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Heavy mineral suites in Oligocene–Miocene sediments (Fore-Sudetic Monocline, SW Poland): Provenance signals versus weathering alteration

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Abstract The paper describes the diversity of the heavy mineral suites in the Oligocene and Miocene sediments that were deposited in the foreland of the Sudetic part of the Bohemian Massif. The observed mineral variability is the result not only of changes in sediment transport directions, but also of chemical weathering and hydrodynamic sorting of the minerals by density. All the heavy mineral assemblages lack olivines, pyroxenes and amphiboles, i.e. chemically unstable minerals. Moreover, the terrestrial sediments are impoverished in non-resistant heavy minerals in comparison to the marine ones.

The central and eastern part of the Fore-Sudetic Block and, from the Middle Miocene, a part of what are now the Sudetes Mts. constituted the main source areas supplying detrital material to the Fore-Sudetic Monocline. Generally, the heavy minerals document a gradual lowering of the western fragment of the Meta-Carpathian Arch separating the North-West European Basin from the Paratethys, and a distinct shift in source areas delivering detrital material to the basin in the Middle Miocene. Furthermore, a pyroclastic origin for some heavy minerals from the sands/silts of the Middle Miocene Mużaków formation is suggested.

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INTRODUCTION

During the Tertiary, the area of the Fore-Sudetic Monocline was situated in the eastern, marginal part of the Northwest European Basin, where it was periodically reached by marine transgressive pulses (Dyjor, 1986; Vinken [ed.], 1988). To the south, the Fore-Sudetic Monocline was bordered by the northeastern, Sudetic part of the Bohemian Massif, which at that time had differentiated into the Sudetes Mts. and the Fore-Sudetic Block. The central and eastern part of the Sudetic area was a western prolongation of the Meta-Carpathian Arch[1], separating the Northwest European Basin from the Paratethys.

An intensive reconstruction of the areas located south and southeast of the Fore-Sudetic Monocline took place in the Neogene: uplift of the Sudetes Mts., downfaulting of the Fore-Sudetic Block and Carpathian folding, all accompanied by volcanic activity and faulting. The sediments of the Fore-Sudetic Block and the Fore-Sudetic Monocline recorded the stages of the Neogene movements and the changes in palaeogeography, as stated in numerous papers (e.g. Oberc & Dyjor, 1969; Dyjor, 1975, 1993). However, the conclusions were drawn mainly on the basis of the general lithology and composition of the gravel fraction.

This study concerns heavy minerals from the Oligocene–Miocene sandy/silty deposits of the Fore-Sudetic Monocline, where fine-grained sediments prevailed. This paper addresses the question of changes of denudation areas and phases in the uplift history of the Sudetes Mts. and some crystalline massifs in the Fore-Sudetic Block during the Oligocene and Miocene.

A reconnaissance study of three samples from the Upper Eocene and Lower Oligocene sediments of the Fore-Sudetic Monocline revealed zircon-rich assemblages in the former, and tourmaline-andalusite assemblage in the latter (Kosmowska-Ceranowicz, 1981). These were interpreted

1 The term “Meta-Carpathian Arch”, meaning a zone separating the Northwest European Basin from the basins of the Carpathian Domain, is used here after Kutek (1994). In the Tertiary, the Meta-Carpathian Arch constituted a belt of uplifts corresponding to the present-day belt of the Middle Polish Uplands. In the Badenian, the Sudetic area was separated from the Meta-Carpathian Arch by a Paratethys bay.

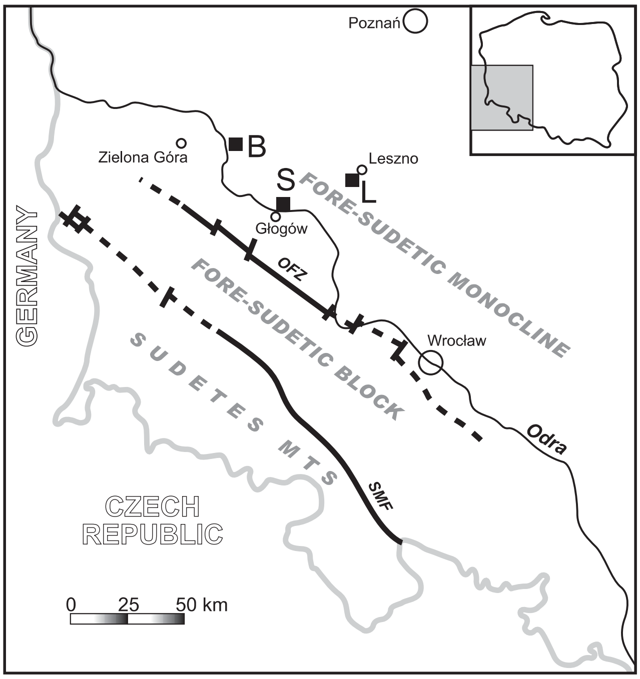

Fig. 1. Location of the B, S and L boreholes in the Fore-Sudetic Monocline. OFZ – Odra Fault Zone; SMF – Sudetic Marginal Fault.

as the effects of denudation of the Fore-Sudetic Block sedimentary cover and the unroofing of crystalline rocks, and thus validated the usability of heavy mineral analysis in provenance studies in this area.

Heavy minerals, more diverse than the typical assemblage of a sandy light fraction, can provide significant provenance information and have been effectively used in palaeogeographical reconstructions for many years (e.g. Turnau-Morawska, 1955; Morton, 1985). However, the distribution of heavy minerals in sediments is controlled not only by temporal changes in the detritus shed from the source area but also by weathering in that area, in transit and at the site of deposition, and by hydrodynamic sorting and post-depositional alterations (Morton & Hallsworth, 1999). The very strong influence of these factors on heavy mineral suites from the Tertiary North Sea Basin sediments was reported e.g. by Morton (1984) and Friis (1974, 1978). This study is also aimed to determine weathering impact on mineral diversity in the Oligocene–Miocene Sude- tic sediments and to assess how much this factor causes misinterpretation in palaeogeographical reconstructions.

