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A petrogenetic comparative study of zircons from the mylonites of the Niemcza Shear Zone and the gneisses of the Góry Sowie Block (SW Poland)

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Abstract The morphological features and typological distributions of zircon in the mylonites of the Niemcza Shear Zone (NZ) and in the gneisses and migmatites of the Góry Sowie Block (GSB), in the NE part of the Bohemian Massif, SW Poland, provide important petrogenetic indicators in the strongly deformed metamorphic rocks. The observed similarities between the zircon populations (combined with other field and petrographic evidence) strongly suggest that at least a part of the mylonites developed at the expense of rocks similar to the GSB gneisses and migmatites. The protoliths of the gneisses and migmatites (both in the GSB and within the NZ) were predominantly of sedimentary character, but the zircons suggest that crustal-type granites (in the case of the NZ gneiss and mylonite protoliths) and hybrid mantle/crustal-type granites (in the case of the GSB migmatite protoliths) could have been important sources for the original, mostly detrital (?) material. The large proportion of zircon grains in the NZ mylonites, showing effects of disintegration, can result from sedimentary abrasion of detrital material, and this apparently corroborates the hypotheses that a part of the NZ mylonites derived from protoliths other (more strongly reworked by sedimentary processes?) than those typical of the gneisses and migmatites of the GSB. However, there is also evidence that mylonitization could have influenced the morphometric features of the zircon crystals, generally increasing the proportion of fractured and broken crystals and, most spectacularly, reducing the mean size of the zircon grains in the mylonites. The controversy remains open and to find better constraints would require further detailed petrological studies.

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INTRODUCTION

Several studies have documented the mechanical and chemical resistance of zircon crystals to various petrogenetic processes, such as deformation (e.g. Lancelot *et. al.*, 1983; Vavra, 1990) and anatexis (e.g. Watson & Harrison, 1982). Since the classic work of Poldervaart (1956, see also refs. in Majerowicz 1975, 1981), the shape of euhedral zircon crystals has been used as an index of magmatic origin. Later on, crystal typology (e.g. Pupin & Turco, 1972, 1975; Pupin, 1980, 1985) and internal zircon structure, best visible in cathodoluminescence or BSE images (e.g. Vavra 1990, 1994), have been exploited as key sources of petrogenetic information. However, zircon, as a very hard but brittle mineral, tends to be ground during transport of detrital material and becomes more or less rounded. A large amount of such zircon grains in metamorphic rocks indicates their supracrustal affinity, i.e. sedimentary origin or derivation from an S-granite protolith (e.g. Klimas-August, 1989).

A possible response of zircon to deformation due to ductile strain under metamorphic conditions, e.g. in shear zones, was discussed by a number of petrologists (e.g. Boullier, 1980; Wayne & Krishna Sinha, 1988; Sturm, 1999; Steyrer & Sturm, 1995, 2002). An example described from the mylonitic rocks of the Adrar des Iforas in the Republic of Mali shows that the size of brittle minerals, including zircon and feldspars, decreases towards the centre of the shear zone, and that it attains an "equilibrium stage", where the grain size and shape become stable. Therefore, the size of brittle minerals seems to be independent of finite strain but dependent on applied stress (Boullier, 1980). However, the SEM photographs of zircons from the mylonitised Henderson gneiss in North Carolina (Wayne & Krishna Sinha, 1988) indicate that strain-related fracturing and the size reduction of the grains were accompanied by Pb loss throughout the mylonite zone. Stresses imposed by the expansion of initially

U-rich, α-damaged portions of the crystals resulted in microfracturing of the more brittle crystalline material proximal to the U-rich zones. During mylonitisation, the fractures propagated preferentially along these zones, allowing metamorphic fluids to penetrate the easily-leached, α-damaged portions of the zircons. Removal of ~75% of the radiogenic Pb from zircons in the least deformed zones of the mylonites may have occurred via this mechanism.

The zircons from the amphibolite facies fine-grained mylonite from the Austrian Moldanubicum (Sturm, 1999) show, partially, significant physical and chemical changes compared to the grains from the protolith. The crystals from the mylonitised rock display distinct fracturing and rounding of the steep pyramids. However, zircons from the undeformed wall rock and from the most highly deformed ultramylonite at Miëville, Switzerland (Steyer & Sturm, 2002), show only minor alterations and mechanical damage of the crystals, even in an extreme state of deformation. This high stability of zircon crystals evidently controls the Zr behaviour as a generally immobile element, which is used as a passive marker for the calculation of mass and volume changes during deformation processes (op. cit.).

The aim of this work is to present new data on the petrogenesis of various mylonite varieties of the Niemcza Shear Zone (NZ), east of the Góry Sowie Block (GSB) in the NE part of the Bohemian Massif, SW Poland. Our considerations are based on the morphology and morphometry of zircon crystals found in the mylonites and in the country rocks. We make an attempt to evaluate the influence of mylonitization intensity on the morphology and morphometry of zircon grains inherited from the protoliths. We also use the morphology and typology of zircons to test whether the mylonites developed from the GSB gneisses and migmatites, or whether other protoliths could have been involved in the regional-scale mylonitization.

GEOLOGICAL SETTING

The N–S trending Niemcza Zone is a major shear zone c. 20 km long and up to 5 km wide, developed along the eastern margin of the Góry Sowie Block (Scheumann, 1937; Teisseyre *et al.*, 1957; Fig. 1). Its boundaries correspond to regions of a high strain gradient which separate the mylonitized rocks from the surrounding lower strain units. The origin and development of the Niemcza Zone were controversially interpreted during the past decades. Bederke (1929) and Dziedzicowa (1985, 1987) considered the rocks of the zone to be metasedimentary schists. Following this concept, Żelaźniewicz (1995) and Cwojdziński & Żelaźniewicz (1995) treated the Niemcza Zone as a 5 km wide belt consisting of cordierite- and andalusite-bearing metagreywackes with subordinate quartzites and clasts of the Góry Sowie gneisses, with the whole sequence having been deposited on the mylonitized gneissic bedrock. The metasedimentary succession zonally underwent polyphase shearing and mylonitization prior to the intrusion of the c. 340 Ma Niemcza granodiorite (Franke & Żelaźniewicz, 2000). The latter is one of several small bodies of undeformed to little deformed Lower Carboniferous granitoids and syenites/diorites scattered along the Niemcza Zone.

