Annales Societatis Geologorum Poloniae (2009), vol. 79: 41–52.

DEFORMATION STRUCTURES IN THE GNEISSIC EXOTIC PEBBLES FROM THE AREA OF WOŁOSATE (CISNA SANDSTONE, DUKLA TECTONIC UNIT, OUTER CARPATHIANS, POLAND)

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Kania, M. & Wolska, A., 2009. Deformation structures in the gneissic exotic pebbles from the area of Wołosate (Cisna sandstone, Dukla tectonic unit, Outer Carpathians, Poland). *Annales Societatis Geologorum Poloniae*, 79: 41–52.

Abstract: Gneissic exotic pebbles from the Cisna beds (Dukla tectonic unit) in the region of Wołosate (Bieszczady Mts., Eastern Carpathians) were investigated. These exotic pebbles are from 9.5 to 13 cm in size. Basing on the structural features, the following groups of exotic pebbles were distinguished: granitic gneisses, laminated gneisses, flaser gneisses and mylonitic gneisses. Granite – granodiorite protolith was deformed in the shear zone; strain partitioning was probably an important process during deformation. The observed structures allow to determine the temperature of metamorphism as 500–550°C. The lower limit of pressure was determined basing on phengite geobarometer as 5 kbar. The nature and localization of the source area can be similar to the Bretila sequence from the Romanian Eastern Carpathians.

Key words: gneissic exotic pebbles, foliation, metamorphism, mica fish, Bieszczady Mts, Outer Carpathians, Poland.

Manuscript received 5 May 2008, accepted 16 April 2009

INTRODUCTION

The investigations of exotic pebbles from the Carpathian flysch started in the second half of the 19th century. New data available in this field and new research methods give more possibilities of genetic interpretation of exotic pebbles in the context of palaeofacies, palaeobiogeographical, geodynamic and palinspastic research. Exotic pebbles of metamorphic rocks were described from many localities of the Polish Carpathian flysch (*i.e.* Książkiewicz, 1931; Wieser, 1949, 1970; Michalik *et al.*, 2004; Skulich 1986, 2002). Nevertheless, there is still some material worth to be studied. The exotic pebbles of metamorphic rocks from the Dukla tectonic unit cropping out near Wołosate village in the Bieszczady Mountains (Eastern Carpathians) are the subject of this investigations. This paper aims at describing microstructures of 15 exotic pebbles from the Dukla tectonic unit. Petrographic description of the pebbles was used for the interpretation of the source of sedimentary material in the Dukla tectonic unit (also called the Dukla Nappe).

Bąk and Wolska (2005) described exotic pebbles of metamorphic rocks from the Cisna beds of the Dukla tectonic unit near Wołosate village. These authors subdivided the pebbles into the following groups: gneisses containing albite porphyroblasts, gneisses with microcline porphyroblast, and strongly cataclased granitic gneisses. Geochemical investigations documented peraluminous S-type granitoids as protolith (Bąk & Wolska, 2005). The dating of micas from these gneisses, using K/Ar method, reveals the age 304.9 ± 11.4 Ma (Poprawa *et al.*, 2004). The mineral composition of exotic pebbles is similar to the that of the Cisna Sandstone.

GEOGRAPHICAL AND GEOLOGICAL SETTING

The investigated exotic pebbles were collected in the area of Wołosate village in the Bieszczady Mountains (southeastern Poland). The Bieszczady Mts. constitute the westernmost part of the Eastern Carpathians and extend from the Łupków Pass and Osława River in the west to the Świca River (Vyshkovskyi Pass, Ukraine) in the east. The exotic pebbles were collected in three creeks: Wołosatczyk, Połoninka (Zworczyk Księży on some maps) and Szczawianka (Szczawinka on some maps). These creeks are left tributaries of the Wołosatka stream (Fig. 1), and have their headwaters in so-called "Border Ridge".

The Bieszczady Mts. are part of the outer Eastern Carpathians. Two main tectonic units (nappes) in this area are the Silesian Unit and the Dukla Unit. The overthrust of the Dukla unit over the Silesian Nappe is located a little west-

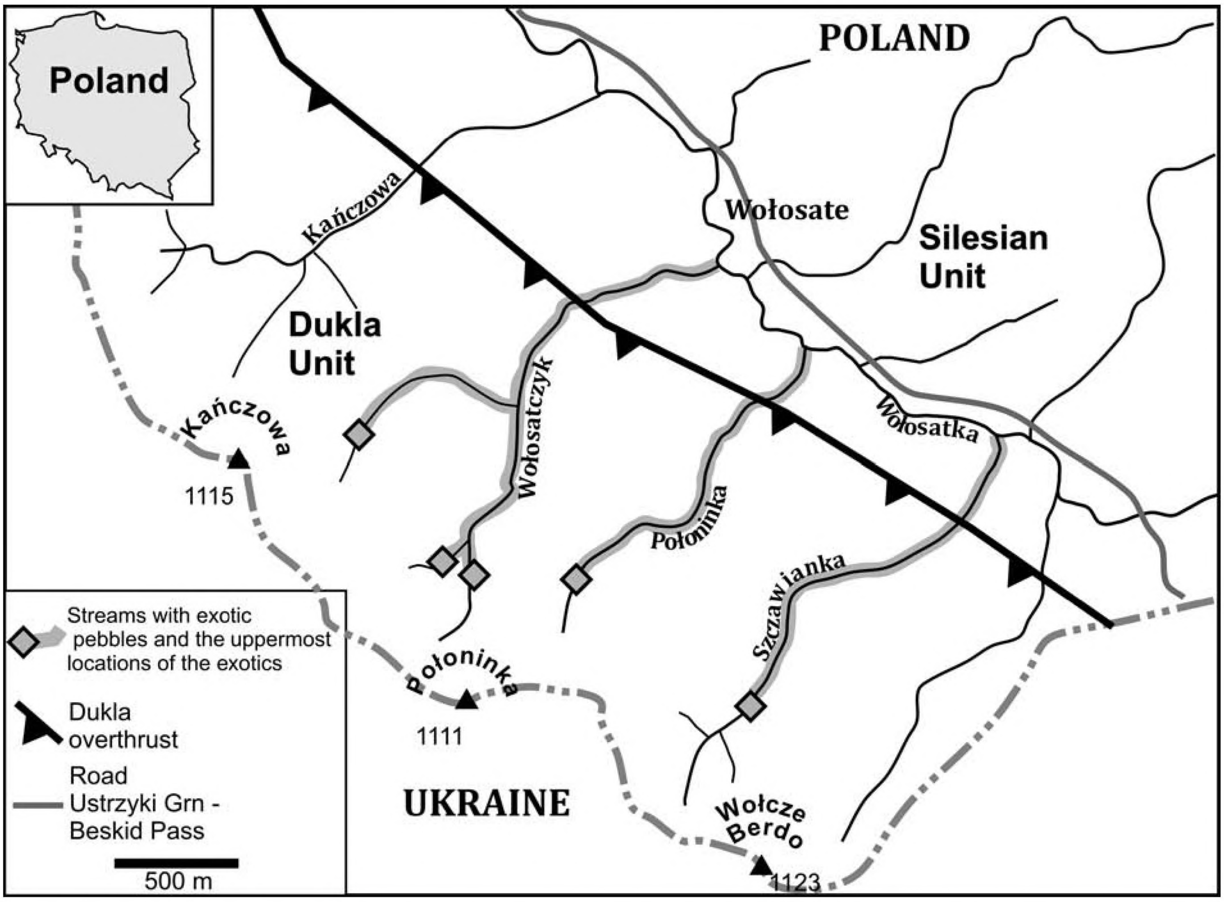

Fig. 1. Localization of the exotic pebbles studied in the area of Wołosate village, Bieszczady Mts. The position of the Dukla overthrust after Bąk and Wolska, 2005; simplified