MATERIALS AND METHODS

Thirty-one samples were taken from the sandy/silty parts of three cores drilled by the HYDROCONSULT Bureau, Poznań, in the Fore-Sudetic Monocline in the vicinity of Głogów, Zielona Góra and Leszno (the Serby, Bojadła and Leszno-Zaborowo boreholes, further described as the S, B and L sections respectively – Fig. 1). The thickness of the Tertiary sediments varied from 150 m (B) to 220 m (S), but the bottom of the Tertiary was not pierced. The core output in each borehole was high enough (*ca.* 70–80%) to conduct sedimentological observations.

In order to evaluate the general grain-size distribution of the studied sediments, sands were sieved at ca. 0.5 phi intervals from 4 to –2 phi (0.063 to 4 mm). When the sediments contained significant amounts of fines, the < 0.1 mm fraction was analysed using the pipette method. Heavy minerals were separated from the 4 to 3 phi (0.063–0.125 mm) fraction using an aqua solution of sodium polytungstate (specific gravity 2.83). Restricting the analysis to a single, small size fraction reduces effects of hydrodynamic sorting by size, which can bias heavy mineral populations and make provenance study difficult (Carver, 1971). Moreover, the 4 to 3 phi fraction was found to contain the majority of heavy minerals in the Sudetic (Grodzicki, 1972) and North Sea sands (Morton, 1985).

Mineral grains were mounted onto a glass slide in Canada balsam and identified using a petrographic microscope. Approximately 300 translucent heavy mineral grains were counted in randomly selected traverses for each sample. Biotite, chlorite and opaque heavy minerals were also counted but omitted in the final specifications for two rea-

Table 1

Lithostratigraphic units* distinguished in the S, B and L sections

Lithostratigraphic units**	Lithostratigraphic units***	Age****	Thickness (meters)
Poznań formation *Henryk seam 1*	Poznań fm. *I group of seams*	Middle to Late Miocene/Early Pliocene	0–55
Mużaków formation *Lusatian seam 2*	Pawłowice fm., Adamów fm. *II group of seams*	Middle Miocene	20–60
Silesian-Lusatian fm. *Ścinawa seam 3*	Ścinawa fm. *III group of seams*	Early to Early/Middle Miocene	20–35
Żary formation *Głogów seam 4*	Rawicz fm, Żary member *IV group of seams*	Early Miocene	10–55
Lubuska formation	Leszno fm.	Oligocene	2–90, *not pierced*

*The lithostratigraphic units are diachroneous and their age assignments are approximate.
**Lithostratigraphic units after Dyjor (1970, 1986).
***Lithostratigraphic units proposed by Piwocki (in: Piwocki & Ziębińska-Tworzydło, 1995) for the Polish Lowland.

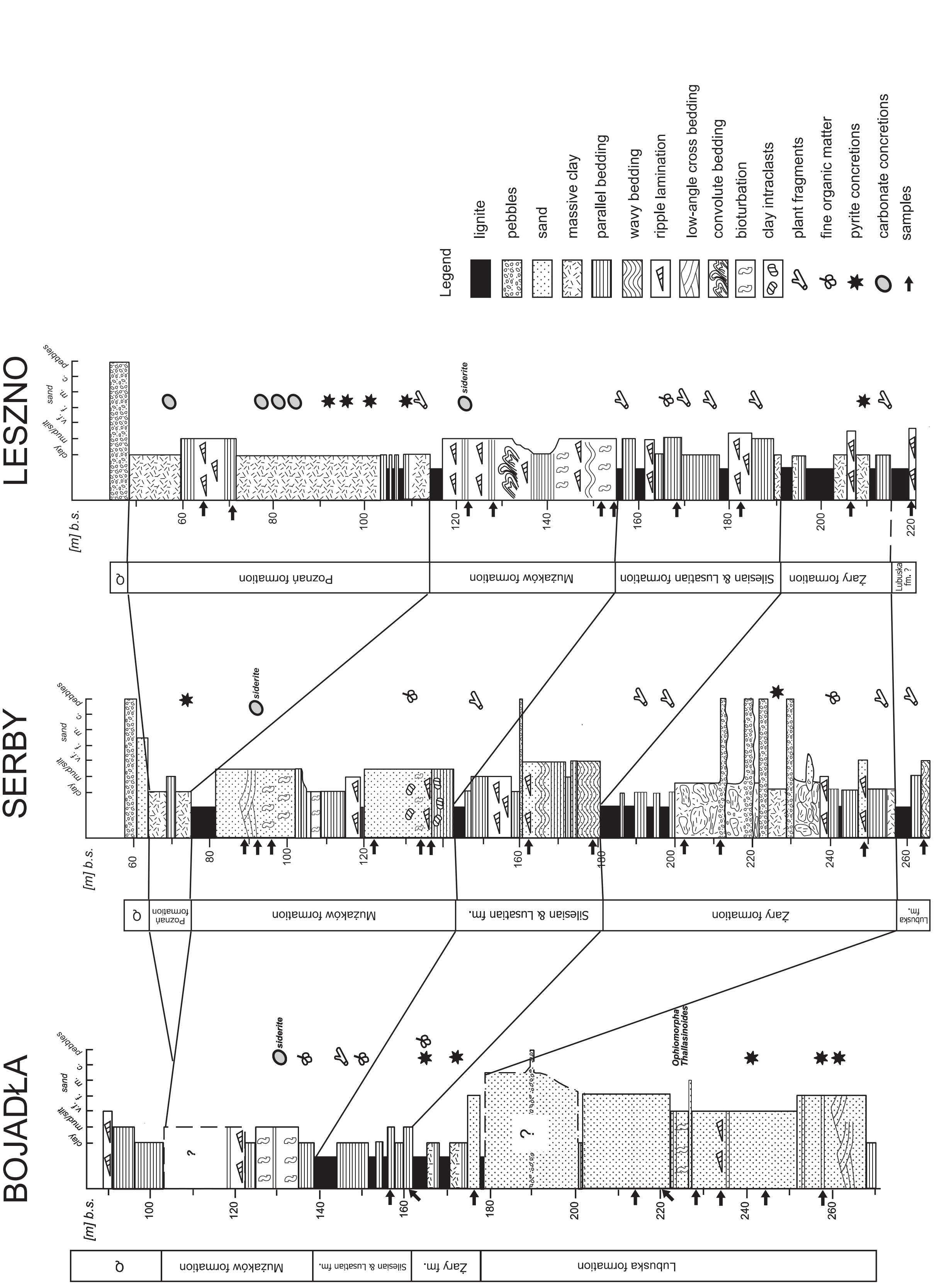

Fig. 2. Measured vertical sections of the Oligocene–Miocene sedimentary rocks from the Fore-Sudetic Monocline (according to Biernacka & Duczmal-Czernikiewicz, unpublished data). Lithostratigraphic units after Dyjor (1970, 1986).

