Cal 8	2.96	0.00	0.00	97.04	427	427
				Cal 2	2.01	0.00	0.06	97.93	351	351
				Cal 7	1.83	0.45	0.00	97.72	331	342
	Ż35a	Piotrowice, Grodowa Mt.	Dol-Cal-Chl	Cal 1	2.85	0.00	0.24	96.91	420	420
				Cal 2 śr	2.37	0.06	0.00	97.57	384	385
				Cal 3 śr	2.11	0.00	0.00	97.89	361	361
	Ż25	Żelazno, Dębowa Mt.	Dol-Cal-Ms-Chl	Cal 2 śr	2.73	0.07	0.09	97.11	411	413
				Cal 3	2.85	0.18	0.07	96.90	420	423
				Cal 4	3.00	0.17	0.16	96.67	429	432
	ZS7a	Złoty Stok	Cal-Fo-Sp	p 22	4.15	0.01	0.02	95.82	491	491
				p 13	4.40	0.11	0.12	95.37	502	504
				p 23	4.19	0.07	0.00	95.74	493	494

Representative mineral analyses for three calcite cores from each sample depict the Mg-content established near the temperatures of development of the consecutive mineral assemblages. The temperatures were constrained using the Cal-Dol geothermometer according to Anovitz & Essene (1987). The Mg-solvus geothermometer in the calcite marbles (also in the Di-bearing marbles) could not be applied due to their low Mg-saturation.

temperatures yield ca. 510°C for the Mt. Krzyżnik region and ca. 430°C for the marbles in Żelazno (Tab. 5) concurring with the retrogressive mineral record.

In the marbles, the subsequent tectonic stages, D4 and D5, were not accompanied by dynamic recrystallisation or new mineral-forming reactions, which could involve new fabrics of new assemblages along the axial planes of both NW- and NE-plunging folds. The retrograde reactions under static conditions, i.e. chloritizaton of phlogopite and replacement of Ca-amphibole by talc which gathered near the edges or along the cleavage planes of the Ca-amphiboles, were commonly observed (Fig. 3e, f).

Contact metamorphism?

The presence of forsterite and spinel in the dolomite-calcite marble bodies located 2 km south-west of Złoty Stok could indicate a higher grade of metamorphism than that of most of the LSMU marbles. Calcite grains presumably coexisting with this assemblage in calcite lenses (Fig. 3c, d) yield a roughly stable $X(MgCO_3) = 4.1–4.4$, which represents temperatures of ca. 490–505°C (Tab. 5). The phase equilibrium for reaction $2Dol + Chl = 2Cal + 3Fo + Spl + 2CO_2 + 4H_2O$ at 7 kbar requires very high temperatures (e.g. 710°C at $X(CO_2) = 0.05$, 735°C at $X(CO_2) = 0.2$). Therefore, it is suggested that this uncommon mineral assemblage does not reveal typical regional metamorphism, but contact metamorphic overprinting the Dol-Phl assemblage, preserved in the matrix (Fig. 3c). According to the published data (Wierzchołowski, 1976; Wojciechowska, 2002), the Kłodzko-Złoty Stok granitoids had a wide contact aureole extending 2.5 km from the intrusion boundary, and therefore it could also embrace the marble bodies located 1 km away from the intrusion. At 1.5 kbar, the pressure of emplacement of the Kłodzko-Złoty Stok granitoids (estimated by Wierzchołowski, 1976), the reaction involving forsterite and spinel at low $X(CO_2)$ (expected to occur due to a fluid infiltration in the contact aureole), requires much lower temperatures of 540–560°C, which are more adequate to those obtained by Cal-Dol geothermometry.

Other exceptional minerals recognised in the calcite marble samples occur in the calcite marbles from Janowa Góra (Tab. 3). The occurrence of fluorite and piemontite in the marbles located close to the Staré Město-Kletno-Marcinków fault zone suggest them to be of a hydrothermal origin.

Remarks on the dynamometamorphic development of the carbonate minerals

When considering the question of the origin of the carbonate segregation, discussed previously by Witek (1976) and Karwacki (1987), among others, the recognised deformational and metamorphic evolution of the marbles provides some additional implications. The microstructural data show that both the isoclinal folds and the tight F2 folds deform the Cal-Dol mineral banding. Consequently, the observed carbonate segregation is believed mainly to be a pre-tectonic and pre-metamorphic feature, however inconclusively, whether representing the S0 bedding or developed at an early-diagenetic dolomitization stage. In the calcite marbles, the above-mentioned dolomite-consuming reactions led to a depletion of dolomite or even its disappearance, as observed in some tremolite-abundant samples from the Stronie Śląskie quarry and diopside-bearing ones from Kamienica. However, in most of the studied calcite marbles, the silicate minerals produced in these reactions are minor constituents suggesting a minor primary amount of consumed dolomite in such rocks. In the dolomite-bearing marbles, the progressive reactions depleting dolomite led to the formation of the new sparse calcite laminae (mainly along the axial planes of the F2 folds, cross-cutting the primary dolomite horizons in the hinge zones of the F2) or lenses composed additionally of coexisting silicates (Fig. 3c). These observations only partially confirm the results of earlier studies (Butkiewicz, 1968; Karwacki, 1987) revealing that the dolomite formed during the diagenesis of the carbonate sediments, while the calctie blastasy was related to the polyphase structural and metamorphic rebuilding. The interstitial position of the calcite between the dolomite boundaries, which is scarcely observed in the dolomite and dolomite-calcite marbles, would also confirm its later development. However, the observed microstructures related to the consecutive stages of the teconometamorphic evolution in the marbles suggests more readily that the volume of the new calcite produced in the metamorphic conditions was insignificant in its general amount in the dolomite-bearing marbles.

In conclusion, the tectonometamorphic development in the LSMU marbles led predominantly to the recrystallisation of carbonate minerals during an isochemical metamorphism (in accordance with Witek, 1976) associated with the slender dynamo-metamorphic transposition of Cal-Dol mineral banding and slight changes in the volume proportions between the two carbonate minerals.