wards of the Wołosatka stream and is observed through the lowest parts of creeks, where the examined exotic pebbles were collected (Fig. 1). The following lithostratigraphic units constitute the Dukla Unit in this area: Łupków beds, Cisna beds, Majdan beds and Hieroglyphic beds.

The Cisna beds form one of the main litostratigraphic units of the eastern part of the Dukla Nappe (Ślączka, 1971). The Cisna beds build the majority of mountain ridges in this part of the Carpathian Mts., due to their resistance to weathering. The unit, built of flysch deposits, is up to 1200 meters thick. It attains the greatest thickness in the Bystre and Solinka region. The thickness decreases southeastwards. Two main sandstone types are characteristic for the Cisna beds (Ślączka, 1971).

The first one consists of thick-bedded coarse-grained polymictic sandstones. They are composed mainly of quartz, feldspars and clasts of lidites and metamorphic rocks. In finer grained beds, muscovite and biotite are also present. The rocks are greyish-blue to yellowish-grey on weathered surface. Quartz constitutes up to 50% of the rock mass. In the coarse fraction, the grains of polycrystalline quartz occur. Feldspars are mostly altered (sericitization, kaolinitization). Plagioclases dominate, but K-feldspars are also present. Moreover, sandstones contain lithoclasts of quartzites and organogenic limestones. Microfauna is poorly represented in this type of sandstones.

The second type of the Cisna beds sandstones consists of fine-grained mica sandstones, grey in colour. They occur mainly in the southern part of the Dukla Unit, southeast of Ustrzyki Górne, where the exotic pebbles in question were collected. Sandstone beds are separated by thin layers of hard, grey shales. Poorly represented agglutinating foraminifera indicate the late Campanian–early Paleocene age of the Cisna beds (Ślączka, 1971).

MATERIALS AND METHODS

The field work was limited to collecting gneissic exotic pebbles from the creeks, according to permission from the Bieszczady National Park (the investigated area is located in the part closed for the public). Eight samples have been offered by Krzysztof Bąk. All the material studied consists in total of thirty six samples (Tab. 1).

During the field work, it was not possible to determine the position of the gneissic exotic pebbles-bearing layer in the Cisna beds section. According to our own observations and earlier suggestions (Bąk & Wolska 2005), it is possible to state that they surely come from the Cisna Sandstone, probably from the lower part of the succession. The following facts lead to this conclusion: (1) gneissic exotic pebbles were found in the lowest parts of creeks, their number in-

Table 1

List and dimensions (in centimetres) of all collected specimens of exotic pebbles

Połoninka				Szczawianka				Wołosatczyk			
Sample	Short axis	Middle axis	Long axis	Sample	Short axis	Middle axis	Long axis	Sample	Short axis	Middle axis	Long axis
P1	6	4	3	***SZ1***	5	3	3	**WK1**	7	5	4
P2	5	2	1.5	***SZ2***	6	5	5	**WK2**	5	5	5
P3	6	3	3	***SZ3***	4	3	3	**WK3**	15	10	4.5
P4	13	10	6	**SZ4**	4.5	4	3	**WK4**	5	5	1
P5	6.5	5.5	2	SZ-a	2.5	1	1	**WK5**	15	9	4
P6	3.5	3	2.5	SZ-b	5	2.5	1.5	**WK6**	10	6	5
P7	4	2.5	2	SZ-c	3	1.5	0.5	**WK7**	9	7.5	3
P8	3.5	2	1					**WK8**	7	6	3
P-a	3.5	2	1					WK9	5.5	3.5	2.5
P-b	2.5	1	0.5					WK-a	2	1	0.5
P-c	2	1.5	0.5					WK-b	2.5	1.5	1
P-d	1.5	1	0.5					WK-c	3	2	1.5
P-e	1	0.5	0.5					WK-d	2	1.5	1
P-f	0.5	0.5	0.5					WK-e	1.5	0.5	0.5
								WK-f	0.5	0.5	0.4

Samples offered by K. Bąk are shown in *italics*. Samples selected for analyses are marked in **bold**

creases when going upstream, (2) in the uppermost parts of streams, the exotic pebbles are lacking. It is important to emphasise that the exotic pebbles constitute only small part of the creek debris. Their main components are blocks of sandstones of the Cisna beds.

Different shapes of the collected exotic pebbles are shown on the Zingg diagram (Fig. 2). The exotic pebbles represent all four shape classes. Due to small size of the majority of samples, e.g. middle axis B of the largest is about 15 cm (Table 1), it is difficult to determine whether they represent whole rock or only its most resistant parts. Because of this fact, only relatively large pebbles, with B > 4 cm, were selected for detailed research. Moreover, in many, also larger samples, advanced weathering processes are observed, evidenced e.g. by the Liesegang rings.

The main investigation method was optical microscopy (Nikon Eclipse E600POL microscope). Universal thin sections were cut perpendicularly to the foliation. Microphotographic documentation was made using Nikon digital camera. Mineral composition of the rocks was determined using the modal composition method (Table 2). About 1200 points were counted in every thin section. Moreover, microphotographic documentation of rocks was made. Two types of quartz were distinguished: (1) quartz in pure quartz layers, and (2) quartz in quartz-feldspars layers. Similarly, feldspars were counted separately for these in the matrix and in augens. The grains showing optical features typical for biotite were counted as this mineral. Other minerals similar to biotite or chlorite, and clean chlorite were counted in one group: "biotite alterations products"

Th chemical composition of the main rock-forming minerals was determined using SEM-EDS method. Universal thin sections of selected samples were analysed using microscope JEOL 5410 with EDS spectrometer NORAN Voyager 3100. Time of analysis was 100s for a point, accelerating current 20 kV. The ZAF correction algorithm was used.