Table 2

Summary of the lithological features of the studied sedimentary rocks

Lithostratigraphic unit	Description		Interpretation
	Texture	Structure	
Poznań formation	light green clays, silts; horizons enriched in concretions (calcite, siderite, some septarian)	clays: in majority structures non-detectable (tectonically disturbed), horizontal lamination, locally numerous leaf imprints; silts: horizontal lamination, ripple lamination, small scale through cross stratification	sediments deposited from suspension and from currents; locally subaerial environment
Mużaków formation	upper part: light grey, very fine sands and silts, numerous mica flakes & siderite microconcretions middle part: black muds and clays, lenses of sands, S section - 1-m thick lignite layer lower part: light grey, very fine sands and silts, numerous mica flakes	horizontal & ripple lamination, low angle cross stratification, locally strongly bioturbated; L section: 2 m of disturbed sediments with convolute bedding; middle part: horizontal lamination, S section - alternately laminated and bioturbated horizontal & ripple lamination, locally bioturbated, muddy intraclasts (S section)	shallow marine (brackish) sediments, L section: probable record of an earthquake
Silesian-Lusatian formation	mainly black, in the upper part grey and beige, muds, clays & very fine sands; numerous plant fragments; S section: 15 cm interlayer of quartz gravels	horizontal lamination, flaser, lenticular & wavy bedding, cross stratification; locally: massive, rootlet traces	alluvial - mainly flood plain with subordinate channel and bar sediments, L and B sections: palaeosoil horizons
Żary formation	white & grey kaolinite-rich diamictons, clays (kaolins) & gravels, poorly sorted; pebble composition: angular quartz, K-feldspar and lithic grains (ryolites, mica schists) up to 4 mm (rarely 1 cm); lower part of the S section: black or dark brown clays, muds and sands with lignite fragments	massive (chaotic), locally normally graded beds, several centimeter clay intraclasts in clay matrix lower part: horizontal bedding and ripple marks	debris flow sediments on the distal part of an alluvial fan, the S section located nearby (< 15 km) fault scarp of uplifted block covered by thick kaolinite-rich weathering residua; lower part: fluvial (flood plain) sediments
Lubuska formation	light grey, very fine to fine sands, very well sorted, numerous mica flakes, locally enriched in small pyrite nodules; lower part: single glauconite grains & foraminifers	low angle cross stratification, horizontal lamination, rarely ripple lamination; locally bioturbated (*Ophiomorpha*, *Teichichnus*)	nearshore sediments deposited under well or poorly oxygenated conditions, with diverse salinity (Gedl, 1998)

sons. Because of their shape, micas have different hydraulic behaviour than the rest of the non-opaque mineral suite, and are thus particularly sensitive to selective sorting. Furthermore, quantification of micas is difficult because their densities straddle that of the heavy liquid. For that reason, the ubiquitous and predominant muscovite flakes were not counted at all, and the biotite flakes were not included in the final analysis. Opaque minerals were not identified according to mineral species; as a result, distinguishing diagenetic pyrite from detrital opaque heavy minerals was sometimes difficult. Nevertheless, the percentage contents for six groups – opaque and translucent heavy minerals, biotite, chlorite, carbonate grains, and glauconite – were calculated on the basis of 300 grains, and are presented in Tab. 4.

LITHOSTRATIGRAPHY AND DEPOSITIONAL ENVIRONMENT

The Late Eocene glauconitic calcareous sands passing into the Early Oligocene quartzeous sands are the oldest Tertiary sediments known from the Fore-Sudetic Monocline (Matl & Śmigielska, 1977; Martini, 1981). They contain marine calcareous micro- and macrofossils as well as nannoplankton; accordingly, their correlation with the an-

Table 3

Grain-size parameters for the studied sediments calculated by the graphic method

Samples	Mużaków formation						Sil.-Lus. fm.		Żary formation			L. fm.
	S89	S92	S95	S122.5	S135	S137	S162	S179.5	S202	S212.5	S249	S264
Mean, Mz [phi]	3.6	3.9	4.3	4.0	4.0	4.6	3.6	3.4	10.5	6.1	3.2	2.9
Sorting, σ_1	1.1	0.9	1.2	0.7	0.6	0.7	0.7	1.0	8.2	5.3	1.6	1.2
Skew-ness, SK_1	0.6	0.4	0.5	0.1	0.1	0.6	0.6	0.4	0.5	0.4	0.3	0.6
Sediment type	fine sand	v. fine sand	v. fine sand	v. fine sand	v. fine sand	silt	v. fine sand	v. fine sand	sandy clay	sandy clay	v. fine sand	fine sand

Samples	S.-L. fm.	Żary formation		Lubuska Formation					
	B157	B161.7	B177	B124	B220	B229	B234	B244	B258
Mean, Mz [phi]	3.6	3.2	3.3	2.9	3.0	3.3	3.3	3.3	3.5
Sorting, σ_1	1.4	0.7	2.5	0.5	0.3	0.4	0.4	0.3	1.1
Skewness, SK_1	0.5	0.6	0.8	0.2	0.4	0.3	0.2	0.1	0.1
Sediment type	v. fine sand	v. fine sand	fine sand	fine sand	fine sand	v. fine sand	v. fine sand	v. fine sand	v. fine sand

Samples	Poznań formation		Mużaków formation				Sil.-Lus. fm..		Żary fm.	L. fm.
	L65.5	L71	L123	L128.5	L151	L154.5	L168.5	L182	L206	L218.7
Mean, Mz [phi]	5.1	5.7	5.1	5.0	4.7	4.5	7.7	4.2	4.2	4.9
Sorting, σ_1		3.5	$\sigma_\Phi = 1.3$	1.9	1.7	1.8	5.0	0.7	1.1	0.3
Skewness, SK_1		0.8	0.9	0.8	0.7	0.6	0.7	0.4	0.3	0.3
Sediment type	silt	silt	silt	silt	silt	sandy silt	silt	sandy silt	sandy silt	silt

cient North Sea and Paratethys Basin sediments was possible (*op. cit.*). The overlying deposits lack calcareous fauna, so parastratigraphic palaeobotanical zones were distinguished in the Upper Oligocene and Neogene sections, based on a model of cyclic climatic changes. It was never possible to create a precise geochronological scale or make exact correlations with the North Sea and Paratethys subdivisions, although the close proximity of the Silesian part of the Paratethys permitted comparative palynological studies to be carried out, giving some definition to the chronology (e.g. Dyjor & Sadowska, 1986).