DISCUSSION

When it comes to the tectonometamorphic evolution of the marbles, there is still considerable room for debate on the interpretation of the petrological, meso- and microstructural data gathered from the marbles of the Lądek-Śnieznik Metamorphic Unit, supplemented by the available data, geological maps and cross-sections. The original orientation of the successive tectonic fabrics, the tectonic regimes of the five tectonic stages, and a possible explanation for the differences in the peak metamorphic conditions are discussed in this section.

The regime of D2

The analysis of the regional vergence and enveloping surface orientation of the highest-order F2 folds in the marbles plays an essential role in approaching the issue of the kinematics of the foremost tectonic stages. Due to the high angle at which the S2 axial planes intersect the enveloping surfaces of the F2 folds observed in the LSMU gneisses (Dumicz, 1979) and the oblique to perpendicular alignment of the inclusion trails in the garnet porphyroblasts relative to the external schistosity (Romanová & Štípská, 2001), it is believed that the foremost deformational events resulted from an E–W horizontal contraction followed by subvertical flattening (D1 and D2, according to Dumicz, 1979). It is also suggested that the main folding resulted from an eastward thrusting (D2, according Don in Don *et al.*, 1990). Conversely, the significance of the E–W directed tectonic shortening is questioned by Cymerman (1997), who correlates the main structural development of the LSMU to its top-to-the-N (NE) thrusting.

The field observations show a roughly stable meridional alignment of the axes of the F2 folds across the area. The scarce mineral lineation, perpendicular to the fold axes and observed mostly in the folded S1 planes, could be interpreted as having developed during flexural-slip movements (in accordance with Ramsay & Huber's definition, 1987). This indicates that the deformations produced during D2 were probably connected with E–W directed tectonic shortening (in present day co-ordinates). Nevertheless, even in adjoining outcrops, there is variation in asymmetry of the F2 folds that may demonstrate the shear sense during E–W shortening, and in the orientation of the enveloping surfaces of the F2 folds that may be taken as the mean position of the S1 planes. The highest-order, mapable F2 fold that should be taken into account in such investigations occurs in the folded marble interbeds in the Mt. Krzyżnik area, where it is associated with a set of subsequent parasitic mesofolds. Recently, it has been doubted that the Biała Marianna and the Zielona Marianna outcrops form a continuous marble body (Karwacki, 1990). Mesoscopic observations confirm that they differ in their lithology; the Zielona Marianna is frequently intercalated by mica schists, whereas the main body of the Biała Marianna is more homogeneous. However, on the basis of the mesostructural observations, it is suggested that the two outcrops could compose the limbs of a single synform. The studies on the structural record of the natural outcrops belonging to the Zielona Marianna layer indicate that the observed mesofolds, classified as 3rd order ones, could be related to larger, 2nd order folds with eastern vergence, predicted to occur in the eastern limb of the synform. It is suggested that because of its rheology, the Zielona Marianna layer is more abundant in the F2 mesofolds which developed in this frequently intercalated layer. In separate outcrops, the different asymmetry of Z-, S- or M-shaped parasitic F2 folds indicates different local stress conditions. Geological maps of the area (e.g. Oberc, 1966) show that one, synformal part of the folded marble body in the Krzyżnik region was preserved. The unknown length ratio of its limbs and the limited number of preserved F2 folds in the surrounding mica schists, which may represent an up to 4th order of parasitic folds associated with the hypothetical larger structure complicate the judgement of the regional-scale vergence of the D2 folding. The varied asymmetry and differing angle at which the enveloping surfaces crosscut the axial planes might reflect either the existence of higher-order folds similar to those recognised by Żelaźniewicz (1978) in the Orlickie Mts., or a different regional orientation of the S1 planes before the D2 folding. Despite the significantly minor sizes, in most occurrences excluding the Krzyżnik region, the sets of F2 do not reveal a recognisable connection with any hypothetical higher-order structures. These structural observations did not give a univocal answer concerning the relationship between S1 and S2; however, the different plunge angles, from moderate to steep, at which the enveloping surfaces generally intersect the S2 axial planes suggests a mainly oblique position of the S1 before its reorientation with respect to the S2 axial planes. In the microscale, the preferred orientation of Czo and Tr porphyroblasts is sy -mmetrical with respect to the grain-shape foliation marked by carbonates. The stable orientation of the F2 axes (Fig. 4a) and the symmetrical fabric elements suggests that D2 took place in a coaxial regime of pure shearing with σ_1 positioned perpendicularly to S2 and the N–S-trending σ_2.

Moreover, it was recently reported that the various shapes of the inclusion trails in the garnets syntectonic with D2 in the mica schists of the Stronie formation are well interpreted as having developed during a continuous transition of the internal fabric from steep to flat attitudes (Jastrzębski, 2005, according to the non-rotational the Bell & Jonhson model, 1989). Generally, symmetric oligoclase rims growing in the strain shadows also filled by the minerals of S2 confirm that the deformation was coaxial with the σ_1 stress component positioned perpendicularly to the S2 planes (Fig. 5g). Therefore, the microstructures in both the marbles and adjacent mica schists can independently support the model based on mesostructural analysis proposed by Dumicz (1979), who suggested a gravitational collapse (D2) followed by a previous folding resulting from the horizontal compression (D1). Assuming the subhorizontal orientation of the S2 axial foliation (Dumicz, 1979), the first tectonic stage led to a folding and the development of an early subvertical fabric resulting from E–W directed tectonic compression. As a result of the consequent subvertical gravitational flattening, the originally steep S1 planes were deformed to form the tight, strongly inclined to recumbent F2 folds. At this time, the subhorizontal S2 axial planar foliation developed. Integrated microstructural and petrographic studies evidence that this tectonic stage was connected with the temperature peak of the regional metamorphism of the marbles. Consequently, the original metamorphic zonation, parallel to the subhorizontal S2 planes, was arranged at this time. The burial of the Stronie formation and its progressive regional metamorphism resulting from the E–W subhorizontal shortening (in the present-day coordinates) could be related to the initial stage of development of an accretionary wedge (Moravo-Silesian Domain) of the Bruno-Vistulian terrane. The gravitational tectonics of the D2 when the original isograd pattern in the LSMU developed, could be relevant to the onset of uplift of the Keprnik Dome (Boudin) of the Bruno-Vistulian terrane, after its maximum burial stage, which took place between 350 and 340 Ma (according to the model of Schulmann & Gayer, 2000).