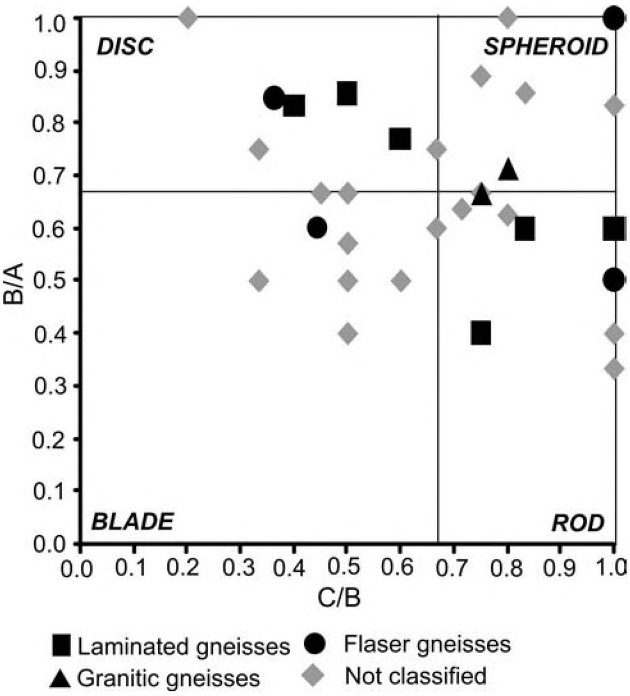

Fig. 2. The position of gneissic pebbles on the Zingg diagram. A – short axis, B – middle axis, C – long axis

Table 2

Modal mineral composition of selected exotics

		Laminated gneisses				Flaser gneisses		Granitic gneisses
		WK8	P2	SZ2	SZ1	P3	WK5	P1
		Number of counted points						
Quartz (in quartz-only layers)		281	352	162	200	359	461	335
Matrix	quartz	136	90	220	203	108	103	278
	plagioclases	491	621	118	611	464	321	380
	alkali feldspars	51	38	45	22	65	80	73
Augens[1]		27	52	214	-	105	108	170
White micas		59	35	49	9	73	52	31
Biotite		0	0	21	0	0	0	0
Biotite alteration products (chlorites, hydromicas)		16	35	21	14	54	22	41
Total		1061	1223	850	1059	1228	1147	1147
		Percentage composition						
Quartz (in quartz-only layers)		26.6	28.8	19.0	18.9	29.2	40.2	25.6
Matrix	quartz	12.5	7.4	25.7	19.1	8.8	9.0	21.2
	plagioclases	46.4	50.7	13.9	57.7	37.8	28.0	29.1
	alkali feldspars	4.8	3.1	5.3	2.1	5.3	7.0	5.6
Augens[1]		2.5	4.3	25.3	-	8.6	9.4	13.0
White micas		5.6	2.9	5.8	0.9	5.9	4.5	2.4
Biotite		0.0	0.0	2.5	0.0	0.0	0.0	0.0
Biotite alteration products (chlorites, hydromicas)		1.6	2.8	2.5	1.3	4.4	1.9	3.1
Total		100.0	100.0	100.0	100.0	100.0	100.0	100.0

[1] Augens in exotic pebbles: P2, SZ2, WK5 and P1 – alkali feldspars. in WK8 and P3 – plagioclases, mylonitic gneiss SZ1 does not contain augens

RESULTS

MINERAL COMPOSITION OF THE EXOTIC PEBBLES

Modal composition was determined in the thin sections of selected rocks (Table 2). The most common mineral is feldspar (especially plagioclases) and quartz. White micas are present in all samples. Unaltered biotite is rare (only in one thin section), while the products of its alterations are common. The chemical microprobe (EDS method) allowed us to determine that the majority of augens are composed of alkali feldspars, whilst feldspars in the matrix are mostly plagioclases. White micas in foliation structures are phengites, containing different amounts of Mg and Fe. A small amount of white mica in the granitic gneisses and mylonitic gneisses is represented by muscovite.

CLASSIFICATION OF EXOTIC PEBBLES

The studied exotic pebbles were classified according to their structural characteristics. The nomenclature of structures and rock types was partially taken from Żaba (1982). The term "structure" was used in spite of "texture", according to the IUGS directives (Smulikowski, 1992).

The classification applied in this paper is shown in Fig. 3. All the investigated exotic pebbles show directional planar structures, which were subdivided into four substructures as follows:

a) Mylonitic structure: layers of fine grained, mylonitized feldspars and quartz. Layers have very sharp boundaries. Augens are not present.

b) Laminated structure: layers are well defined. Layers of quartz and quartz-feldspar matrix surround alkali feldspar augens. This is the most numerous group of the investigated samples. The pebbles in this group can be further subdivided according to the size of augens: fine augens <5 mm, medium augens 5–10 mm, and coarse augens >10 mm.

c) Flaser structure: characterized by interlayering. Common are also bands of micas, most of them being short (up to 15 mm). All flaser gneisses contain augens, 5–10 mm in diameter (medium augens).

d) Granite-gneissic structure: directional planar structure present, but very poorly visible, emphasized by elongation of blasts.

REVIEW OF STRUCTURAL TYPES OF GNEISSES

Mylonitic gneisses

Sample SZ1 is a small exotic pebble, showing yellowish-rusty colour. On the fresh surface white quartz-feldspars layers, up to 3–4 mm thick, alternate with thin (1 mm) quartz ones (Fig. 4a). The sample does not contain augens. It should be taken into account however, that small exotic pebbles may represent only a part of the augen-free rocks.

Two types of layers may be distinguished using optical microscope (Fig 4a). The first type is represented by quartz

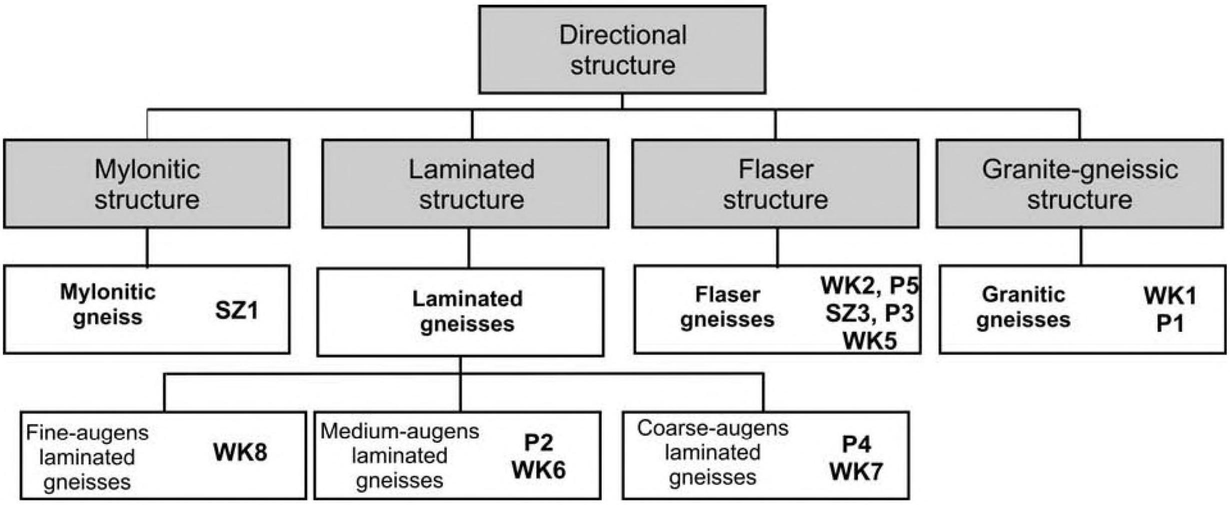

Fig. 3. Structural classification of gneissic pebbles studied. Nomenclature partially after Żaba (1982)