In none of the examined cores was a Tertiary basement observed, and all of the cores lack the glauconite-rich sands of the Upper Eocene. The studied sediments were classified according to the informal lithostratigraphic subdivision proposed by Dyjor (1970) for the area of the Fore-Sudetic Block and Monocline (Tab. 1, Fig. 2). For comparison, the lithostratigraphic scheme after Piwocki (in: Piwocki & Ziembińska-Tworzydło, 1995) for the Polish Lowland is also presented in Tab. 1. In the subdivision used here, lignite seams mark the boundaries of the lithostratigraphical units, the age of which was determined on the basis of numerous palynological studies conducted for the area of the Fore-Sudetic Block and Monocline, and neighbouring areas (e.g. Sadowska, 1995). However, because of the diachronity of the lithostratigraphic units, the age designations used in this paper are approximate.

In order to check the age and depositional environment of the examined sediments, thirty-three samples from three sections were chosen for dinoflagellate analysis. Only the sediments of the Lubuska formation from the B section contained well-preserved and diverse assemblages of dinoflagellate cysts, which were interpreted as Oligocene in age, deposited in a marine/brackish environment of variable salinity (Gedl, 1998). The sediments were classified as belonging to the Lower and Upper Oligocene, although the boundary between them was not precisely determined (*op. cit.*). Except for the clayey lowest part, no significant lithological changes were observed. Thus, the conducted studies confirmed the Oligocene age of the Lubuska formation, assumed in existing lithostratigraphic schemes.

A short description of lithology is included in Tab. 2, and the grain-size parameters calculated for the studied sediments are listed in Tab. 3. The depositional environments were interpreted on the basis of sediment textures and structures, including mineral composition. Several

Table 4

Quantitative composition of the heavy components in the 3–4 phi fraction (in grain %)

Sample	Heavy fraction content [weight %]	Opaque minerals	Translucent minerals*	Biotite	Chlorite	Carbonate grains	Glauconite
S89	1.1**	32	66	0	2	0	0
S92	0.3	21.5	34	1	0.5	41.5	1.5
S95	0.1	17	15	4	0.5	63	0.5
S122.5	0.5	56	35	5	3.5	0.5	0
S135	0.4	59	38	1	2	0	0
S137	0.4	67	17	13	3	0	0
S162	0.3	71	29	0	0	0	0
S179.5	0.2	70	29	0	0	1	0
S202	0.3	53.5	46.5	0	0	0	0
S212.5	0.5	74	26	0	0	0	0
S249	0.8	35	65	0	0	0	0
S264	0.2	57	42	0	0	1	0
B157	0.2	62	38	0	0	0	0
B161.7	0.6	46	54	0	0	0	0
B177	0.7***	54	46	0	0	0	0
B214	0.5	58	42	0	0	0	0
B220	0.5	60	40	0	0	0	0
B229	0.3	70	24.5	0.5	5	0	0
B234	0.2	55	30	1	14	0	0
B244	0.2	53	33	1	13	0	0
B258	1.0***	83.5	14	0.5	2	0	0
L65.5	0.1	55	38	0	0	7	0
L71	0.2	47	48	0	4	0	0
L123	0.7**	8	3	7	0	75.5	1.5
L128.5	0.6**	35.5	20	0.5	0	41.5	1.5
L151	1.6**	57.5	36	0	0	1.5	0
L154.5	0.3	59	20	6	0	0	0
L168.5	0.1	75.5	24.5	0	0	0	0
L182	0.2***	91.5	8	0	0	0	0
L206	0.9***	85	15	0	0	0	0
L218.7	0.1	64	35	1	0	0	0

* Translucent heavy minerals without biotite and chlorite
** Muscovite-rich samples
*** Pyrite-rich samples

lines of evidence suggest that the sands and silts of the Lubuska and Mużaków formations were deposited in a shallow marine environment (*see* Tab. 2). The remaining sediments were deposited in alluvial settings. The clays and silts of the Poznań formation, present only in the L section, are for the most part tectonically disturbed; therefore, they are not interpreted in terms of their depositional environment.

RESULTS

The quantitative composition of the heavy fraction in the Oligocene–Miocene sands and silts is presented in Tab. 4, and the composition of the non-micaceous translucent heavy minerals is given in Tab. 5. A comparison of the content of key heavy minerals in five subsequent formations is presented in Fig. 3. In the case of a strong mineral diversity

Table 5

Composition of the translucent heavy minerals (in grain %, in the 3–4 phi fraction) from the Oligocene and Miocene sediments, Fore-Sudetic Monocline

	S89	S92	S95	S122.5	S135	S137	S162	S179.5	S202	S212.5	S249	S264
Zircon	4	3	6	12	7	3	8	28	14.5	24.5	1	2.5
Tourmaline	10	13	18	17	23	25	26	24	23	8	8.5	11
Rutile	8	8	4	7	12.5	4	23	21	2.5	8.5	2.5	4.5
ZTR index	22	24	28	36	42.5	32	57	73	40	41	12	18
Andalusite	2.5	1.5	3.5	14	11	7	3.5	1	34	17.5	21	21.5
Syllimanite	0	2	2.5	6	11	12	6	1	0.5	1	3	5
Kyanite	0.5	0.5	1.5	3	5	8	5.5	3	1	1	1	9
Garnet	55	50.5	40	10.5	5	6	2	1	0	0	2	2
Staurolite	3	6	6.5	4	4	6	14.5	10	0	2.5	13	29
Epidote group*	4	2	1	11	9	14	0	2	0.5	11	34	9
Apatite	5	7	10.5	2	0	0	0	0	0	0	0	0
Anatase**	6	4.5	4.5	12	9.5	13	9.5	6.5	23	25.5	2	4
Others	2	2	2	1.5	2	2	1	2.5	2	0.5	2	2.5
Number of counted grains	317	307	238	333	310	142	291	208	318	335	314	302