Contrastingly, Scheumann (1937) and Mazur & Puziewicz (1995) considered the Niemcza Zone a large mylonitic band derived from the Góry Sowie gneisses. The mylonites were thought to have developed due to a left-lateral strike-slip ductile shear, localized in gneisses along their eastern contact with the Kamieniec Metamorphic Belt (Fig. 1). Accordingly, minor inclusions of non-mylo- nitic gneisses, quartzo-graphitic schists and serpentinites represent original components of the initial gneiss complex. The mylonites were subdivided into high- and low-temperature varieties, respectively formed under amphibolite and greenschist facies conditions (Mazur & Puziewicz, 1995). The widespread mylonitization in the Niemcza Zone inspired Cymerman and Piasecki (1994) to interpret it as a major strike-slip terrane boundary developed during the Variscan terrane accretion.

The triangular Góry Sowie Block, ca. 600 km^2 in size, is divided into mountainous and foreland parts by the Sudetic Marginal Fault. It consists of predominant gneisses and migmatites, with intercalations of HT-HP granulites, and of amphibolites, serpentinites and minor bodies of other lithologies (Grocholski, 1967; Kryza, 1981; Żelaźniewicz, 1987). Problematic microfossils from calc-silicate intercalations in the gneisses were interpreted to indicate ages no older than the Cambrian (Gunia, 1997). Ages between ca. 370 and 480 Ma have been obtained for zircon, monazite and xenotime in the gneisses, antectic granites and pegmatites, and, using the Rb-Sr method, in the migmatites. The younger ages are considered to be the time of the ceasing stage of HT metamorphism and migmatization (e.g. Bröcker *et al.*, 1998; Timmermann *et al.*, 2000, and refs. therein).

The metamorphic and tectonic evolution of the GSB was polyphase and the resulted structural pattern is complicated (Grocholski, 1967; Żelaźniewicz, 1987, 1990). A rather widespread feature of the gneisses and migmatites is the presence of polygenetic, usually centimetre-scale thick shear zones, with mineral parageneses ranging from amphibolite (Sil + K-fsp) to greenschist facies (Chl + Ep) conditions; they are found in many places in both the mountainous and foreland part of the gneissic block. Along the eastern margin of the GSB, the main tectonic foliation in the gneisses and migmatites stikes N–S and is steeply inclined, generally parallel to the main tectonic fabric in the Niemcza Shear Zone (Grocholski, 1967; Dziedzicowa, 1985; Cwojdziński & Żelaźniewicz, 1995; Żelaźniewicz, 1995; Franke & Żelaźniewicz, 2000).

Fig. 1. Geological sketch map of the Sudetes with the study area outlined in the box. BB – Bardo Basin; EFZ – Elbe Fault Zone; ISF – Intra-Sudetic Fault; KMB – Kamieniec Metamorphic Belt; KU – Kłodzko Metamorphic Unit; KZG – Kłodzko – Złoty Stok Granitoid; LG – Lustian Granitoid Massif; MGCH – Mid-German Crystalline High; MO – Moldanubian Zone; NM – Niedźwiedź Massif; NP – Northern Phyllite Zone; NZ – Niemcza Shear Zone; OFZ – Odra Fault Zone; RH – Rhenohercynian Zone; ŚB – Świebodzice Basin; SBF – Sudetic Boundary Fault; SCM – Strzelin Crystalline Massif; ST – Saxothuringian Zone; SZ – Skrzynka Shear Zone. *Age assignments*: Pt –Proterozoic; Pz –Palaeozoic; Cm – Cambrian; Or – Ordovician; D – Devonian; C – Carboniferous: C_1 – Early; C_2 – Middle; C_3 – Late.

SAMPLE LOCATION AND MAIN PETROGRAPHIC FEATURES OF SPECIMENS

The samples selected for the zircon study (Fig. 2) represent the two varieties of the NZ mylonites defined by Mazur and Puziewicz (1995):

– high temperature mylonites deformed under amphibolite facies conditions: specimens 1, 6, 8, 9, 9A and 11,

– low temperature mylonites deformed under greenschist facies conditions: specimens 5, 5A and 19.

In addition, we take into account the results obtained by Jendrzejaczyk (1998) in her MSc thesis on zircons from the Góry Sowie gneisses in the Fore-Sudetic Block. For the rock types, sample symbols and location, see Table 1.

The mylonites contain porphyroclasts of plagioclase, garnet and, locally, cordierite, embedded in a fine-grained, laminated matrix composed of quartz and plagioclase. They are accompanied by synkinematic biotite, white mica and chlorite. According to Mazur and Puziewicz (1995), the assemblage of porphyroclasts in the mylonites, together with field evidence (gneiss and mylonite alterna-