Origin of the N–S trending lineations, proposed correlation to those of the orthogneisses

The character and kinematics of the meridionally trending lineation in the LSMU have been widely discussed and diversely interpreted. As this lineation could be a composite tectonic feature (neglection of that fact can lead to erroneous, simplified conclusions), its interpretation has to be carried out with respect to the superimposed deformational events distinguished in the rocks of the LSMU. A very important aspect of this investigation is the correlation of the N–S trending tight recumbent folds preserved mostly in the metapelites of the Stronie formation and similarly, the N–S (NE–SW) trending stretching lineation mostly observable in the orthogneisses. The N–S trending lineation in the Stronie formation has been considered to be associated with the N–S trending tight folds (e.g. Teisseyre, 1975; Don, 1982). The development of the N–S trending rodding lineation in the gneisses has been interpreted as coincidental either to a N–S tectonic escape induced by the E–W shortening (Żelaźniewicz, 1988) or to a NE–SW strike-slip transpression (Cymerman, 1997).

Based on the structural reconstruction and geothermometric calculations carried out for the marbles of the Stronie formation, it can be stated that the N–S trending linear structures observed in the rocks of the Stronie formation developed in two separate events characterised by different metamorphic and kinematic conditions. This explains the ascertained occurrence of two lineations: intersection (L2i) and stretching (L3), with each of them becoming locally dominant. The orientation of the L2i intersection lineation delineates the Y-axis of the strain ellipsoid representing the tectonic stage related to the temperature peak of metamorphism. The formation of the subsequent stretching lineation was connected with the uplift and retrogression. Unlike the intersection lineation, its orientation shows the direction of the maximum strain axis. These observations could partially explain the controversy regarding the presence of a mineral lineation nearly parallel to the fold axis. In the orthogneisses, the high temperature conditions at which the rodding lineation was formed indicate its connection with the N–S directed tectonic escape induced by E–W shortening (according to Żelaźniewicz, 1988). The transition from prolate to oblate shapes of the rodding lineation (Żelaźniewicz, 1991) could be related to the flattening strain responsible for folding in the Stronie formation (D2). Later top-to-the-NE reactivation under greenschist facies conditions (Żelaźniewicz, 1991) concurs with the late shearing that yielded the L3 stretching lineation under the retrogressive conditions in the Stronie formation.

The kinematics and origin of the D3 shearing

The kinematic criteria of the D3 shearing, i.e. the angular relationships between the developed S- and C'-type planes and the geometry of ó-clasts, indicate top-to-the-N (NW, NNE) movement along the reactivated former planar structures. Indicators of the opposite sense of shear are sporadically observed. The top-to-the-N shearing recognised within the LSMU can be correlated with the sinistral movements in the Złoty Stok-Skrzynka Zone, as mylonitic structures in this zone have the same position in the sequence of deformation (as in Dumicz, 1989). This deformational stage could be linked to NNE-directed thrusting of the Orlica-Śnieżnik Dome (Cymerman, 1997; Schulmann & Gayer, 2000), when it interacted with the adjacent terranes. Therefore, the D3 shearing under retrogressive conditions could reasonably be correlated with the thrusting of the boudins (domes) of the Moravo-Silesian Domain associated with the disturbance of the metamorphic isograds in the East Sudetes (Schulmann & Gayer, 2000). Top-to-the-N shearing followed the main tectonometamorphic collisional episode, which had been connected with the burial and the subsequent gravitational relaxation at the temperature peak of the regional metamorphism (D1-D2). The late interaction with the adjacent Kłodzko Metamorphic Unit and the Moravo-Silesian Domain could be confirmed by a slight deflection of the mylonitic L3 lineation along the boundaries of the LSMU within its marginal domains, where the L3 assumes a NE–SW direction in the Złoty Stok-Skrzynka Shear Zone, NNW–SSE in the NW of the Krowiarki Mts. region (Fig. 4b). Within the LSMU, the deformation was heterogeneous and accumulated into laminae, hence parallel to the former S2 axial planes. Nevertheless, the structures formed under extensional strain conditions, i.e. boudinage and S-C'-type fabric, prevail over the asymmetrical folds and S-C-type fabric, which would favour a regional extension in a N–S direction instead of the postulated transpressional stress conditions. However, the extension responsible for the development of the boudinage microstructures often orientates along the S-cleavage of the S-C mylonites. Thus, the extensional farbics, which represent the finite strain, could result from the progressive deformation during top-to-the-N thrusting.

Consequences of the D4 and D5 folding

The differences in the spatial orientations of the S2||S3 foliations across the LSMU area, with poles in the NW parts of the Lądek-Snieżnik forming a pattern with the belt of the great circle having its girdle axis near 330/20, indicate that F4 mesofolds are connected with larger structures. An analysis of the density of their poles on the stereographic projections indicates that the axial planes of these folds steeply incline towards the NE (Fig. 4d). Their geometric features suggest that the F4 mesofolds could be the mesoscopic equivalents of the large NW-plunging, SW-verging concentric folds which determine the structural architecture of the Krowiarki Mts. (e.g. Kuźniar, 1960), and could be connected with the NW branch of the converging macrostructures defined by Don (1964). Assuming the enveloping surfaces of the F4 folds are subhorizontal, slightly dipping towards the fold axes and have SW-directed vergence (according to the cross-sections in Kuźniar's study, 1960), it is suggested that the D4 folding of the subhorizontally oriented S2||S3 foliations resulted from NE–SW shortening with a SW-directed shear component. However, it should be mentioned that the continuity of the marble layer in the Krowiarki Mts., and therefore its subhorizontal enveloping surface, has also been questioned (Don, 1964; Cwojdziński, 1983).