	B157	B161.7	B177	B214	B220	B229	B234	B244	B258
Zircon	1	5.5	15	7.5	12	1	1.5	2	25
Tourmaline	24	17	15	15	15	15	13	10	9
Rutile	2	4	11	12	14	4	4	4	5
ZTR index	27	26.5	41	34.5	41	20	18.5	16	39
Andalusite	36.5	22	14	9.5	3	6	14	8.5	4
Syllimanite	9	3	10	13	14	18	19	13.5	5
Kyanite	5	5	9	13	11	26	17	17	7
Garnet	2	5.5	1	18	19	20	18	14	15
Staurolite	5	5	18	6	6	2	5	3	5
Epidote group*	5	20.5	1	1	0	1	0.5	11	20
Apatite	1	0	0	0	0	0	0	2	2
Anatase**	8	7	5	2	4	5	6	10	1
Others	1.5	5.5	1	3	2	2	2	5	2
Number of counted grains	318	311	300	300	300	300	300	300	300

	L65.5	L71	L123	L128.5	L151	L154.5	L168.5	L182	L206	L218.7
Zircon	17.5	9	2.5	1.5	11	3.5	13	11.5	1	0
Tourmaline	22.5	30	29.5	30.5	12	14.5	33	32	28	61
Rutile	13.5	12	0	2	3	9	15	15	1.5	0
ZTR index	53.5	51	32	34	26	27	61	58.5	30.5	61
Andalusite	0	0.5	0	5	9.5	6	0	3.5	14	14.5
Syllimanite	2	1	3.5	2	4	7.5	1.5	5	3	5.5
Kyanite	1	0	2	0	3	13	7	4	11	10.5
Garnet	16	21.5	27	22.5	5	5	0	2.5	0	0
Staurolite	5	6	5	6	8.5	11.5	9.5	14	21	2
Epidote group*	5	4	6	6.5	32.5	17	1.5	1	10.5	0
Apatite	0	0.5	14	10	0	1.5	0	0	0	0
Anatase**	16.5	11.5	9.5	11.5	6	10	18	9.5	6.5	0.5
Others	1	3.5	1	2.5	5.5	1.5	0.5	2	3.5	6
Number of counted grains	305	325	85	336	305	146	256	204	250	270

* Epidote group and minor zoisite; ** Anatase and minor titanite; L218.7 – fraction 2–3 phi

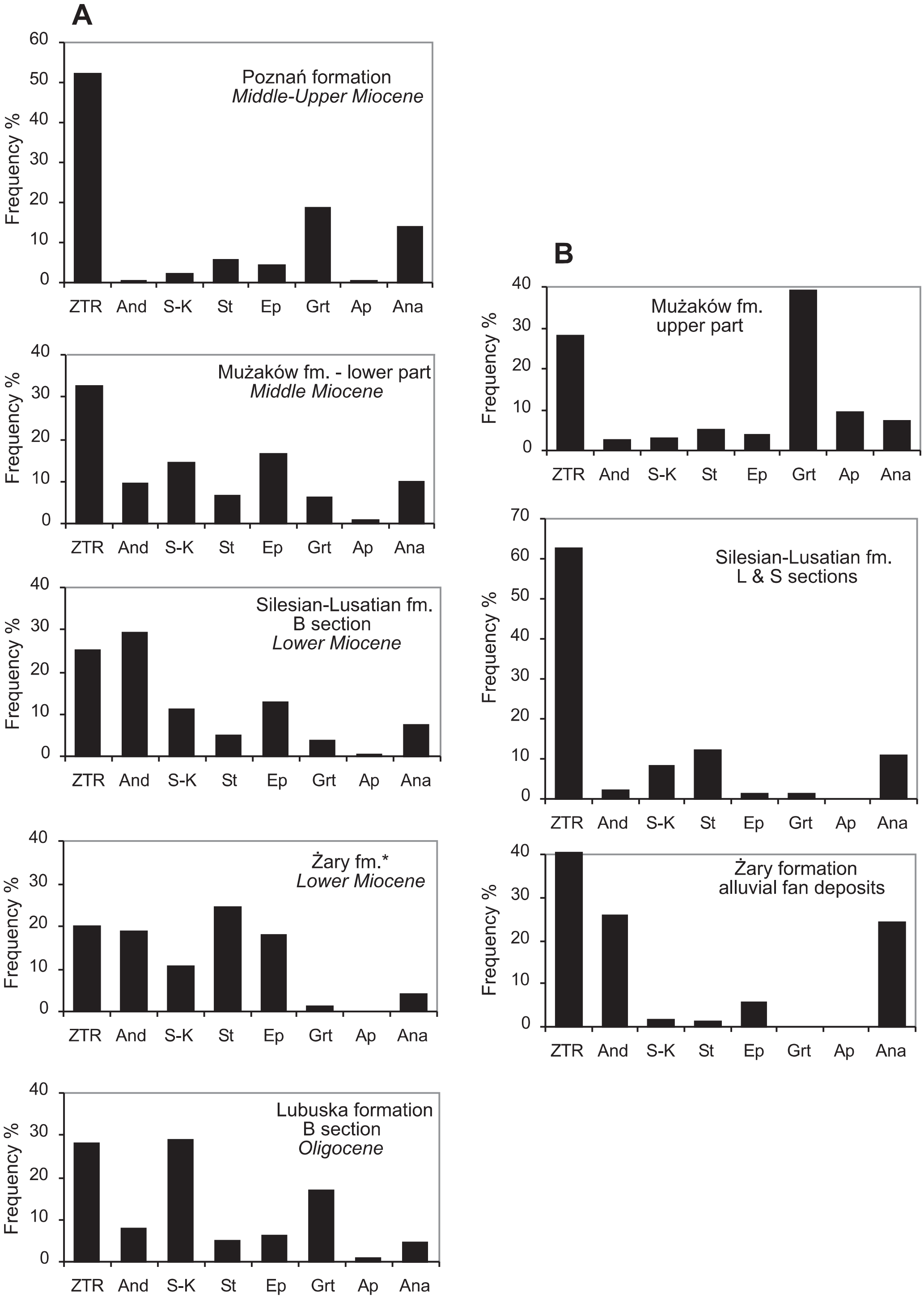

Fig. 3. Content of major heavy minerals in the Oligocene–Miocene sediments, Fore-Sudetic Monocline, shown as percentages of the total non-opaque heavy minerals. ZTR – zircon, tourmaline and rutile; And – andalusite; S-K – sillimanite and kyanite; St – staurolite; Ep – epidote; Grt – garnet; Ap – apatite; Ana – anatase. Żary fm.* – L, B and lower part of S sections.

in the samples from one formation, the heavy mineral content is shown in separate diagrams (Fig. 3A–B).