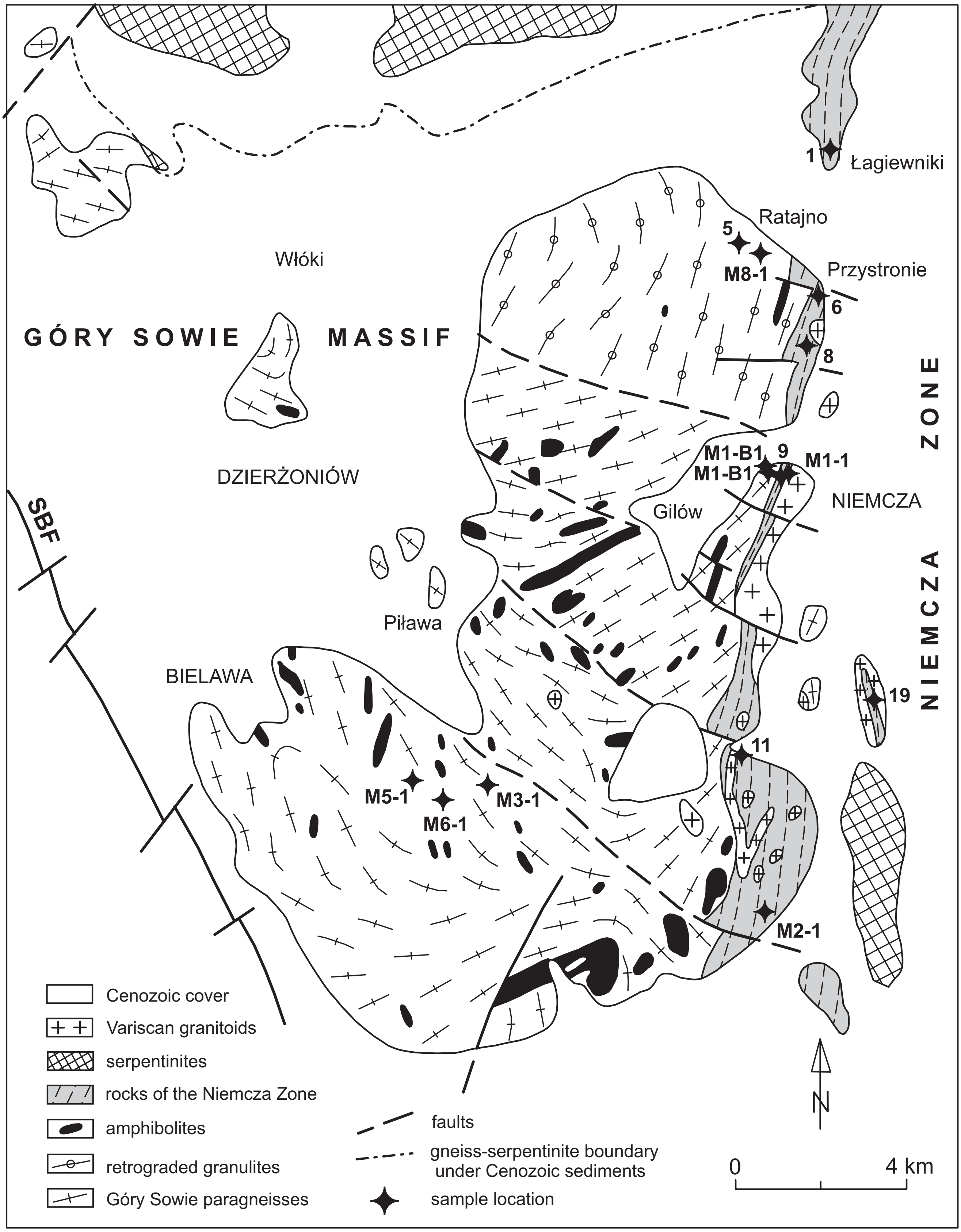

Fig. 2. Location of investigated samples on the geological sketch of the Niemcza Zone and the adjacent part of the Góry Sowie Massif (based on Żelaźniewicz, 1995). SBF – Sudetic Boundary Fault.

Table 1

Location and petrography of the investigated samples

Area rock	Sample	Rock type and location	Petrography	Ondicators of metamorphic facies	Accessory minerals
NZ amphibolite facies mylonites	1*	mylonite, quarry on S slope of hill 200.3 m, N of road Łagiewniki–Dzierżoniów	fine-grained, layered (Qtz+Fsp and Bt+Ms) matrix, with Fsp porphyroclasts (4x2 mm), Pl porphyroclasts often sericitized, fabric indicating non-coaxial deformation (Mazur & Puziewicz, 1995)	fibrolite, often overgrown with Bt, Crd, Grt	opaques, zircon
	6*	mylonite, Szwedzki Okop, W of Przystronie	fine-grained, Pl+Qtz+Bt matrix, variably laminated, flattened and partly recrystallised porphyroclasts of Pl and Grt and elongated lenses of Qtz+Pl, distinct extensional crenulation cleavage, evidence of non-coaxial deformation	fibrolite, Grt	opaques, zircon in Pl porph. and in mosaic Qtz
	8*	dark mylonite, hill 244.5 m, S of road Przystronie–Ligota W	porphyroclasts of Pl, Kfs, Crd & Grt and elongated Qtz in fine-grained Qtz+Pl+Bt matrix	fibrolite, Crd, abundant Grt	opaques, scarce zircon
	9*	mylonite, Piekiełko Gorge, east of Gilów	fine-grained rock, with Fsp+Qtz, and Bt+Ms lamination, locally distinct S-C fabric, variably distributed extensional crenulation cleavage, evidence of non-coaxial deformation	fibrolite	opaques, zircon in synkinematic matrix
	9A** M1-1	mylonite, Piekiełko Gorge, east of Gilów	fine-grained rock, with Fsp+Qtz and Bt+Chl+/-Ms lamination, distinct S-C fabric	fibrolite	opaques, zircon
	11*	mylonite, quarry S of road Piława Górna–Przerzeczyn Zdrój	fine-grained, weakly laminated rock composed of Pl+Qtz+Bt+Ms	fibrolite	opaques, zircon, monacite
NZ greenschist facies mylonites	5*	mylonite, old quarry, S of Ratajno	unequigranular (serial texture) rock, with Fsp+Qtz and Chl+Ms lamination, flattened Qtz porphyroclasts and Qtz & Pl aggregates, variably developed extensional crenulation cleavage, evidence of non-coaxial deformation	Chl, Grt	opaques, zircon in Qtz porph. & syn-kinematic matrix
	5A** M8-1	mylonite, old quarry, SW of Ratajno	fine-grained laminated rock, with light Qtz+Kfs+Pl and dark Bt laminae, weak S-C fabric	Grt	opaque min, zircon
	19*	mylonite, Strach hill near Koźmice	fine-blastic, Pl+Qtz+Bt+Chl+Ms matrix, locally laminated, with Pl & Grt porphyroclasts in light laminae, and Ms & Chl porphyroclasts in dark laminae, Pl and Qtz aggregates, common S-C fabric and extensional crenulation cleavage, evident non-coaxial deformation	Chl, Grt	opaque min, zircon, apatite, tourmaline
NZ migmatites	9b** M1 B1	migmatite (schliren gneiss), Piekiełko Gorge, east of Gilów	schliren structure, Qtz+Kfs+Pl laminae of leucosome, dark schliren of Bt+fibrolite melanosome	fibrolite	opaques, zircon, apatite
	9c** M1 B2	migmatite (nebulite) Piekiełko Gorge, east of Gilów	medium-grained Qtz+Pl matrix, oriented structure marked by Bt+Chl+Kfs blasts	Chl	opaques, zircon, apatite
GSB migmatites	M3-1M***	layered migmatite (melanosome), NE vicinity of Owiesno	melanosome of leyered migmatite, Bt-rich, minor Qtz, Pl & Kfs	Grt	opaques, zircon
	M3-1L***	layered migmatite (leucosome), NE vicinity of Owiesno	leucosome of leyered migmatite, Qtz+Pl+Kfs -rich, minor Bt	Grt	opaques, zircon
	M5-1***	veined-gneiss, NW vicinity of Owiesno	veined rock with indistinct lamination of Pl+Kfs+Qtz and Bt+Fibr+Chl+Ms	fibrolite, Grt	opaques, zircon, apatite
	M2-1***	schliren gneiss, Buk hill S of Brodziszów	fine-grained rock, with Qtz+Pl+Bt+Fibr+Chl and minor Kfs & Ms matrix, locally schliren structure	fibrolite	opaques, zircon, apatite
GSB granite-gneiss	M6-1***	granite-gneiss, NW vicinity of Owiesno	medium-grained, locally weakly laminated rock, with elongate aggregates of Qtz+Kfs+Pl in dark laminae of Bt+Fibr+Ms	fibrolite, Grt	opaques, zircon

The new petrographic observations from thin sections and heavy mineral concentrates have been combined with the results of Mazur & Puziewicz (1995) and Jendrzejaczyk (1998).
* symbols and location of samples as in Mazur and Puziewicz (1995);
** symbols and location of samples as in Jendrzejaczyk (1998), samples from localities studied by Mazur & Puziewicz (1995) and Klimas & Mazur (2002);
*** symbols and location of samples as in Jendrzejaczyk (1998).
Mineral abbreviatons: Qtz – quartz; Pl – plagioclase; Fsp – feldspars; Kfs – K-feldspar; Bt – biotite; Chl – chlorite; Ms – muscovite; Fibr – fibrolite; Grt – garnet; Crd –cordierite.