In the LSMU, the NW-plunging concentric folds are replaced by NE-plunging ones towards the S and E of the area; their axes conform to the girdle axes of the foliation belts on the stereographic projections. The comparable low-ductile character of deformation in the marbles during D4 and D5 may suggest heterogeneous activity of nearly coincident NE–SW and NW–SE compressional regimes in the LSMU; this could be responsible for the development of the fan-like pattern of the macrofolds. Nevertheless, this idea can apply to the observations from rocks near the marble interbeds, which are distributed irregularly across the LSMU area. There is not enough evidence that the NE-plunging F5 folds distinguished in this paper are associated with the macroforms of the eastern part of the LSMU.

The distribution of the different mineral assemblages marking the S2 axial plane foliation indicates decreasing metamorphic conditions towards the NW/W (in accordance with Karwacki, 1990 and Don *et al.*, 2003). Thus, the calcite marbles of the lower part of the lithostratigraphic profile (taken after Koszela, 1997) occupied the lower metamorphic levels. Along the SE–NW section, from Mt. Krzyżnik to Żelazno, the ca. 100°C temperature difference related to the D2 stage throughout the area is consistent with the observed mineral zonation. The temperatures of the D3 shearing also decrease in the same manner. The pattern of the diopside and tremolite isograds in the marbles is incomplete; however, in the SW part of the LSMU, it is roughly consistent with the boundary between the gneisses of the lower structural level and the rocks of the Stronie formation. This suggests that the major NW-plunging F4 folds not only folded S2 planes but also the established D2 isograds. According to the existing P-T estimates presented by, among others, Józefiak (1988), Romanová & Štípská (2001), Jastrzębski (2003) and Murtezi (2003), the stage of the peak temperature conditions correlated with D2 took place at a geothermal gradient of ca. 25°C/km. Under such conditions, the differences in the temperature peak estimates from Stronie Śląskie to Żelazno are preferably explained by the inclination of the isotherms towards the NW at an angle of 20°, similar to the mean of the plunge angles of the F4 fold axes (Fig. 4c). Consequently, the results of this study confirm the anticlinorial structure of the gneiss units (as in Don, 1964) and indicate that the macrostructures mainly developed by deformational event(s) following the temperature peak of the regional metamorphism. The inclination of both the S2 foliations and metamorphic isograds towards the NW (W) took place in the final stages of interaction of the LSMU with the Moravo-Silesian Domain and could be explained by the more intense uplift in the eastern part of the LSMU resulting from the NW–SE tectonic shortening, oriented perpendicularly to the eastern boundary of the LSMU.

CONCLUSIONS

Both the meso- and microstructural record indicates that the marbles in the Lądek-Śnieżnik Metamorphic Unit underwent a polyphase structural evolution from ductile, medium-grade metamorphic conditions to more brittle, low-grade ones. The deformations related to the distinguished tectonic events reveal a heterogeneous manner between individual tectonic domains and within particular outcrops. The earliest recognised tectonic stage, D1, led to the inclination of the Cal-Dol mineral layering (generally originated as a pre-tectonic and pre-metamorphic feature), and its transposition to the oblique to subvertical, metamorphic S1 foliation resulted from E–W subhorizontal shortening. The mesoscopic equivalents of these planes could be the scarce, small-scale isoclinal, intrafolial folds preserved in the marbles and surrounding mica schists. As a result of the subsequent, subvertical D2 flattening, the S1 planes deformed to form tight, inclined to recumbent F2 folds (in accordance with Dumicz, 1979). The N–S trending tight folds are associated with the penetrative S2 axial planar foliation marked by a grain shape fabric defined by the parallel arrangement of flattened carbonates, and needle- and plate-shaped silicates: Tr-Phl-Ms-Czo. The F2 folds on the S1 planes are more evident within the marbles, especially in their impure variants, than in the mica schists, where the S2 axial plane schistosity developed as a dominant tectonic feature. The non-penetrative flexural-slip movement on the folded planes and the formation of the well-preserved L2i intersection lineation accompanied the folding. The D2-related mineral assemblages and temperature conditions show that D2 was associated with the temperature peak of the regional metamorphism yielding amphibolite facies conditions. The progression of the regional metamorphism was associated with the mineral sequence Phl → Tr → Di in the dolomite-bearing marbles, presumably initially equilibrated at low to moderate X(CO_2). Under the attained peak conditions, the original flat arrangement of the metamorphic isograds was developed. Progressive reactions contemporaneous to D2 scarcely segregated the carbonate phases into new aggregations. Nonetheless, the dynamic recrystallisation associated with D2 and D3 resulted in the transition of the grain shape of the carbonates, yielding the metamorphic grain shape S2 or L3/S3 fabric.

Subsequently, under retrogressive conditions related to temperatures ca. 100°C lower than those of D2, deformation localised in shear zones (mostly reactivating S2 planes) occurred as a result of the N (NEE) directed tectonic transport of the LSMU, when the Orlica-Śnieżnik interacted with adjacent units, i.e. the Kłodzko Metamorphic Unit and the Moravo-silesian Domain. Developed locally across the study area and zonally within particular outcrops, the mylonitic fabric (S3 planes with a N–S trending

L3 lineation) was associated with the elongation and size reduction of carbonate grains within S-C' or S-C mylonites.