The heavy fraction content is diverse, but, generally, it exceeds 0.5% (by weight) in samples rich in mica, authigenic pyrite or siderite microconcretions. The latter are present in significant amounts only in the upper part of the Mużaków formation, where, other than siderite, glauconite grains have been observed. Biotite is relatively common in the Lubuska and Mużaków formations, and chlorite in the Lubuska, Mużaków and Poznań ones. The opaque mineral content (average 56% as a grain percentage of the heavy fraction) is also very diverse; opaque minerals are dominated in many samples by authigenic pyrite. Other than pyrite, leucoxene occurs in considerable amounts.

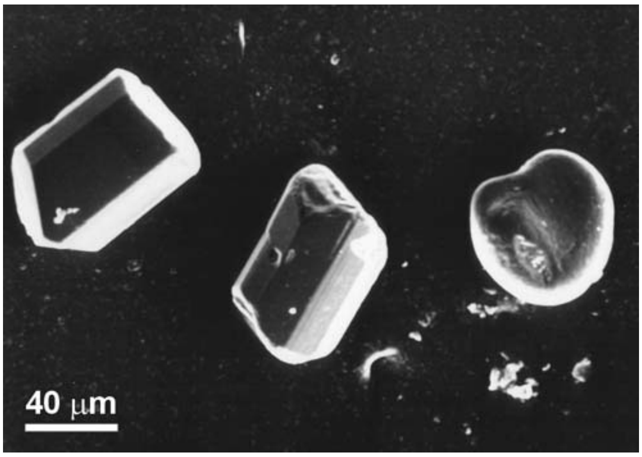

Fig. 4. SEM photomicrograph of different morphological types of tourmalines. Sample S179.5.

The content for a given heavy mineral is reported hereafter as a percentage of the total translucent non-micaceous heavy mineral assemblage content. The ZTR index (sum of the percentage contents of zircon, tourmaline and rutile – Hubert, 1962) varies between 12% and 73%. It reaches its highest values in the Silesian-Lusatian and Poznań formations (average 50% and 52%, respectively), and its lowest in the Mużaków and Żary formations (average 30% and 28%). Of the ultra-stable heavy minerals, tourmaline is much more abundant than zircon and rutile. In some samples, its content exceeds several times that of zircon or rutile. Moreover, the average content of tourmaline in the L samples is almost twice that of the S or B samples (29%, 17%, 17% respectively). The tourmaline grains have distinct pleochroism (light yellow to dark brown, rarely light blue to navy blue) and are of two major morphological types, rounded and euhedral (Fig. 4); both types are present in the majority of the studied samples. Sharp-edged splinters were also found. Sample L 218.7 is an exception – it has a 61% tourmaline content, and almost all the tourmaline grains are rounded. Significant amounts of zircon occur in the Poznań, Żary (alluvial fan) and Silesian-Lusatian formations (average 13%, 19.5% and 11% respectively). Both rounded and euhedral zircon grains are present in the sediments.

Minerals of the Al_2SiO_5 group, including andalusite, sillimanite and kyanite, are found in all the studied samples, although in the silts of the Poznań formation their content is dramatically lower than elsewhere, and averages 2%. These minerals are also uncommon in the upper part of the Mużaków formation with an average content of 5%.