Table 2

Morphology, morphometry and typology of zircons from mylonites and migmatites of the Niemcza Zone and from gneisses and migmatites of the Góry Sowie Block

Morphology and morphometry of zircons	Amphibolite facies mylonites (NZ)					Greenschist facies mylonites (NZ)			Migmatites of the NZ		Migmatites of the Góry Sowie Block				Granite-gneiss GSB
Sample	1*	6*	11*	9*	9A** M1-1	5*	5A** M8-1	19	9b** M1 B1	9c** M1 B2	M3-1M***	M3-1L***	M5-1***	M2-1***	M6-1***
Quantity of investigated zircons	100	100	50	100	100	100	100	100	100	100	100	100	100	100	100
Euhedral and subhedral crystals, %	20	0	12	24	59	0	43	27	39	65	35	45	40	55	58
Subrounded forms, %	57	9	28	35	41	24	40	37	36	30	43	27	37	13	23
Rounded grains, %	5	88	54	18	0	69	16	28	25	5	22	24	23	32	19
Angular forms, %	18	3	6	23	-	7	-	8	-	-	-	-	-	-	-
Broken zircons, %	10	1	8	17	10	17	10	4	6	10	8	20	6	15	6
Fractured zircons, %	2	5	0	0	-	4	-	4	-	-	-	-	-	-	-
Zircons with "extinction angle", %	8	22	8	6	-	22	-	4	-	-	-	-	-	-	-
Mean length, mm	0.06	0.06	0.07	0.08	0.13	0.07	0.11	0.10	0.13	0.15	0.14	0.17	0.15	0.12	0.12
Standard deviation of length, mm	0.02	0.02	0.02	0.02	0.03	0.02	0.02	0.02	0.03	0.05	0.03	0.04	0.03	0.03	0.02
Mean width, mm	0.04	0.04	0.04	0.05	0.07	0.04	0.06	0.05	0.06	0.07	0.07	0.07	0.07	0.06	0.06
Standard deviation of width, mm	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.02	0.01	0.02	0.02	0.01	0.01
Mean elongation	1.8	1.5	1.6	1.8	2.1	1.6	2.0	1.9	2.1	2.5	2.2	2.4	2.0	1.9	2.0
Standard deviation of elongation	0.5	0.3	0.4	0.5	0.5	0.5	0.4	0.5	0.6	0.6	0.6	0.6	0.4	0.4	0.3
Main typological forms	S_7, S_2	0	S_{17}	S_2, S_7, S_{12}, S_{11}	S_4, S_{13}, S_7	0	S_4, S_{25}	S_7, S_2, S_{12}	S_9, S_4, S_3	S_2, S_3, S_7	S_{17}, S_{18}, S_{12}	S_{17}, S_{18}, S_{22}	S_{12}, s_7, S_2	S_7, S_8, S_9	S_7, S_9, S_{13}
Subordinate typological forms	S_3, S_4	0	S_{22}, S_{12}	S_1, S_8	S_8, S_2, S_{12}	0	S_9, S_8, S_{14}	S_3, S_{13}	S_8, S_7, S_{13}	S_1	S_{22}, S_{13}	S_{23}, S_{19}, S_{12}	S_{13}, S_4	S_2, S_{13}	S_4, S_8, S_2

* symbols and location of samples as in Mazur and Puziewicz (1995);
** symbols and location of samples as in Jendrzejaczyk (1998), samples collected from localities studied by Mazur and Puziewicz (1995);
*** symbols and location of samples as in Jendrzejaczyk (1998);
Samples 5, 5A collected in old quarries, S and SW of Ratajno;
Samples 9, 9A, 9b, 9c from Piekiełko Gorge, east of Gilów;
Samples M3-1 to the NE, a M5-1 and M6-1 to the NW of Owiesno (M3-1M = melanosome, M3-1L = leucosome);
Sample M2-1 from Buk Hill, S of Brodziszów.

tion and gradational contacts between the two) indicate that the mylonites were produced at the expense of the GSB gneisses and migmatites. On the other hand, Franke and Żelaźniewicz (2000) argue that the often observed presence of cordierite and andalusite in the NZ mylonites is in contrast with the "typical" mineralogy of the GSB rocks, and may indicate that they had different protoliths. However, this argument is equivocal, as within the GSB gneisses, alumina-rich varieties (e.g. sillimanite-rich and cordierite-bearing types) are not uncommon.

Samples representing the high temperature variety of mylonites developed under amphibolite facies conditions (Table 1 – localities 1, 6, 8, 9 and 11) contain significant amount of synkinematic fibrolite. Furthermore, in samples 8, 9 and 11, the abundant fibrolite is accompanied by cordierite. Samples 5 and 19 represent the low temperature variety of the mylonites which were formed under greenschist facies conditions. Besides quartz, plagioclase and micas, they contain synkinematic chlorite. Garnet was found in samples 5, 8 and 19. In the particularly garnet-rich sample 8, zircon is lacking. Samples representing different degrees of mylonitization were selected for zircon analysis from both the high- and low- temperature varieties of the mylonites. The rock collection was supplemented by two samples of migmatites from the NZ (9b, 9c) and three samples of migmatites and one of granite-gneiss from the GSB (Tables 1, 2, and Fig. 2).

METHODS

A jaw crusher was used to break up the samples (of a rough average weight of 2–3 kg) to a grain size $< 300\ \mu$m. Heavy mineral concentrates were separated using conventional sieving, heavy-liquid and magnetic techniques. The main physical and morphological properties of zircons: morphology, morphometry and typology (e.g. Pupin & Turco, 1975; Klimas-August, 1989) were assessed using binocular and polarizing microscopes.