layers, up to 1 mm thick, composed only of its fine grains, showing undulatory extinction. Small plagioclases (below 0.1 mm) are sporadically present between the quartz grains. The layers of the second type are composed mainly of plagioclases (oligoclase, $Ab_{72-88}An_{12-28}$) and quartz, and subordinately of alkali-feldspars (orthoclase, $Or_{80-97}Ab,An_{3-20}$ and albite $Ab_{92}An_8$; Table 3). Feldspar blasts are bimodal in size: some have diameter about 0.1 – 0.3 mm, the other show diameters about 0.01 mm. All the plagioclases show advanced sericitization process.

The bands of phyllosilicates are composed mainly of small amount of dispersed, non-phengitic with #mg (= MgO/ (MgO+FeO.)): 0.00–0.07 white mica (Table 4). Moreover strongly chloritized dark mica forming thin, subtle laminae occur.

Laminated gneisses

A characteristic feature of these exotic pebbles is the presence of augens of different size (Fig. 3). All other structural features and mineral composition are similar. These rocks are light-grey or greenish on fresh breaking surfaces (samples P2, WK6, P4, WK7, WK8), or dark-grey to black in samples SZ2, SZ4.

Pale-grey gneisses are the most numerous group of all the collected exotic pebbles. All these rocks show planar structure, emphasized by quartz and quartz-feldspar layers. Laminated structure is not as distinct as in the mylonitic gneiss (sample SZ1). However, the microscopic observations allow classifying these gneisses as laminated.

Microscopic observation shows very well separated quartz and quartz-feldspar layers (Fig. 4b). The thicknesses of layers vary in the range 0.2–3 mm. the layers often cross one another. The diameter of quartz blasts in quartz layers is between 0.2 and 0.3 mm. Most of the blasts show undulatory extinction.

Feldspar-quartz layers contain mostly sericitized plagioclases (albite or oligoclase; $Ab_{89-99}An_{1-11}$), and small amount of K-feldspars ($Or_{95-96}Ab,An_{3-8}$; Table 5), 0.01–0.3 mm in size. In the largest plagioclase blasts polysynthetic albite twins occur.

Table 3

Microprobe analyses of feldspars in mylonitic gneisses

	SZ1-1a	SZ1-2c
SiO_2	69.23	65.22
Al_2O_3	16.50	24.08
K_2O	11.75	0.59
Na_2O	1.77	7.81
CaO	0.30	2.13
Fe_2O_3	0.06	0.17
TiO_2	0.39	0.00
Total	100.00	100.00
Cations basing on 32 O atoms in the formula		
Si	12.460	11.376
Al	3.500	4.952
K	2.698	0.131
Na	0.617	2.643
Ca	0.057	0.398
Fe^{3+}	0.008	9.023
Ti	0.052	0.000
Ab	18	83
An	2	13
Or	80	4

Augens are composed mainly of alkali feldspars (orthoclase Or_{92-97}, with albite perthites; Table 5). Sometimes microcline and pericline twins form typical cross-hatched twinning. However, this "tartan" is often developed only partially on the section surface. Besides, infiltrating perthites can be observed. Some alkali feldspar augens contain relics of strongly sericitized plagioclases showing lamellar twins. Between alkali feldspars and fine-grained plagioclase, background myrmekite is observed.