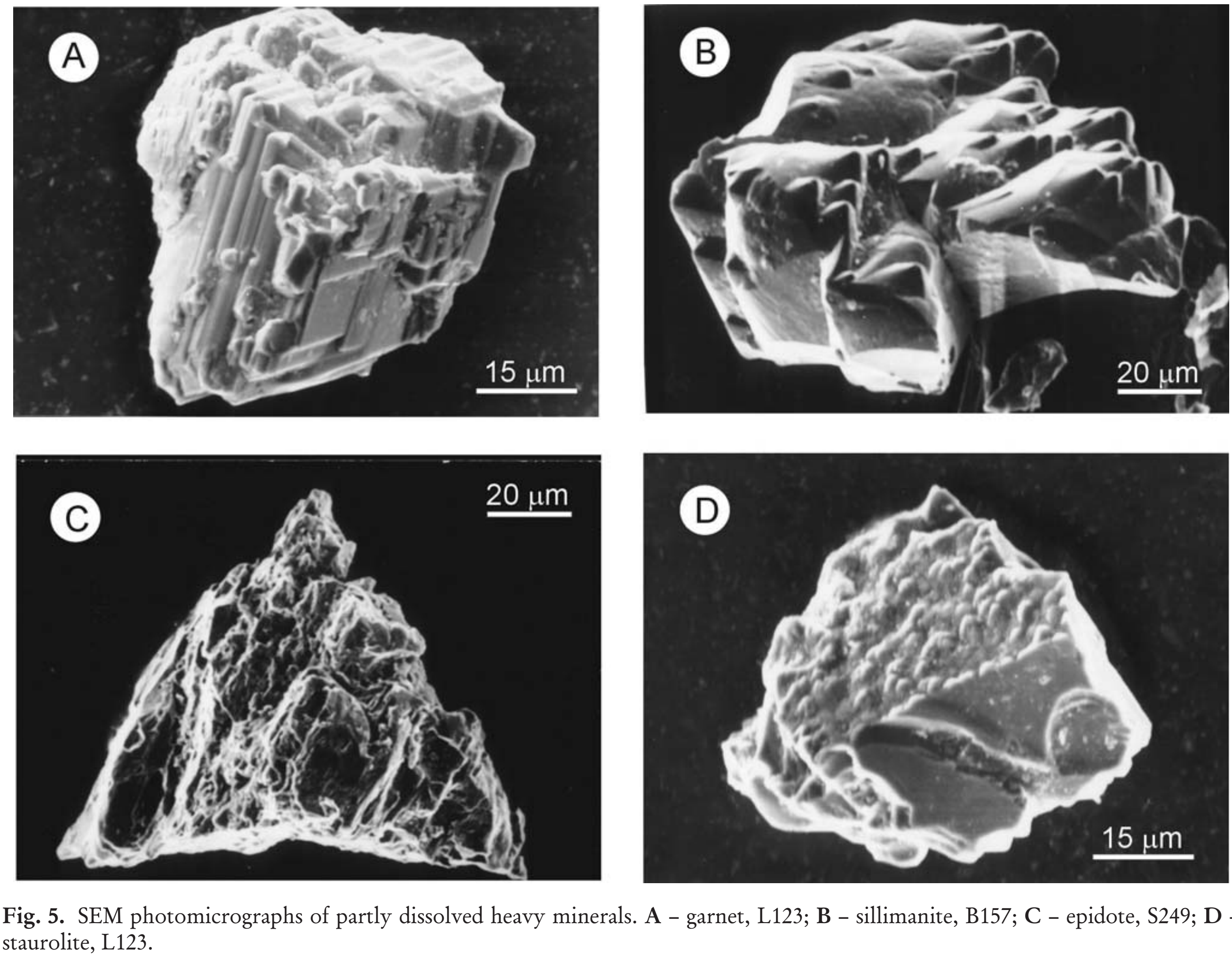

Fig. 5. SEM photomicrographs of partly dissolved heavy minerals. **A** – garnet, L123; **B** – sillimanite, B157; **C** – epidote, S249; **D** – staurolite, L123.

Andalusite, which here rarely displays pink pleochroism, is usually more abundant than sillimanite or kyanite, and reaches peaks of 29% and 26% (average content) in the Silesian-Lusatian (B section) and Żary (alluvial fan) formations, respectively. The Lubuska formation is characterized by the highest content of sillimanite and kyanite grains (average in the B section – 29%); the sillimanite content is comparable with that of kyanite, and, in the majority of the B samples, is even higher than the andalusite content. All the Al_2SiO_5 minerals in the Lubuska formation are fresh, non-altered and non-rounded, with sharp edges. By contrast, these minerals (especially sillimanite) show traces of corrosion in samples from the upper part of the section (Fig. 5B).

The average staurolite content is 5–10%, although in the Żary formation it is present in a wide range of quantities. It is rare in the kaolins of the Żary formation (alluvial fan facies; av. 1%) but reaches a peak of 24% (av.) in the L and lower part of the S and B sections (Fig. 2). The staurolite grains frequently show traces of dissolution (Fig. 5D), especially in the Silesian-Lusatian formation.

Epidote group minerals, including epidote, clinozoisite and zoisite, are present in a range of quantities from an average of 1% in the Silesian-Lusatian formation (the L and S sections) to 18% (av.) in the Żary formation and 17% (av.) in the lower part of the Mużaków formation. The content of these minerals in the Lubuska formation also varies between 0% and 20%. The epidote grains are either strongly altered, corroded (Fig. 5C) and even partly opaque, or fresh and transparent. Both types are present in almost all the samples; in general, the amount of non-altered grains increases with increasing epidote content.

The garnet content displays considerable variation. Garnets are almost absent in the Żary and Silesian-Lusatian formations (ca. 1%), while they make up 6% and 17% (av.) of the transluscent heavy mineral content in the lower part of the Mużaków and Lubuska formations, respectively, and 39% and 19% (av.) in the upper part of the Mużaków and Poznań formations, respectively. In the majority of the samples, the garnets are partly dissolved, occurring in the form of so-called facetted grains (Fig. 5A).

Apatite occurs in minor amounts only in the Lubuska and Mużaków formations, but in the latter, it is found in a range of quantities The lower part of the Mużaków formation contains an average of 1% apatite, and the upper part 9% (av.). The majority of apatite grains in the upper part of the Mużaków formation occur as colourless, transparent, long-prism crystals of euhedral habit.

Anatase makes up from 0% to 14% of the translucent heavy mineral content, with the exception of samples from the kaolins of the Żary formation, where its content averages 24%. The anatase occurs in the sediments in the form of small euhedral crystals grouped in aggregates.

Other minerals, occurring in negligible amounts, include titanite, topase, Cr spinel and vesuvian (?). Topase and spinel occur in the Mużaków formation; titanite and vesuvian (?) were found in sands of the Lubuska formation.

INTERPRETATION

The S, B and L sections are located in the foreland of the Sudetes Mts. and the Fore-Sudetic Block; therefore, detrital material must have been at least partly delivered from their denudation. However, the Oligocene and Miocene geographical frame differed from that of the present-day: a distinct morphological partition between the Sudetes Mts. and the Fore-Sudetic Block did not exist. Although the onset of dislocations along the Sudetic Marginal Fault, which separates the two units, is dated for the Late Oligocene (Grocholski, 1977; Birkenmajer *et al.*, 1977), this is still a subject of controversy, and Early Miocene (Dyjor, 1975, 1986), Late Miocene (Oberc & Dyjor, 1969; Dyjor & Kuszell, 1977) and even Pliocene ages (Wojewoda *et al.*, 1995) are also considered. The present-day Sudetes Mts. are composed of a mosaic of crystalline and sedimentary rocks that are relatively well exposed. By contrast, the crystalline basement of the Fore-Sudetic Block is covered by thick Cainozoic sediments and available for direct observations only in crystalline islands. Its lithology is known from drillings and geophysical data, and considered to be a continuation of the Sudetes Mts. basement and to represent a 5-km deeper crustal level (Cwojdziński & Żelaźniewicz, 1995).

Assumptions

Large lithological diversity in a relatively small area and complicated relationships between geological units make provenance study difficult, and can lead to ambiguous results. Therefore, for the purpose of this study, only a few areas that are the sources of characteristic heavy mineral assemblages were chosen (*see* Fig. 7) and assessed.