One hundred zircon grains were observed under transmitted light in heavy mineral concentrates from samples 1, 6, 11, 9, 5 and 19 from the NZ mylonites (Table 1, Figs. 1, 2). In the remaining rock samples, ca. 200 zircon crystals were investigated using the same technique, but after manual concentration of the mineral under the binocular microscope. To verify the consistency of both procedures of observation, an additional test comparing the morphology and morphometry of zircons from the NZ mylonites and from the gneisses of the Strzelin Massif was performed (Klimas & Mazur, 2002).

RESULTS

The morphology and morphometry of zircons

The zircon crystals from the investigated GSB gneisses and migmatites and from the NZ mylonites differ considerably in their morphological and morphometrical features (length, width and elongation) as well as in their calculated statistical parameters: the mean length, width, elongation and their standard deviations (Table 2, Fig. 3).

From the basic morphological and morphometric characteristics, it is evident that the zircons from most of the NZ mylonites differ from those obtained from the gneisses and migmatites of the GSB (Table 2, Fig. 3). The NZ mylonites, compared with the GSB gneisses and migmatites, are characterised by:

a) a dominance of fine-grained zircon fractions,

b) lower elongation values,

c) lower standard deviations of length, width and elongation of grains,

d) a considerably lower proportion of euhedral and subhedral crystals and a higher amount of subrounded, rounded and angular grains (in the GSB migmatites, only melanosome M3-1M shows a dominance of subrounded and rounded grains),

e) a higher amount of broken and angular grains representing fragments of larger crystals,

f) a greater number of grains with cracks and fractures.

Additional distinct features (Table 2, Fig. 3) that can serve as important petrogenetic indicators include:

1. The large number of subrounded and rounded, nearly ellipsoidal and anhedral zircon grains in a few samples of the NZ mylonites (e.g. samples 5 and 6). Zircon populations of 100 counted grains quite often contain no euhedral crystals (samples 5 and 6 in Table 2).

2. The small size of the majority of the zircon grains (mean length in the range of 0.06–0.07 mm) and their relatively low diversity in several samples of the NZ mylonites, particularly those representing the amphibolite facies mylonites (e.g. samples 1, 6 and 11). The zircons from these samples are often of the same size as the crystals in the laminated fine-grained mylonite matrix composed of quartz, plagioclase and micas. The mean length of such zircons is usually equal to the mean width of zircon crystals derived from all the investigated samples of the GSB migmatites and granite-gneiss (samples M3-1M, M3-1L, M5-1, M2-1, and M6-1) as well as from the NZ migmatites (samples 9b, 9c, Table 2, Fig. 3).

3. Among the samples representing the high temperature mylonites, those showing higher strain (e.g. sample 5) contain a greater number of rounded and anhedral zircon grains, whereas the lower-strained samples bear more abundant euhedral and subhedral zircon crystals (e.g. sample 19, Table 2, Fig. 4B).

The typology of the zircons

Although there are similarities in them, the typological diagrams of Pupin & Turco (1975) and Pupin (1980), produced for zircons from the NZ mylonites and associated gneisses and migmatites and for those from the GSB migmatites and granite-gneiss, show considerable differences in subtype populations between particular samples (Fig. 7). In a few specimens, a large variety of zircon subtypes is also documented within an individual sample (e.g. samples 1, 5, 5A, 9, 9A and M5-1, Fig. 7).

The typological distribution (Pupin, 1980) indicates that both the NZ gneisses and migmatites (9b and 9c) and mylonites (9 and 9A) which alternate in the exposure of Piekiełko Gorge (near the boundary between the GSB and NZ; Figs. 1, 2) have very similar zircon subtypes (Fig. 7, Table 2). Similar forms are also found in the greenschist facies NZ mylonite (sample 19) from Strach Hill near Koźmice, and in the GSB granite-gneiss (M6-1) from Owiesno (Fig. 7, Table 2). Furthermore, the NZ mylonite sampled south of the Piława-Przerzeczyn road (sample 11) contains zircon subtypes roughly similar to those from the melanosome M3-1M and leucosome (M3-1L) of the GSB migmatite collected to the NE of Owiesno and from

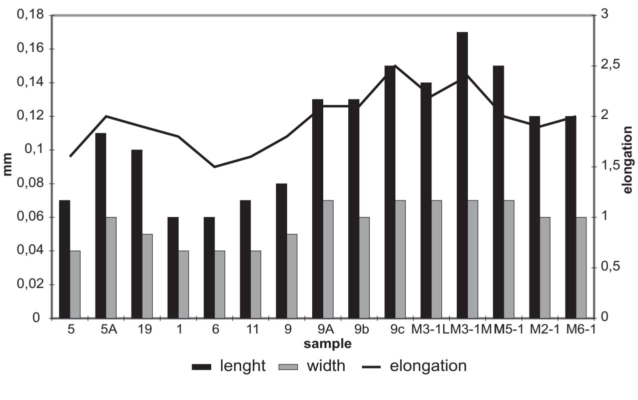

Fig. 3. Mean length, mean width and mean elongatin of the investigated samples.

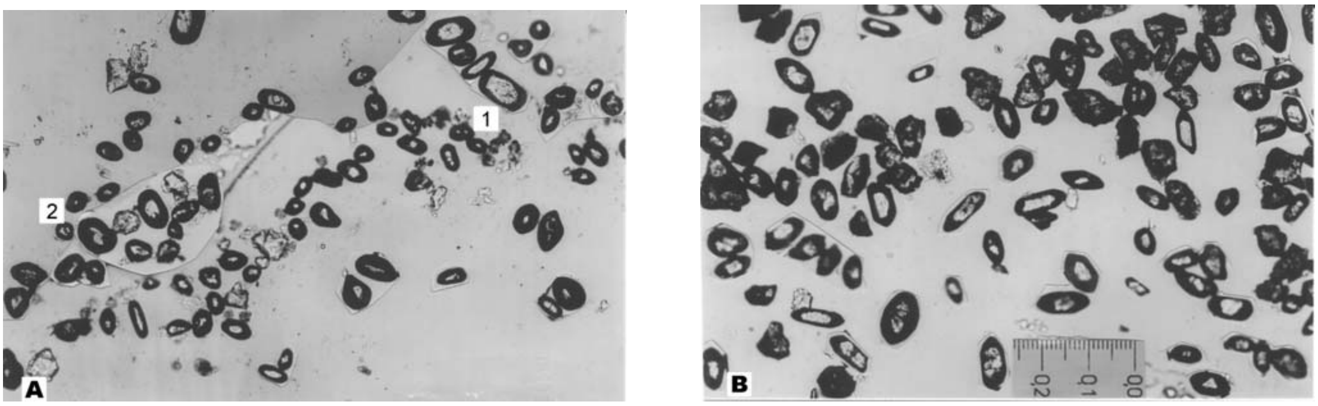

Fig. 4. Typical zircons from: **A** – sample 6 of the amphibolite facies mylonite (1 & 2 – see text); **B** – sample 19 of the greenschist facies mylonite; one polarizer, scale in mm.

the GSB migmatite (M5-1) cropping out in the NW vicinity of Owiesno (Figs. 2 & 7, Table 2). Similar subtypes, S_{13} and S_{12}, are also present in sample 6 of the NZ mylonite (Szwedzki Okop, west of Przystronie, (Figs. 2, 7, Table 2). In the remaining samples of the GSB migmatites, the observed typological distribution is wider than that in the samples of mylonites and migmatites from the NZ. Most typically, the gneisses and migmatites of the GSB comprise dominant subtypes S_{17}, S_{18} and S_{22} (Fig. 7, Table 2), whereas in the migmatites and mylonites of the NZ, subtypes S_7, S_2, S_{12} and S_8 are the most common.