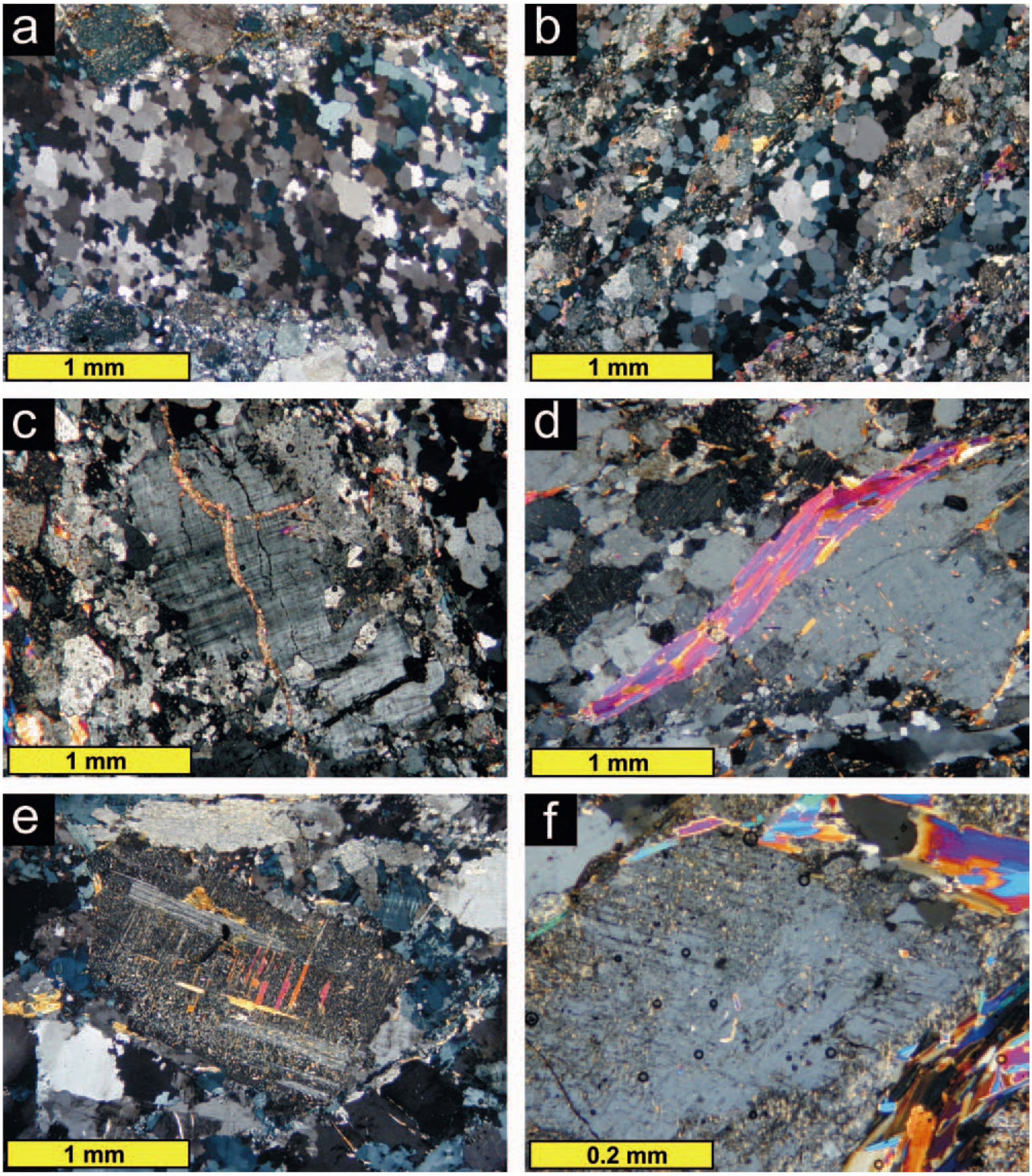

Fig. 4. Optical microphotographs of gneisses from the Wołosate area. All the photos at crossed polars. **a** – quartz layers in mylonitic gneiss SZ1, **b** – laminated structure in laminated gneiss P2, **c** – broken K-feldspar augen in flaser gneiss P4, **d** – phengite mica fish, flaser gneiss P5, **e** – sericitized plagioclase augen in granitic gneiss P1, **f** – plagioclase augen and white mica in a pressure shadow; granitic gneiss WK1

Phyllosilicates are distributed chaotically in the rocks. White mica (phengite) forms mainly layers and mica fishes, 0.05–0.2 mm thick. The sum (FeO+MgO) in these minerals vary from 1.6 to 7.6%, but the majority of analyses show the amounts above 3%, and #mg>0.2 (Table 4). Unaltered biotite is present in samples SZ2 and SZ4 (#mg:0.15; Table 6).

Chlorites are common secondary minerals, being responsible for macroscopically greenish colour of the rock. Chlorites are often associated with veins of opaque minerals.

Flaser gneisses

Five samples (WK2, WK5, P3, P5, SZ3) were included into this structural group.

Table 4

Microprobe analyses of white micas

	SZ1-10b (MG)	SZ2-1b (LG)	P4-1b (LG)	P3-3b (FG)	WK2-7c (FG)	SZ3-2c (FG)	P1-3d (GG)	WK1-2a (GG)
SiO_2	48.44	47.27	47.85	51.22	49.43	47.42	48.57	51.09
Al_2O_3	36.21	32.63	34.14	30.80	31.93	34.19	34.55	34.03
TiO_2	0.04	0.96	x	0.93	0.92	0.97	0.99	0.28
MnO	0.01	0.09	0.11	x	0.06	0.05	0.00	x
FeO	2.05	4.73	3.36	2.46	3.74	2.84	2.26	0.87
MgO	0.17	0.62	0.66	1.41	1.04	0.49	0.60	0.84
Na_2O	0.16	x	0.28	x	x	0.29	x	0.16
K_2O	12.69	13.70	13.60	13.18	13.08	13.75	12.77	12.36
CaO	0.23	x	x	x	0.15	x	0.26	0.37
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Cations basing on 22 O atoms in the formula								
Si	6.217	6.213	6.233	6.569	6.409	6.175	6.252	6.491
AlIV	1.783	1.787	1.767	1.431	1.591	1.825	1.748	1.509
AlVI	3.694	3.269	3.472	3.383	3.287	3.422	3.493	3.587
Ti	0.004	0.095	x	0.033	0.089	0.095	0.096	0.026
Mn	0.001	0.010	0.012	x	0.006	0.006	0.000	x
Fe^{2+}	0.220	0.520	0.366	0.264	0.406	0.309	0.243	0.092
Mg	0.032	0.121	0.127	0.269	0.201	0.096	0.115	0.159
Na	0.039	x	0.072	x	x	0.072	x	0.039
K	2.078	2.297	2.259	2.083	2.107	2.284	2.097	2.003
Ca	0.031	x	x	x	0.140	x	0.035	0.050
#mg	0.077	0.116	0.164	0.364	0.218	0.147	0.210	0.491

MG: mylonitic gneiss, LG – laminated gneiss, FG – flaser gneiss, GG – granitic gneiss; x – below limit of detection; #mg=MgO/MgO+FeO

Table 5

Microprobe analyses of feldspars in the laminated gneisses

	Augens				Matrix				
	P2-1a	P2-1b	P4-1c	P4-3c	P2-2b	P2-3b	P4-3b	P4-3d	P4-5b
SiO_2	63.13	70.34	63.44	63.27	62.96	70.71	70.76	71.08	69.96
Al_2O_3	17.76	19.81	17.66	17.55	17.45	19.6	19.46	19.11	19.86
K_2O	17.77	0.38	18.19	17.69	18.11	0.00	0.11	0.08	0.11
Na_2O	0.17	9.40	0.35	0.48	0.26	9.49	9.40	9.52	9.34
CaO	0.41	0.08	0.37	0.44	0.32	0.20	0.19	0.21	0.52
BaO	0.77	x	x	0.57	0.90	x	0.08	0.01	0.20
Total	100.01	100.01	100.01	100.00	100.00	100.00	100.00	100.01	99.99
Cations basing on 32 O atoms in the formula									
Si	11.891	12.158	11.911	11.909	11.903	12.198	12.217	12.265	12.114
Al	3.942	4.035	3.909	3.893	3.888	3.986	3.960	3.887	4.054
K	4.270	0.084	4.356	4.247	4.368	0.000	0.024	0.018	0.025
Na	0.063	3.149	0.127	0.174	0.094	3.173	3.145	3.185	3.136
Ca	0.082	0.014	0.073	0.090	0.065	0.038	0.036	0.038	0.097
Ba	0.057	x	x	0.042	0.066	x	0.005	0.000	0.013
Ab	1	97	3	4	2	99	98	98	96
An	2	0	2	2	1	1	1	1	3
Or	97	3	95	94	96	0	1	1	1

x – below limit of detection

Table 6

Microprobe analyses of biotites

	SZ2-4a (LG)	SZ2-4c (LG)	SZ3-2b (FG)	SZ3-7b (FG)
SiO_2	33.65	35.1	33.52	33.55
Al_2O_3	16.56	15.92	17.21	16.85
TiO_2	3.64	3.60	3.04	4.12
MnO	0.57	0.69	0.41	0.60
FeO	30.34	29.54	30.38	29.27
MgO	5.55	5.43	5.43	5.04
Na_2O	x	x	0.76	x
K_2O	9.46	9.50	9.24	10.49
CaO	0.23	0.21	x	0.08
Total	100.00	99.99	99.99	100.01
Cations basing on 22 O atoms in the formula				
Si	5.196	5.383	5.174	5.184
Al^{IV}	2.804	2.617	2.826	2.816
Al^{VI}	0.21	0.262	0.302	0.252
Ti	0.423	0.415	0.352	0.479
Mn	0.074	0.089	0.054	0.079
Fe^{2+}	3.918	3.789	3.922	3.784
Mg	1.278	1.242	1.25	1.160
Na	x	x	0.228	x
K	1.864	1.859	1.820	2.069
Ca	0.038	0.035	x	0.014
OH	4	4	4	4
#mg	0.155	0.155	0.152	0.147

LG – laminated gneiss, FG – flaser gneiss, x – below limit of detection; #mg=MgO/MgO+FeO

Directional planar structure of the flaser gneisses is not as obvious as in the laminated ones. The borders between quartz and quartz-feldspar layers are not sharp. The most characteristic feature of these gneisses is the presence of thin, up to 1–2 mm thick, directional aggregates of dark mica or their alterations products (chlorites).