The meridionally trending linear structures observed in the marbles in the Lądek-Śnieżnik Metamorphic Unit were generated in two separate tectonic events, D2 and D3, which are characterised by different metamorphic and kinematic conditions. The orientation of the S2/S1 intersection lineation L2i delineates the Y-axis of the strain ellipsoid representing D2, related to the temperature peak of metamorphism. The formation of the subsequent stretching lineation was related to the retrogression during D3. Contrary to the intersection lineation, its orientation shows the direction of the maximum strain component. The high temperature conditions at which the rodding lineation was formed in orthogneisses (Żelaźniewicz, 1988) indicate its connection with the N–S directed tectonic escape induced by E–W shortening, probably correlated with the E–W shortening referred to as D1 in the Stronie formation. The transition from prolate to oblate shapes of the rodding lineation (Żelaźniewicz, 1991) could be related to the flattening strain responsible for folding in the Stronie formation (D2). The later top-to-the-NE reactivation under greenschist facies conditions (Żelaźniewicz, 1991) could be correlated with top-to-the-N D3 shearing in the Stronie formation.

The consolidation of the LSMU within the adjacent terranes, shown by the deflection of the L3 lineation, continued during the closing tectonic stages, D4 and D5, respectively related to the SW–NE (WSW–ENE) and NW–SE (NNW– SEE) directed tectonic shortening. The diversity of the mineral assemblages marking the S2 foliation concurs with the different temperature estimations for the related areas and indicates the decreasing metamorphic grade towards the NW (W) of the LSMU, from ≥ 600°C near Stronie Śląskie to ≥ 490°C near Żelazno. Similarly, the estimations of the D3 shearing near Stronie Śląskie yield temperatures ca. 100°C higher than those related to D3 in the Żelazno region. The spatial orientations of the S2||S3 foliations throughout the LSMU mainly relate to their position within the superposed macroscopic F4 folds and the low-order F5 folds. It is proposed that the closing compressional stages D4 and D5 reoriented both tectonic structures and metamorphic isograds together. The deformation of the metamorphic and structural surfaces around the NW-plunging F4 fold axes, and their slope towards the NW parts of the Krowiarki Mts. corresponds with the anticlionorial character of the gneiss macrostructures (in accordance with Don, 1964). Their inclination could be explained by the more intense uplift in the eastern part of the LSMU, which is thought to have resulted from the late NW–SE tectonic shortening positioned perpendicularly to the eastern boundary of the LSMU with the Moravo-Silesian Domain, resulting in the mesoscopic F5 folds. The incomplete pattern of the D2-established metamorphic Di-in and Tr-in isograds, but roughly referring to the shape of the gneisses-schists boundary, confirms that the macrostructures could have mainly developed in deformational event(s) following the temperature peak of the regional metamorphism.

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REFERENCES

ANOVITZ, L. M. & ESSENE, E. J., 1987. Phase Equilibria in the System CaCO3-MgCO3-FeCO3. *Journal of Petrology*, 28: 389–414.

ALEKSANDROWSKI, P. & MAZUR, S., 2002. Collage tectonics in the northeasternmost part of the Variscan Belt: the Sudetes, Bohemian Massif. In: Winchester, J. A., Pharoah, T. C. & Verniers, J. (Eds.), *Palaeozoic Amalgamation of Central Europe. Geological Society, London, Special Publication*, 201: 237–277.

BAKUN-CZUBAROW, N., 1992. Quartz pseudomorphs after coesite and quartz exsolutions in eclogitic clinopyroxenes of the Złote Mountains in the Sudetes (SW Poland). *Archiwum Mineralogiczne*, 48: 3–25.

BANAŚ, M., 1962. Skarnoids from the metamorphic complex of Śnieżnik Kłodzki (Sudetes Mts.). *Prace Geologiczne, Komisja Nauk Geologicznych PAN*, 12: 7–29. {in Polish with English Summary}

BELL, T. H. & JOHNSON, S. E., 1989. Porphyroblast inclusion trails: the key to orogenesis. *Journal of Metamorphic Geology*, 7: 279–310.

BLENKINSOP, T. G. & TRELOAR, P. J., 1995. Geometry, classification and kinematics of S-C and S-C' fabrics in the Mushandike area, Zimbabwe. *Journal of Structural Geology*, 12: 397–408.

BORKOWSKA, M., CHOUKROUNE, P., HAMEURT, J. & MARTINEAU, F., 1990. A geochemical investigation of age, significance and structural evolution of the Caledonian-Variscan granite-gneisses of the Śnieżnik metamorphic area (central Sudetes, Poland). *Geologia Sudetica*, 25 (1-2): 1–27.

BRÖCKER, M. & KLEMD, R., 1996. Ultra-high pressure metamorphism in the Śnieżnik Mountains (Sudetes, Poland): P-T constraints and geological implications. *Journal of Geology*, 104: 417–433.

BRUECKNER, H. K., MEDARIS, L. G. & BAKUN-CZUBAROW, N., 1991. Nd and Sr age and isotope patterns from Variscan eclogites of the eastern Bohemian Massif. *Neues Jahrbuch für Mineralogie, Abhandlungen*, 163 (2/3): 169–196.

BUCHER, K. & FREY, M., 2002. Petrogenesis of Metamorphic

Rocks. Springer-Verlag; Berlin, Heidelberg. 341 p.

BUTKIEWICZ, T., 1968. Crystalline schists in the Krowiarki Range of the Kłodzko Mts. Geologia Sudetica, 4, 47–113. {in Polish with English Summary}

CWOJDZIŃSKI, S., 1976. Szczegółowa Mapa geologiczna Sudetów w skali 1:25000, arkusz: Złoty Stok. Wydawnictwa Geologiczne, Warszawa.

CWOJDZIŃSKI, S., 1979a. Szczegółowa Mapa geologiczna Sudetów w skali 1:25000, arkusz: Krosnowice. Wydawnictwa Geologiczne, Warszawa.

CWOJDZIŃSKI, S., 1979b. Szczegółowa Mapa geologiczna Sudetów w skali 1:25000, arkusz: Trzebieszowice. Wydawnictwa Geologiczne, Warszawa.