DISCUSSION: PROTOLITHS AND ZIRCON RESPONSE TO MYLONITIZATION

The described similarities in the typology of zircons from the NZ mylonites and the GSB gneisses and migmatites indicate that the mylonites could have developed from the GSB rocks. Indeed, some subrounded and ellipsoidal grains in the mylonites can represent fragments of crystals belonging to subtypes often found in the GSB migmatites (Figs. 4A, 4B, 7, 9). However, significant differences in zircon populations were found in a number of samples. In some of the mylonites and migmatites of the NZ, zircon subtypes characteristic of granites of crustal affinities (e.g. S-type) prevail (c.f. Pupin, 1980). By contrast, a number of samples of the GSB migmatites mainly comprise zircon subtypes more typical of material (igneous or reworked/sedimentary) coming from hybrid granites of mixed crustal and mantle origin – mainly subtypes S_{17}, S_{18}, S_{19} and S_{22}, and even S_{24} in sample M3-1L (Figs. 5, 6, 7, Table 2).

Taking into account our new data, it is likely that the zircons in both the NZ mylonites and GSB migmatites are inherited from sedimentary protoliths rather than from igneous rocks. This is spectacularly evidenced by the high amount of rounded and subrounded zircon grains in the examined sample of migmatite melanosome, M3-1M. Also, most of the zircon populations typical for the Niemcza Zone mylonites display typological distributions and features indicating a less frequent input of mafic components in their protoliths compared to the GSB migmatites. Furthermore, in the mylonites (e.g. in samples 11,

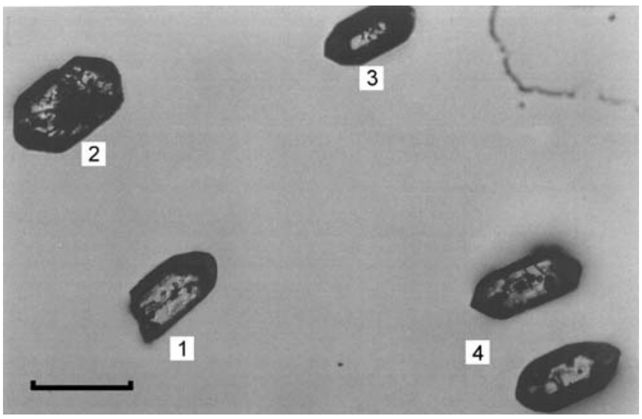

Fig. 5. Zircons from sample 9A of the amphibolite facies mylonite: 1 – broken S_3; 2 – S_{25}; 3 – S_{13}; 4 – S_{25} (subtypes by Pupin, 1980); one polarizer, scale bar = 0.1 mm.

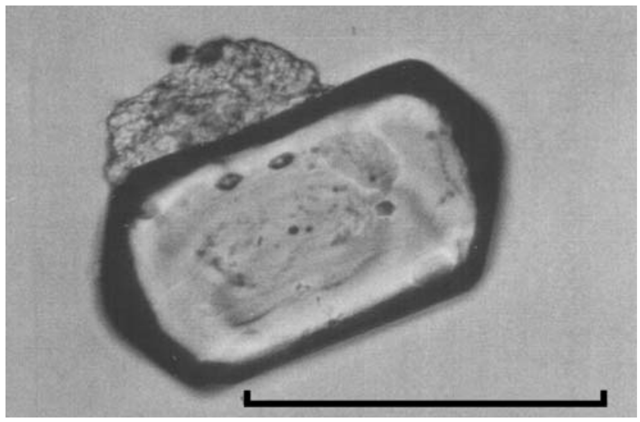

Fig. 6. Zircon from sample 5A of the greenschist facies mylonite: subtypes S_{25} (Pupin, 1980); one polarizer, scale bar = 0.1 mm.