In macroscopic observation some exotic pebbles (SZ2) have very well visible mica fish composed of biotite, 10 mm long and 2 mm wide. Irregular weathering rusty zones are observed on the surface of most of the exotic pebbles.

Microscopic observations show that in all of the flaser gneisses the augens are composed of alkali feldspars ($Or_{94-98}Ab,An_{2-6}$; Table 7). Microcline "tartan" is common (as in WK5) and well developed. Infiltrating perthites caused by albitization ($Ab_{98}An_2$) and enclaves of serictized plagioclase are present in the alkali feldspar. In sample SZ3, plagioclases 2–3 mm in diameter, containing inclusions of white mica, oriented parallel with the internal fracture and occurring mainly in central parts of the blasts, are present also in matrix.

The matrix of the rocks studied is composed of quartz and plagioclases (from andesine to albite, $Ab_{65-98}An_{2-35}$; Table 7) which are often sericitized. Blasts of quartz, 0.5–1mm in diameter, show undulatory extinction and are often elongated according to the weak foliation.

As stated above, a characteristic feature of all the flaser gneisses is the presence of phyllosilicates. The size of these aggregates is variable, in most cases less than 0.5 mm, sometimes up to 2 mm, and they often form characteristic 'mica fish' structures (Fig. 4d). These minerals are represented mostly by phengites (#mg:0.15–0.36; Table 4). Some exotic pebbles contain more biotite (sample no. SZ3; #mg: 0.14–0.15; Table 6) and the products of its alterations.

Granitic gneisses

This group is poorly represented in the collected pebble material (samples WK1 and P1). Granitic gneisses show macroscopically very poorly visible foliation, expressed mainly by the occurrence of elongated quartz domains. White-yellowish, irregular feldspar zones are present between quartz zones. Besides, feldspar relic augens, up to 7–8 mm in diameter, are present. Because of advanced processes of shearing the broken augens crystals and curved twin lamellae (Fig. 4e) can be observed. Very weak foliation is expressed by elongation of quartz crystals and the occurrence of mica aggregates around porphyroclasts.

The augens are composed of large, elongated alkali feldspars (P1, $Or_{95-98}Ab,An_{2-5}$ or Ab_{90-99},An_{1-10}), and of plagioclases (WK1, $Ab_{49-78}An_{51-22}$, Table 8). The longest axes of blasts are up to 15 mm in size. Repeated albite lamellar twins are observed. In some plagioclases, altered areas are observed (microprobe chemical analyse reveals albitization processes). All the augens contain inclusions of quartz, white mica (muscovite) and chlorite (Fig. 4e). Albitization is more advanced in the areas enriched in inclusions of white mica. White phengitic micas containing relatively small amount of Fe and Mg are present in pressure shadows of augens (Fig. 4f) The matrix of these rocks is composed of coarse-blasted quartz, showing undulatory extinction, strongly granulated quartz, and strongly sericitized plagioclases (chemical composition similar to those in augens, oligoclase, andesine and albite). Phyllosilicates are represented by white mica (Table 4), containing 2–2.9% (FeO+MgO), #mg: 0.20–0.49, sometimes forming nest-shape aggregates, as well as by small amounts of biotite and chlorite.

DISCUSSION

SHAPE AND PRESERVATION OF PEBBLES

As shown in the Zingg diagram (Fig. 2), the collected pebbles represent all the four classes of shape. This suggests that the transport of exotics pebbles was not too long. A long transportation would make one class of shape dominating. It can be assumed that during long transport the clasts of gneisses should acquire mainly discoidal and ellipsoidal shapes, whilst granitic gneisses pebbles should be more spherical. We have not observed such differences.

HYPOTHETICAL PROTHOLITH ROCK TYPES

Among the analysed pebbles there are no undeformed rocks, which could be interpreted as fragments of primor-

Table 7

Microprobe analyses of feldspars in the flaser gneisses

	Augens				Mtrix			
	WK2-3b	SZ3-1a	SZ3-2a	WK2-1b	WK2-1c	WK2-2c	SZ3-2d	SZ3-3b
SiO_2	70.55	62.76	62.84	69.84	63.25	63.63	64.55	62.49
Al_2O_3	19.63	17.70	17.61	20.43	23.30	23.20	22.68	23.50
K_2O	0.11	16.89	17.72	0.91	0.16	0.47	0.11	0.39
Na_2O	9.34	0.77	0.66	8.53	6.85	7.05	7.26	6.75
CaO	0.27	0.31	0.29	0.25	6.40	5.65	5.40	6.84
BaO	0.11	1.57	0.89	0.03	0.04	0.00	0.00	0.03
Total	100.01	100.00	100.01	99.99	100.00	100.00	100.00	100.00
Cations basing on 32 O atoms in the formula								
Si	12.186	11.864	11.870	12.084	11.163	11.221	11.343	11.069
Al	3.996	3.943	3.920	4.167	4.846	4.822	4.698	4.905
K	0.024	4.073	4.270	0.202	0.037	0.105	0.024	0.089
Na	3.128	0.282	0.241	2.863	2.346	2.412	2.474	2.318
Ca	0.05	0.063	0.058	0.046	1.210	1.067	1.018	1.298
Ba	0.007	0.116	0.066	0.002	0.002	0.000	0.000	0.002
Ab	98	6	5	92	65	67	70	63
An	2	1	1	2	34	30	29	35
Or	1	93	94	6	1	3	1	2

x – below limit of detection

dial crystalline massif. However, the authors tried to interpret the petrological nature of this massif, basing on mineral composition of pebbles.

In order to determine the petrographic character of the protolith, the results of line scanning (Table 2) were projected on the IUGS classification diagram for plutonic rocks (Smulikowski, 1975; Fig. 5). It was assumed that the mineral composition of rocks has not been significantly changed during metamorphism. The position of the projection points shows granodiorite and granite composition as possible protolith. Basing on geochemical analyses of orthogneissic pebbles from this area, the protolith was classified as S-type granite (Bąk & Wolska 2005).