CWOJDZIŃSKI, S., 1983. Szczegółowa Mapa geologiczna Sudetów w skali 1:25000, arkusz: Stronie Śląskie. Wydawnictwa Geologiczne, Warszawa.

CYMERMAN, Z., 1997. Structure, kinematics and an evolution of the Orlica-Śnieżnik Dome, Sudetes. *Prace Państwowego Instytutu Geologicznego*, 156. 120p.

CYMERMAN, Z., PIASECKI, M. A. J. & SESTON, R., 1997. Terranes and terrane boundaries in the Sudetes, Northeast Bohemian Massif. *Geological Magazine*, 134: 717–725.

DON, J., 1964. The Złote and Krowiarki Mts. as structural elements of the Śnieżnik metamorphic massif. *Geologia Sudetica*, 1: 79–117. {in Polish with English Summary}

DON, J., 1976. Następstwo deformacji marmurów góry Krzyżnik w nawiązaniu do makrostruktur metamorfiku Śnieżnika. In: Dumicz, M. (Ed.), *Problem wieku deformacji serii zmetamorfizowanych Ziemi Kłodzkiej*. Materiały konferencji Terenowej, Wydawnictwa Uniwersytetu. Wrocławskiego: 95–101. {in Polish}

DON, J., 1982. The Sienna Synform and the relationship of gneisses to the deformational stages distinguished in the Śnieżnik Metamorphic Massif (Sudetes). *Geologia Sudetica*, 17: 103–124. {in Polish with English Summary}

DON, J., 1988. Tektonika strefy złożowej Kletno - Janowa Góra. In: Wojciechowska, I. (Ed.), *Wybrane zagadnienia geologii i mineralizacji metamorfiku Śnieżnika*. Materiały konferencji terenowej, Wydawnictwa Uniwersytetu Wrocławskiego: 57–80. {in Polish}

DON, J., 1991. Seria Młynowca oraz problem następstwa gnejsów w świetle tektoniki fałdowej metamorfiku Snieżnika. In: Dumicz, M. (Ed.), *Następstwo serii skalnych Masywu Śnieżnika w świetle kartografii geologicznej, analizy strukturalnej i badań radiometrycznych*. Materiały konferencji terenowej, Wydawnictwa Uniwersytetu Wrocławskiego: 26–41. {in Polish}

DON, J., DUMICZ, M., WOJCIECHOWSKA, I. & ŻELAŹNIEWICZ, A., 1990. Lithology and tectonics of the Orlica-Śnieżnik Dome, Sudetes - Recent State of Knowledge. *Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen*, 197 (2/3): 159–188.

DON, J., SKÁCEL, J. & GOTOWAŁA, R., 2003. The boundary zone of the East and West Sudetes on the 1:50 000 scale geological map of the Velké Vrbno, Staré Město and Śnieżnik Metamorphic Units. *Geologia Sudetica*, 35: 25–59.

DUMICZ, M., 1979. Tectogenesis of the metamorphosed series of the Kłodzko District: a tentative explanation. *Geologia Sudetica*, 14: 29–46.

DUMICZ, M., 1989. Złoty Stok-Skrzynka structural element in the light of mesostrucrtural analysis of Lądek-Śnieżnik metamorphic terrain. *Geologia Sudetica*, 23 (2): 83–106 {in Polish with English Summary}

ESSENE, E. J., 1983. Solid solutions and solvi among metamorphic carbonates with applications to geologic thermobarometry. In: Reeder, R. J. (Ed.), *Carbonates: Mineralogy and Chemistry, Reviews in Mineralogy*. 11: 77–96.

FISCHER, G., 1936. Der Bau des Glatzer Scheegebirger. *Jahrbuch Preussiches Geologisches Landesamt*, 56: 712–732. {in German}

FLOYD, P. A., WINCHESTER, J. A., CIESIELCZUK, J., LEWANDOWSKA, A., SZCZEPAŃSKI, J. & TURNIAK, K., 1996. Geochemistry of early Palaeozoic amphibolites from the Orlica-Śnieżnik Dome, Bohemian Massif: petrogenesis and palaeotectonic aspects. *Geologische Rundshau*, 85: 225–238.

FRANKE, W. & ŻELAŹNIEWICZ, A., 2000. The eastern termination of the Variscides: terrane correlation and kinematic evolution. In: Franke, W., Haak, V., Oncken, O., Tanner, D. (Eds.), *Orogenic processes: Quantification and Modelling in the Variscan Belt. Geological Society of London Special Publications*, 179: 63–86.

FRĄCKIEWICZ, W. & TEISSEYRE, H., 1976. Szczegółowa Mapa geologiczna Sudetów w skali 1:25000, arkusz: Międzygórze. Wydawnictwa Geologiczne, Warszawa.

GIERWIELANIEC, J., 1971. Szczegółowa Mapa geologiczna Sudetów w skali 1:25000, arkusz: Lądek Zdrój. Wydawnictwa Geologiczne, Warszawa.

GRZEŚKOWIAK, A. & ŻELAŹNIEWICZ, A., 2002. On the Significance of Gneissic Enclaves in the 500 Ma Metagranite, the Lądek-Śnieżnik Metamorphic Unit, the West Sudetes. *Geolines*, 14: 28–29.

GRZEŚKOWIAK, A., 2004. Genesis of the Diversification of the Międzygórze Structure Gneisses, Śnieżnik Metamorphic Unit. Ph.D. Thesis, Adam Mickiewicz University. Poznań.

GUNIA, T., 1984a. Microfossils from the quartzitic schists in vicinity of Goszów, Śnieznik Kłodzki Massif, Central Sudetes. *Geologia Sudetica*, 18 (2): 47–57. {in Polish with English Summary}

GUNIA, T., 1984b. Microflora of the crystalline limestones from the vicinity of Nowy Waliszów (Krowiarki Mts., Cental Sudetes). *Geologia Sudetica*, 19 (2): 75–86. {in Polish with English Summary}

HOLLAND, T. J. B. & POWELL, R., 1998. An internally consistent thermodynamic data set for phases of petrological interest. *Journal of Metamorphic Geology*, 16: 309–343.