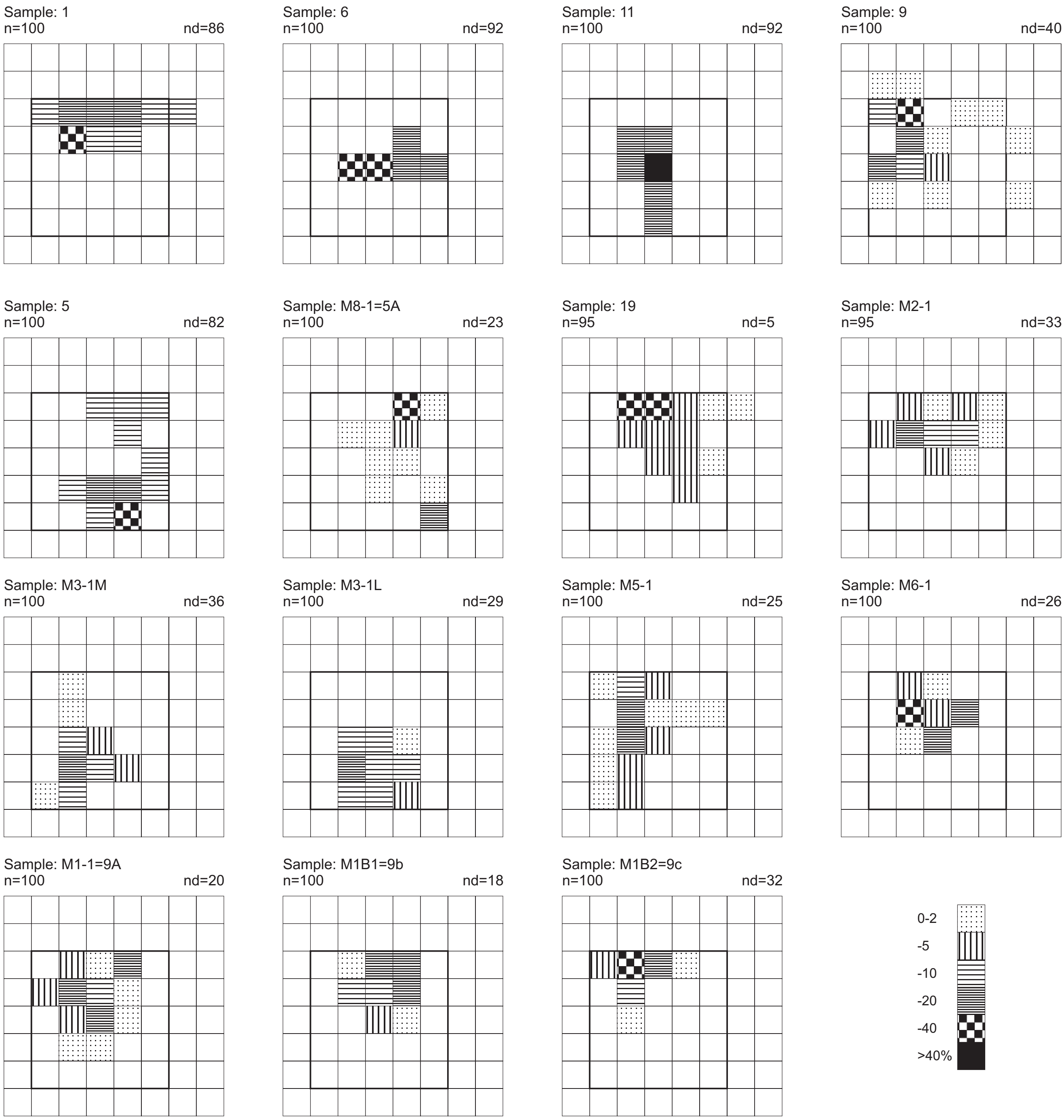

Fig. 7. Typological diagrams (Pupin, 1980) of the investigated samples.

5, 5A and 19, Fig. 7), subtypes S_{23}, S_{24}, S_{25} and S_{19} have been encountered; these are considered the most susceptible to deformation, and could have been the source for the blunty-ended prisms (Figs. 4A-1, 9B) and pyramid-dominated ellipsoidal grains (Figs. 4A-2 & 9 C,D) in the strongly deformed mylonites. These tentative conclusions would have to be verified in further studies of a greater number of samples representing both the NZ mylonites and the GSB gneisses and migmatites.

A range of the observed differences in the morphology and morphometry of the zircon crystals from the NZ mylonites and the GSB migmatites can have resulted from mylonitization. Some of these features can be indicative for zircons occurring in mylonites subjected to differentiated but generally high strain (e.g. Boullier, 1980; Wayne and Krishna Sinha, 1988). However, similar effects can also be produced during the transport and deposition of detrital grains (Klimas-August, 1989). The high amount of subrounded and rounded zircon grains in the melanosome of the GSB migmatite M3-1M and in migmatite M5-1 strongly suggests their sedimentary provenance. Similarly, the exclusive presence of rounded, subrounded and angular zircon grains in some samples of the NZ mylonites (e.g. samples 5 and 6) can be interpreted as evidence for their derivation from a (meta)sedimentary protolith. In addition, the observed large variation of subtypes de-

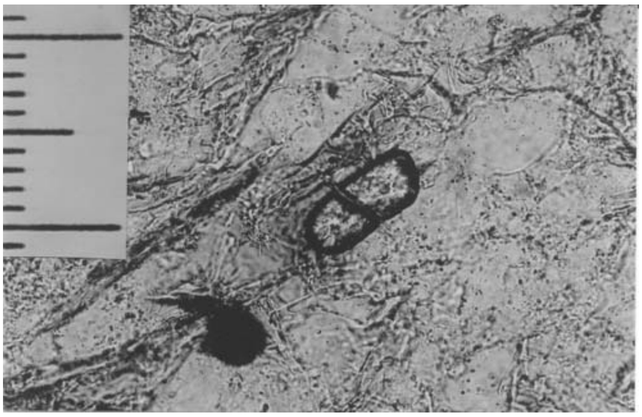

Fig. 8. Subrounded zircon grain split into two parts by a fracture transversal to its elongation. The fracture is filled with synkinematic chlorite; one polarizer, small unit on scale = 0.01 mm.

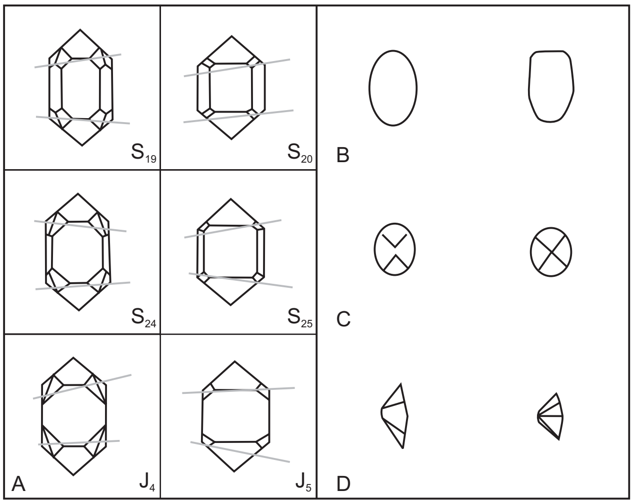

Fig. 9. Possible way of the formation of the subrounded, blunt fragments of prisms and the tiniest ellipsoidal zircon grains, with one side flat and one side pyramidally bulged: **A** – types and subtypes from the lower right corner of Pupin's (1980) diagram; **B** – ellipsoidal and subrounded, blunt fragments of prisms; **C, D** – tiniest ellipsoidal zircon grains, with one side flat and one side pyramidally bulged (seen, respectively, from {101} and perpendicularly to the prism).

fined on a small number of euhedral crystals which are associated with dominant rounded, subrounded and angular zircon grains in several mylonite samples (e.g. sample 1, 5, Fig. 7) indicates their sedimentary derivation. Also, in mylonite sample 9A, subtypes S_3, S_{13} and S_{25} coexist, with a considerable amount of broken crystals (Fig. 5-1); evidence of a most likely detrital origin.

Consequently, the zircons in most of the described samples probably represent detrital grains inherited from the mylonite precursors, subsequently subjected to intense mylonitization. The inspection of thin sections confirms that several features of the zircons extracted from the mylonites were produced during their deformation, and not inherited from detrital grains. For instance, in the mylonite from locality 5, subhedral and partly rounded zircon crystals are split into smaller parts by fractures transversal to their elongation, which are partly filled with synkinematic chlorite (Fig. 8).