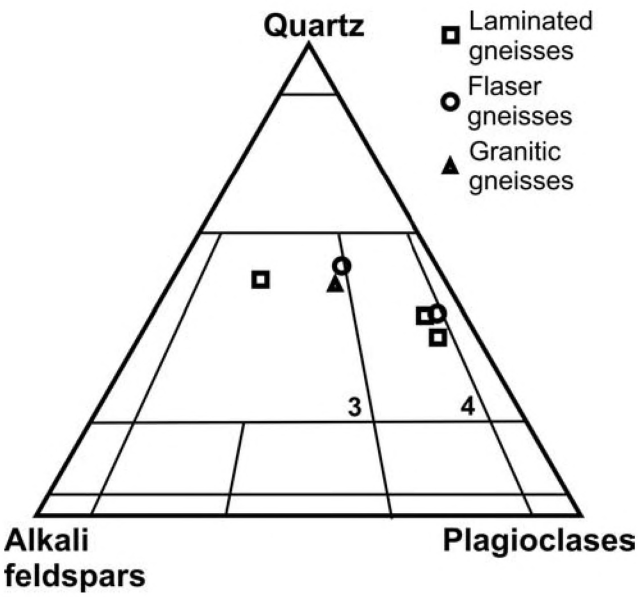

Fig. 5. Position of the gneissic pebbles studied on the IUGS classification diagram for plutonic rocks: 3 – granite, 4 – granodiorite

PROGRESS OF DEFORMATION PROCESSES

The gneissic pebbles studied can be subdivided into four types, according to the stage of their deformation:

Weakly deformed granitic gneisses. In this type of pebbles (samples WK1, P1) the most important process was deformation of minerals, while recrystallization was only of secondary importance. The observed microstructures are characterized by fracturing of feldspar augens (Fig. 4e) and undulatory extinction of quartz. Foliation is poorly visible, being mainly expressed as elongation of feldspar augens.

Initial recrystallization – laminated gneisses. This process is best visible in laminated gneissic pebbles (samples WK6, WK7, WK8, P2, P4, Fig. 4b). In these rocks quartz and quartz-feldspar layers are well developed (Fig. 4b), while mica aggregates are in the initial form. Foliation is expressed by quartz-feldspar, and quartz-feldspar-phyllosilicate layers, characterized by secondary amount of micas. The presence of augens in laminated gneisses is common.

Advanced recrystallization – flaser gneisses. The process of advanced recrystallization is observed mainly in samples WK2, WK5, P5, P3 and SZ3. In this type of peb-

Table 8

Microprobe analyses of feldspars in the granitic gneisses

	WK1-1b	WK1-2b	WK1-4a	P1-3b	P1-4c	WK1-5c	WK1-7b	3a	10a
SiO_2	63.22	66.24	62.86	63.85	70.90	62.91	62.06	63.42	61.73
Al_2O_3	23.24	22.59	23.39	17.52	19.34	25.59	23.29	25.98	17.15
K_2O	0.18	1.80	0.31	18.03	0.09	4.37	0.40	5.14	20.43
Na_2O	7.03	7.46	6.78	0.25	9.44	5.73	6.80	5.21	0.42
CaO	6.25	1.57	6.54	0.35	0.23	0.97	7.45	0.25	0.14
BaO	x	x	x	x	x	x	0.00	x	0.14
Fe_2O_3	0.07	0.34	0.12	x	x	0.43	x	x	x
Total	99.99	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.01
Cations basing on 32 O atoms in the formula									
Si	11.162	11.592	11.114	11.963	12.235	11.127	11.026	11.189	11.799
Al	4.836	4.659	4.874	3.870	3.932	5.334	4.876	5.402	3.863
K	0.040	0.402	0.069	4.309	0.02	0.986	0.091	1.158	4.981
Na	2.407	2.53	2.326	0.091	3.158	1.966	2.341	1.782	0.157
Ca	1.183	0.295	1.239	0.07	0.043	0.183	1.418	0.048	0.030
Ba	x	x	x	x	x	x	0	x	x
Fe^{3+}	0.010	0.045	0.016	x	x	0.057	x	x	0.010
Ab	66	79	49	2	98	93	61	60	3
An	33	9	49	1	1	6	37	1	1
Or	1	12	2	97	1	1	2	39	96

x – below limit of detection

bles, the aggregates of phyllosilicates (mainly white mica, secondary biotite and hydrobiotite or chlorite) occur. Mica fish structures are common (Fig. 4d). Poorly expressed separation of quartz and quartz-feldspar layers can be explained as an effect of obliterating primary structure by the formation of neomorphic quartz and micas formed at the expense of feldspars. Myrmekite is another structure which shows advanced recrystallization

Mylonitization – mylonitic gneisses. In sample SZ1 the evidence of more advanced deformation processes can be observed. The structure of this rock is similar to banded quartz-feldspar mylonites described by Shullman *et al.* (1995), where quartz, feldspars, and micas forming separate layers are completely separated.

In the case of this rock type, alternating quartz and feldspar laminae are visible, while small amounts of white mica are chaotically distributed (Fig. 4a). However, well developed lamination and the lack of augens allow to recognize in this rock the effects of mylonitization, and to call this pebble as mylonitic gneiss.

DEFORMATION CONDITIONS

Generally, there are three main microstructural components present in the studied gneissic pebbles: (1) feldspar augens, (2) matrix and (3) mica fishes or bands. The co-occurrence of these three domains is characteristic for rocks metamorphosed in the greenschist facies,what described by Menegon *et al.* (2008)

The majority of augens is composed of microclinic K-feldspar often with albite perthites and can be interpreted as relic crystals of granitic protholith. The occurrence of plagioclase augens in granite gneisses indicates weaker deformation and metasomatism in this type of pebbles (Lee & Kim, 2005).

Augens are surrounded by fine-grained matrix – aggregate of quartz and feldspar (mainly plagioclase).This matrix mainly consists of quartz ribbons, elongated and parallel to the foliation. Quartz often shows undulatory extinction. This elongation can be interpreted as c-axis crystallographic preferred orientations (CPO, after Menegon *et al.*, 2008). Such a crystallographic fabric can be developed during rotation and slip of grains or in recrystallization process (Law, 1990). Ribbons of elongated quartz observed in the Wołosate gneissic pebbles (Fig. 4a) can be developed during grain boundary migration – GBM recrystallization, according to Williams *et al.* (2000). Fine-grained quartz-feldspar aggregate is an effect of SR process (subgrain rotation, Williams *et al.* 2000).

In the laminated and flaser gneisses, phengite forms bands parallel to the foliation or lenticular fish with points inclined in the direction of foliation (Fig. 4d). It corresponds to the group 2 in the classification proposed by Grotenhuis *et al.* (2003).