JASTRZĘBSKI, M., 2003. P-T-d Evolution of Marbles and Mica Schists in the Krowiarki Range, the Lądek-Śnieżnik Metamorphic Unit, West Sudetes. *Geolines*, 16: 49–50.

JASTRZĘBSKI, M., 2005. Large-Scale Fold Architecture of the Stronie Formation, the Orlica-Śnieżnik Dome, West Sudetes. *Geolines*, 19: 57.

JÓZEFIAK, D., 1998. Wstępne dane o warunkach metamorfizmu paragnejsów i łupków łyszczykowych serii strońskiej (metamorfik Lądka-Śnieżnika). *Polskie Towarzystwo Mineralogiczne - Prace Specjalne*, 11: 108–110. {in Polish}

KARWACKI, A., 1987. Microtextural segregation of mineral phases in marbles of Kłodzko region (Lower Silesia). *Archiwum Mineralogiczne*, 2: 101–110. {in Polish with English Summary}

KARWACKI, A., 1990. Lithology and Petrogenesis of the Kłodzko Marbles. *Zeszyty Naukowe Akademii Górniczo-Hutniczej im Stanisława Staszica*, 47. 152 p. {in Polish with English Summary}

KASZA, L., 1964. Geology of the upper basin of Biała Lądecka stream. *Geologia Sudetica*, 1: 119–167. {in Polish with English Summary}

KLEMD, R. & BRÖCKER, M., 1999. Fluid influence on mineral reactions in ultrahigh-pressure granulites: a case study in the Śnieżnik Mts. (West Sudetes, Poland). *Contributions to Mineralogy and Petrology*, 136: 358–373.

KOSZELA, S., 1997. Petrogeneza marmurów z południowowschodniej części metamorfiku Śnieżnika. *Geologia Sudetica*, 30: 58–115. {in Polish with English Summary}

KRETZ, R., 1983. Symbols for rock-forming minerals. *American Mineralogist*, 68: 277–279.

KRÖNER, A., JAECKEL, P., HEGNER, E. & OPLETAL, M., 2001. Single zircon ages and whole-rock Nd isotopic systematic of early Paleozoic granitoid gneisses from the Czech and Polish Sudetes (Jizerske hory, Karkonosze Mountains and Orlica-Śnieżnik Complex). *International Journal of Earth Science*. 90: 304–324.

KRYZA, R., PIN, C. & VIELZEUF, D., 1996. High pressure granulites from the Sudetes (SW Poland): evidence of crustal subduction and collisional thickening in the Variscan belt. *Journal of Metamorphic Geology*, 14: 531–544.

KUŹNIAR, J., 1960. On the conditions of occurrence of marbles in northwestern Krowianki (Sudeten). *Kwartalnik Geologiczny*, 4: 217–262. {in Polish with English summary}

LANGE, U., BRÖCKER, M., MEZGER, K. & DON, J., 2002. Geochemistry and Rb-Sr geochronology of a ductile shear zone in the Orlica-Śnieżnik Dome (West Sudetes, Poland). *International Journal of Earth Sciences*, 91: 1005–1016.

LANGE, U., BRÖCKER, M., ARMSTRONG, R., TRAPPI, E. & MEZGER, K., 2005. Sm-Nd and U-Pb dating of high-pressure granulites from the Złote and Rychleby Mts (Bohemian Massif, Poland and Czech Republic). *Journal of Metamorphic Geology*, 23: 133–145.

MALUSKI, H., RAJLICH, P. & SOUČEK, J., 1995. Pre-Variscan, Variscan and early Alpine thermo-tectonic history of the north-eastern Bohemian Massif: Ar40/Ar39Ar study. *Geologische Rundschau*, 84: 345–358.

MARHEINE, D., KACHLÍK, V., MALUSKI, H., PATOČKA, F. & ŻELAŹNIEWICZ, A., 2003. The Ar-Ar ages from the West Sudetes (NE Bohemian Massif): constraints on the Variscan polyphase tectonothermal development. In: Winchester, J. A., Pharaoh, T. C., Verniers, J. (Eds.), *Palaeozoic Amalgamation of Central Europe. Geological Society, London, Special Publication*, 201: 133–155.

MURTEZI, M., 2003. P-T Pseudosections, Zoned Garnets and Structural Records from two Structurally Different Mica Schists of the Stronie Formation in the Orlica-Śnieżnik Dome. *Geolines*, 16: 76–77.

MURTEZI, M. & FANNING, M., 2005. Petrogenesis, Age and tectono-Metamorphic Evolution of the Acid Metavolcanites of the Stronie Formation (Orlica-Śnieżnik Dome, Sudetes, SW Poland). Geolines, 19: 85.

NOWAK, I. & ŻELAŹNIEWICZ, A., 2002. Metabasites from Stronie Schists in the Lądek-Śnieżnik Metamorphic Unit, West Sudetes: Geochemistry and P-T-d Path. *Geolines*, 14: 72–73.

OBERC, J., 1966. Tectonics of Limestones at Stronie Śląskie. *Kwartalnik Geologiczny*, 8: 211–223. {in Polish with English Summary}

OBERC, J., 1972. Budowa geologiczna Polski, Tektonika cz.2 Sudety i obszary przyległe. Wydawnictwa Geologiczne Warszawa, 307p. {in Polish}

OLIVER, G. J. H., CORFU, F. & KROGH, T. E., 1993. U-Pb ages from SW Poland: evidence for a Caledonian suture zone between Baltica and Gondwana. *Journal of Geological Society London*, 150: 355–369.

PASSCHIER, C. W. & TROUW, R. A. J., 1996. Microtectonics. Springer-Verlag. Berlin. 289 p.