The investigated samples, in particular those taken from the highest strained mylonites (samples 5 and 6), contain a large amount of tiny zircon grains (average length 0.06 mm) of perfectly ovoid or spheroid shape. They may represent detrital zircons inherited from a sedimentary protolith or, alternatively, primary magmatic crystals disintegrated during early stages of mylonitization under low-temperature metamorphic conditions.

Important arguments in favour of some zircon crystal subtypes' susceptibility to mylonitization in gneisses and migmatites come from the comparison of zircon morphology in selected samples of the GSB rocks (M3-1M, M3-1L, M2-1), NZ mylonites (5, 5A, Fig. 6, and 19, Fig. 4b) and NZ migmatites (9b), all containing mostly S_{14}, S_{15}, S_{19}, S_{20}, S_{24} and S_{25} subtypes (Fig. 7). Particularly characteristic are those zircons with predominant {100} over {110} prisms, and with {101} over {211} pyramids (Figs. 7, 9). The inspection of zircon concentrates from the NZ mylonites, particularly those with a majority of rounded, subrounded and perfectly ellipsoidal grains (e.g. samples 5 and 6, Fig. 4a), reveals the occurrence of distinctly bigger subrounded blunts (Figs. 4A-1, 9B). The latter may represent fragments of prisms broken up during the disintegration of primary normal prismatic crystals belonging to subtypes S_{20}, S_{24}, S_{25} that now are rather rarely found in these samples. The tiniest ellipsoidal zircon grains, one side flat and one side pyramidally bulged (Figs. 4A, 2, 9C, D), can represent the pyramidal endings of these originally euhedral crystals of the abovementioned subtypes, disintegrated during mylonitization or during sedimentary transport of the detrital material. On the other hand, ellipsoidal but more elongated zircon grains may correspond to fragments of subtypes located on the left-side of Pupin's (1980) diagram, especially to those characterised by a significant supremacy of {100} over {110} prisms, i.e. subtypes S_{21}, S_{22}, S_{16} and S_{17}. The same may generally concern the forms with predominant {110} over {100} prisms, i.e. subtypes S_1, S_2, S_6 and S_7 (Fig. 7), although they seem to be more resistant to strain. It is likely, for similar morphological reasons, that the zircons from the amphibolite-facies mylonites from the Austrian Moldanubicum, with dominant S_1 and S_6 subtypes (Sturm, 1999), as well as from the low grade ultramylonites of the Mieville Shear Zone, Switzerland, with L_1, S_1, S_2, S_6, S_7, S_8 and S_{11} as the most common types (Streyer & Sturm, 2002) were found to be much less susceptible to deformation than the zircons from the NZ mylonites. The types least sensitive to deformation and sedimentary abrasion should be those subtypes and types characterised by an approximately equal size of both prisms, {110} = {100}, or by the presence of only one of the prisms, in particular crystals with small elongation. Summing up, the types most resistant to destruction should be short prismatic forms evenly developed in the *a* and *b* crystallographic directions. Those more sensitive to fracturing and grinding seem to be long prismatic crystals with one strongly dominating prism. As interpreted from the shape of some ellipsoidal and anhedral forms (Figs. 4, 9), the junctions between prisms and pyramids are very susceptible to fracturing, particularly in the types and subtypes from the lower right-hand corner of Pupin's (1980) diagram.

If the majority of deformed zircon grains are really a result of mylonitization, it seems that the mean of length 0.06–0.07 mm is the lower limit for size reduction in the study samples. This dimension corresponds to the average grain size of the matrix in the mylonites, mainly composed of quartz and micas. The brittle zircon crystals dispersed in the ductile matrix may have been protected from further grinding because, below a certain mean grain size, most of the strain could have been accumulated by plastic flow in the surrounding mineral matrix. This minimum range of the mean zircon length in the NZ mylonites corresponds to the mean width of zircon grains in the investigated GSB rocks (Fig. 3, Table 2). This morphometric relationship is an important argument for the assumption that the origin of the tiny ellipsoidal grains is connected with the disintegration of the originally larger zircon crystals inherited from the mylonite precursor (Figs. 3, 9).

Other mechanisms of the development of perfectly ellipsoidal or rounded zircon grains have been proposed over the last decade. Ovoidal-shaped zircons can recrystallize during amphibolite-grade metamorphism into football-shaped zircons well-known from felsic granulites (e.g. Vavra *et al.*, 1996, 1999). Such zircons can also crystallize from anatectic melts possibly associated with deformation under upper amphibolite facies conditions (e.g. G_2, G_3 and A forms or, the rarely-described AB_2-AB_5 types of Pupin (1980)). Concentric and ellipsoidal fractures in zircon crystals, which can result in the formation of tiny and perfectly ellipsoidal grains, can be produced during the metamictization of zircons (Lee and Tromp, 1995). Such grains are inclusion-free, and elongated parallel to the crystallographic *c*-axis. To elucidate which of the processes mentioned above contributed to the origin of the small ovoidal and spheroidal grains in the mylonites would require further studies, including e.g. the examination of the internal structure of the ball-shaped grains in BSE, cathodoluminescence images and analysis of the inclusion composition in zircons.

CONCLUSION

The results of our comparative zircon morphology studies show some common features of and some differences between the zircon populations of: (a) the gneisses and migmatites of the GSB; (b) the gneisses enclosed within the NZ mylonites; and (c) the mylonites of the Niemcza Zone. Based on the data obtained so far, the rock complex from which the gneisses and a part of the mylonites of the Niemcza Zone developed seems to have contained dominant material with zircons typical of crustal-derived granites (or their reworked sedimentary products), in apparent contrast with the more lithologically diversified source of the GSB gneisses and migmatites.

The high amount of zircon grains showing possible effects of disintegration can result either from the sedimentary abrasion of detrital material or intense mylonitization. It is likely that effects of the two processes overlapped, i.e. the initial disintegration of zircons due to sedimentary transport could have been overprinted by the subsequent mylonitization-induced break-up of grains.

The particularly high contents of zircons with signs of disintegration in the NZ mylonites corroborate the hypothesis that at least a part of these rocks developed at the expense of sediments more intensely reworked by sedimentary processes, compared with the sedimentary protoliths of the "typical" GSB gneisses and migmatites (e.g. Cwojdziński & Żelaźniewicz, 1995). However, there is evidence that some disintegration features in the NZ mylonites developed during the tectonic deformation (and contemporaneous metamorphic recrystallization) of the rocks. To find better constraints to that controversy would require further systematic studies.

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