The observed structural features described above show that the deformations were developed in the shear zone; the occurrence of mica fish is an important indicator of shear processes (Grotenhuis *et al.*, 2003). The simultaneous occurrence of SR and GBM recrystallization products indicates their development in fault zones at temperature 500°C (Stipp *et al.*, 2002). The fracturing of feldspar augens and plastic deformations of quartz also indicate the temperature range 500–550°C (Passchier & Trouw, 1996). Moreover, the advancement of foliation structures can be connected with the distance to a fault gauge, as shown by Lee and Kim (2005). According to their conclusions, the granite gneisses studied were developed in a most distant zone from the fault and were followed by laminated gneisses, flaser gneisses and mylonitic gneisses.

WHITE MICA AS INDICATOR OF METAMORPHIC CONDITIONS

The amount of Si^{IV} in white mica is controlled by temperature and pressure (Velde, 1967). The following factors play key role in the mica fishes development:(1) pressure solution, (2) diffusional mass transfer, (3) local growth of mica blasts, (4) deformation, (5) dynamic recrystallization, and (6) cataclastic behaviour (Grotenhuis *et al.*, 2003). This allows to interpret white micas in the studied gneissic pebbles as recrystallized during metamorphism. The majority of white micas in the studied laminated and flaser gneissic pebbles are phengites. Therefore, they were used for determining the pressure conditions by phengitic geobarometer proposed by Massone and Schreyer (1987). The lack of phlogopite in the mineral assemblage of the studied rocks allows to determine only the lowest pressure limit. On the basis of the described above structural observations in the rocks studied, the temperature range of 500–550°C was assumed, and the pressure higher than 5 kbar was postulated (Fig. 6).

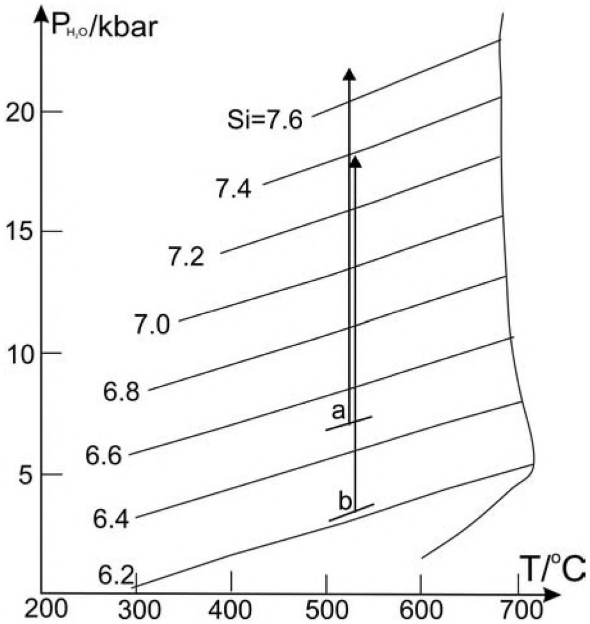

Fig. 6. P-T conditions of metamorphism of selected samples on the phengite barometer diagram after Massone and Shreyer (1987); simplified and modified. **a** – flaser gneiss P3, **b** – laminated gneiss SZ2

THE ROLE OF STRAIN PARTITIONING

The observed suite of rock types in Wołosate and their structures can be interpreted as developed during strain partitioning, by analogy to the structures of gneisses from the Śnieżnik Massif described by Cymerman (1997).

The mechanism of strain partitioning is especially important during deformation in subduction zones (Martinez *et al.*, 2002). This kind of deformation was described in many places on the western margin of the Carpathians by Nemčok *et al.* (1998).

POSSIBLE SOURCES OF GNEISSIC EXOTIC PEBBLES IN THE CISNA SANDSTONE

The studied gneissic pebbles from Wołosate can be described in general as weakly to medium deformed rocks, composed of quartz and plagioclase matrix, augens (mainly K-feldspar,) and white mica (mainly phengite). In the outer Carpathians similar rocks can be observed in many places, such as:

Western Carpathians. The Muráň Gneisses are leucocratic rocks which contain K-feldspar crystals, formed at the pressure 7–8 kbar (Kovačik, 2002). This value was determined according to the phengite geobarometer and fits to the limit determined for the gneisses from Wołosate. The presence of mica schists and amphibolites which occur in the Muráň Gneisses indicate higher pressure conditions. In Veporicum similar gneisses were described in the metamorphic complexes: Lovinobana, Sinec and Predna hol'a (Faryad, 1999). Further to the east, in Gemericum, the Klatov gneiss–amphibolite complex occurs, metamorphosed at 6–10 kbar and 650–700°C.

Eastern Carpathians. Five metamorphic successions were distinguished in the Romanian Eastern Carpathians: Rodna, Bretila, Tulgheş, Negrişoara, and Rebra. Bretila unit contains microcline augen gneisses (Pana *et al.*, 2002), similar to the gneissic pebbles from Wołosate. According to Pana *et al.* (2002), this unit represents a sequence metamorphosed within accretionary wedge while the least deformed rocks of this sequence are remnants of a subduction arc.

CONCLUSIONS

1. Metamorphic rock pebbles from the Cisna beds (Wołosate area, Bieszczady Mts.) belong petrographically to four groups: granitic gneisses, laminated gneisses, flaser gneisses and mylonitic gneisses.

2. The protholith of the studied rocks were S-type granitoids deformed during Variscan orogenesis.

3. Primary granitoids were metamorphosed at the temperature of 500°C and pressure above 5 kbar. Their metamorphism was limited to the greenschist facies.

4. The origin of the observed various structures of the gneissic pebbles studied can be explained as follows:

– deformation of granitoids in a fault zone, at various distances from the fault gauge;

– strain partitioning in tectonic convergence zone.

5. The nature and localization of the source area can be similar to the Bretila sequence from the Romanian Eastern

Carpathians. Sedimentary structures observed in the Cisna beds indicate that the clastic material was transported to the Dukla basin from the SE (Bąk & Wolska, 2005).

Acknowledgements

Thanks are due to Prof. W. Narębski (Museum of the Earth, Polish Academy of Sciences, Warsaw), Prof. W. Zuchiewicz (AGH Univeristy of Science and Technology), and Dr. S. Leszczyński (Institute of Geological Sciencens, Jagiellonian University) for critical reading of this paper and for improving the English text. We thank to Dr. Z. Cymerman (Polish Geological Institute, Lower Silesian Branch) and two anonymous reviewers for valuable opinions and indicators to improve this paper. Thanks are extended to Dr. K. Bąk (Pedagogical University, Kraków) for introduction into area of the research and offered samples. We are indebted to J. Faber, M.Sc. (Scanning Microscope Laboratory of the Institute of Zoology, Jagiellonian University) for chemical microprobe analyses We thank also the authorities of the Bieszczady National Park for the permission to carry out fieldwork.

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