RAMSAY, J. G. & HUBER, M. I., 1987. The techniques of modern structural geology. Volume 2: folds and fractures. *Academic Press*. 391 p.

ROMANOVÁ, M. & ŠTÍPSKÁ, P., 2001. Tectonometamorphic Evolution of the Stronie Series near Javornik. *Geolines*, 13: 107–108.

ROSEN, O., DESMONS, J. & FETTES, D., 2004. A systematic nomenclature for metamorphic rocks. Metacarbonate and related rocks. Provisional recommendations by IUGS Subcommission on the systematics of the metamorphic rocks, web version: http://www.bgs.ac.uk/scmr/docs/scmr_carb_r .pdf

SAWICKI, L., 1995. Geological Map of Lower Silesia with adjacent Czech and German Territories 1:100 000. Państwowy Instytut Geologiczny. Warszawa

SMULIKOWSKI, K., 1979. Polymetamorphic evolution of the crystalline complex of Śnieżnik and Góry Złote Mts in the Sudetes. *Geologia Sudetica*, 14 (1): 7–76. {in Polish with English Summary}

SCHMID, S. M., PATERSON, M. S. & BOLAND, J. N., 1980. High temperature flow and dynamic recrystallization in Carrara marble. *Tectonophysics*, 65: 245–280.

SCHULMANN, K. & GAYER, R., 2000. A model of an obliquely developed continental accretionary wedge: NE Bohemian Massif. *Journal of Geological Society London*, 156: 401–416.

STAWIKOWSKI, W., 2002. Contacts Between High-P Eclogites and Gneisses in the Lądek-Śnieżnik Metamorphic Unit, the West Sudetes. Geolines 14: 84–85.

STAWIKOWSKI, W., 2005. Historia deformacji i metamorfizmu w strefach kontaktów eklogitów z gnejsami w meta -morfiku Śnieżnika. Ph.D. Thesis, Adam Mickiewicz University. Poznań.

STELTENPOHL, M. G., CYMERMAN, Z., KROGH, E.J. & KUNK, M. J., 1993. Exhumation of eclogitized continental basement during Variscan lithospheric delamination and gravitational collapse, Sudety Mountains, Poland. *Geology*, 21: 1111–1114.

ŠTÍPSKÁ, P., SCHULMANN, K. & KRÖNER, A., 2004. Vertical extrusion and middle crust spreading of omphacite granulite: a model of syn-corvengent exhumation (Bohemian Massif, Czech Republic). *Journal of Metamorphic Geology*, 22: 179–198.

SZCZEPAŃSKI, J., ANCZKIEWICZ, R., MAZUR, S. & THIRLWALL, M., 2004. Constrains on timing of ultrahigh pressure metamorphism in the Orlica-Śnieżnik Dome, West Sudetes. *Special Papers, Mineralogical Society of Poland*, 24: 365–368.

TEISSEYRE, H., 1956. Sudetic Caledonides and their Variscan rebuilding. *Przegląd Geologiczny*, 3: 97–104. {in Polish}

TEISSEYRE, H., 1975. Elementy strukturalne grupy górskiej Śnieżnika. In. GROCHOLSKI, A. (Ed.), *Przewodnik XLVII zjazdu Polskiego Towarzystwa Geologicznego*: 63–69. {in Polish}

TEISSEYRE, J., 1959. The Lime-silicate rocks of the Śnieżnik Mountains in the Sudetes. *Archiwum Mineralogiczne*, 23: 155–196. {in Polish with English Summary}

TURNIAK, K., MAZUR, S. & WYSOCZŃSKI, R., 2000. SHRIMP zircon geochronology and geochemistry of the Orlica-Śnieżnik gneisses (Variscan belt of Central Europe) and their tectonic implications. *Geodinamica Acta*, 13: 393–312.

WIERZCHOŁOWSKI, B., 1976. Granitoids of the Kłodzko-Złoty Stok massif and their contact influence on the country rocks (petrographic characteristics). *Geologia Sudetica*, 11 (2): 7–147. {in Polish with English summary}

WITEK, B., 1976. Petrography of marble deposits at Wapniarka and Romanowo Górne in the north-western part of the Krowiarki Range (Eastern Sudetes). *Kwartalnik Geologiczny*, 20: 241–259. {in Polish with English Summary}

WOJCIECHOWSKA, I., 2002. The geotectonic position of the

Kłodzko-Złoty Stok Granitoids. *Special Papers, Mineralogical Society of Poland*, 20: 231–233.

ŽAČKOVÁ, E. & ŠTÍPSKÁ, P., 2004. Differential Exhumation in an Orogenic Root Domain: Snieznik Dome. *Geolines*, 17: 106–107.

ŻELAŹNIEWICZ, A., 1978. Major tectonic structures in the Polish part of the Góry Orlickie. *Geologia Sudetica*, 13 (1): 67–86. {in Polish with English Summary}

ŻELAŹNIEWICZ, A., 1988. Orthogneisses due to irrotational extension, a case from the Sudetes, Bohemian massif. *Geologische Rundschau*, 77: 671–682.

ŻELAŹNIEWICZ, A., 1991. Uwagi o deformacji ortognejsów oczkowych w kopule orlicko-śnieżnickiej. In: DUMICZ, M. (Ed.), *Następstwo serii skalnych Masywu Śnieżnika w świetle kartografii geologicznej, analizy strukturalnej i badań radiometrycznych*. Materiały konferencji terenowej. Wydawnictwa Uniwersytetu Wrocławskiego: 122–136. {in Polish}

ŻELAŹNIEWICZ, A., DÖRR, W., BYLINA, P., FRANKE, W., HAACK, U., HEINISCH, H., SHASSTOK, J., GRANDMONTAGNE, K. & KULICKI, C., 2004. The eastern continuation of the Cadomian orogen: U-Pb zircon evidence from Saxo-Thuringian granitoids in south-western Poland and the northern Czech Republic. *International Journal of Earth Science*, 93: 773–781