1. The epimetamorphic Kaczawa complex occurs in both the Fore-Sudetic Block and the Sudetes Mts., and is composed of metamorphosed volcanogenic and sedimentary rocks. Epidote, chlorite and actinolite are typical for these rocks (e.g. Baranowski *et al.*, 1990).

2. The Góry Sowie gneiss-migmatite complex and its eastern surrounding are composed of a mesozonal gneiss-schist assemblage (Niemcza Zone, Kamieniec Ząbkowicki and Doboszowice Metamorphic Units, Strzelin Massif). The characteristic heavy minerals include sillimanite, kyanite and garnet; andalusite, staurolite, tourmaline and zircon may be also present (e.g. Kryza, 1981; Oberc-Dziedzic, 1999; Achramowicz *et al.*, 1997).

3. The Strzegom-Sobótka granite massif and its metamorphic cover are located in the Fore-Sudetic Block, and are the source of zircon, apatite, biotite, hornblende, andalusite, garnet, chlorite, titanite, tourmaline (Majerowicz, 1972).

4. The Karkonosze granite and the Izera gneisses are both in the Sudetes Mts. The heavy minerals derived from these units are mainly biotite, zircon, apatite, tourmaline, garnet, andalusite, topase (Borkowska, 1966; Wieser, 1958).

Although individual heavy minerals may be delivered from different rocks and areas, heavy mineral assemblages may, to some extent, be diagnostic for transport directions. Moreover, although only metamorphic/igneous complexes are considered here, sedimentary rocks also provided detrital material to thie studied area, as is best evidenced by the occurrence of rounded grains of tourmaline, zircon and rutile. However, such grains are only dominant in one of the analysed mineral suites. On the other hand, many Sudetic sedimentary rocks contain non-rounded heavy minerals that were supplied from Sudetic crystalline rocks (e.g. Felicka, 2000), and as such are not easy to identify.

Oligocene sediments cover the northwestern part of the Fore-Sudetic Block and Miocene deposits lie even further to the east (Oberc & Dyjor, 1969; Dyjor, 1974, 1986). Hence, since the Oligocene this territory had not constituted a denudation site but rather a depositional site, and as such is excluded from the prospective source areas.

Weathering impact

Weathering and diagenesis create additional complications in provenance study. The unquestionable obstacle to interpreting source areas in the case studied is the lack of unstable/semi-stable heavy minerals, such as olivines, pyroxenes and amphiboles, among the recognized heavy mineral suites. This means that the latter do not reflect the whole composition of the heavy fraction in the parent rocks and, further, that the proportions between the remaining heavy minerals may be strongly biased by weathering/diagenetic processes.

The problem of the relative chemical stability of heavy minerals has a long research history (e.g. Pettijohn, 1941; Hubert, 1962; Morton, 1984; Morton & Hallsworth, 1999 and refs. therein). Based on the gradual decrease in unstable heavy mineral contents downwards in some stratigraphic intervals and a comparison of the heavy mineral suites in impermeable concretions and surrounding porous sands, minerals were divided into several stability groups from unstable olivines to ultrastable ZTR (*op. cit.*). Morton (1984) proposed the following order of stability of some common heavy minerals in the presence of acid solutions: olivine, pyroxene < amphibole < titanite < apatite < garnet, epidote < chloritoid, spinel < staurolite < kyanite < andalusite, sillimanite, tourmaline < rutile, zircon. The above sequence is accepted in this study and is the basis for the rule that the presence of less stable minerals, even if they show a high degree of weathering, makes the absence of more stable minerals provenance indicative.

Heavy minerals are subjected to dissolution not only at the denudation site or during alluvial transport, but also in buried sediments *via* a process called intrastratal solution (Pettijohn, 1941), i.e. dissolution in circulating pore-fluids. In the case studied, the degradation of organic matter was undoubtedly the source of the acid solutions that reacted with unstable/semi-stable grains. The common occurrence of corroded grains with saw habits is the evidence that heavy minerals also underwent dissolution after deposition. It is quite probable that during early diagenesis some of the less stable mineral species were completely removed. However, because of the frequent lack of criteria allowing the distinction of the effects of weathering from the effects of diagenesis in shallow burial, here, both processes are termed “weathering”.

The kaolins of the Żary formation may serve as an example of how much weathering reduced the primary heavy mineral diversity. This redeposited kaolinite regolith (S202 and S212.5 samples) practically contains only highly stable minerals, such as ZTR (> 40%), andalusite and anatase. The obtained results are consistent with the observations made by Wyszo- mirski and Muszyński (1991), who examined heavy minerals in the Lower Silesian kaolins and found zircon and titanium minerals as the dominating phases throughout. Such restricted variability is not caused by a poor original composition of the parent rocks, in virtually every case granitoids, gneisses and shales, because in all the Sudetic granitoids and their cover other minerals, such as apatite, titanite, biotite, hornblende, garnets, should occur.

The composition of sands interlayering the lignite seams of the Silesian-Lusatian formation in the L and S sections is another example of weathering impact. The sands are characterized by an exceptionally high ZTR index (> 60%) and an almost complete lack of garnets and epidotes. Moreover, the presence of corroded grains of staurolite and sillimanite also indicates intensive processes of dissolution. By contrast, similar sediments from the B section contain a diverse mineral suite with a drastically lower ZTR index (< 30%). The possible explanation is either less advanced weathering or a different provenance. The latter possibility is rejected on account of the numerous indices of dissolution of less stable grains in the Silesian-Lusatian formation. The solutions that flowed through the sediments of the B section must have been less aggressive than those in other places. Therefore, a conclusion may be drawn that lignite-bearing terrestrial sediments not only contain heavy minerals strongly altered *via* weathering and diagenesis, but also, depending on local conditions, may be strongly differentiated.

The marine sands of the Lubuska formation probably also underwent alterations, although the evidence is not as clear here as in other formations. Towards the top of the section, nearer the terrestrial lignite-bearing sediments, apatite + titanite, epidote and garnet successively disappear (Fig. 6). This might be an important provenance signal but the order in which the minerals disappear is consistent with their chemical resistance. Although Morton (1984) suggested that garnet and epidote are of similar chemical stability, other studies documented that epidote was destroyed before garnet (e.g. Friis, 1974). Besides, the source rocks for the garnets were the same as for the kyanite and sillimanite, and the latter minerals are continuously present in the Lubuska formation. It may thus be stated

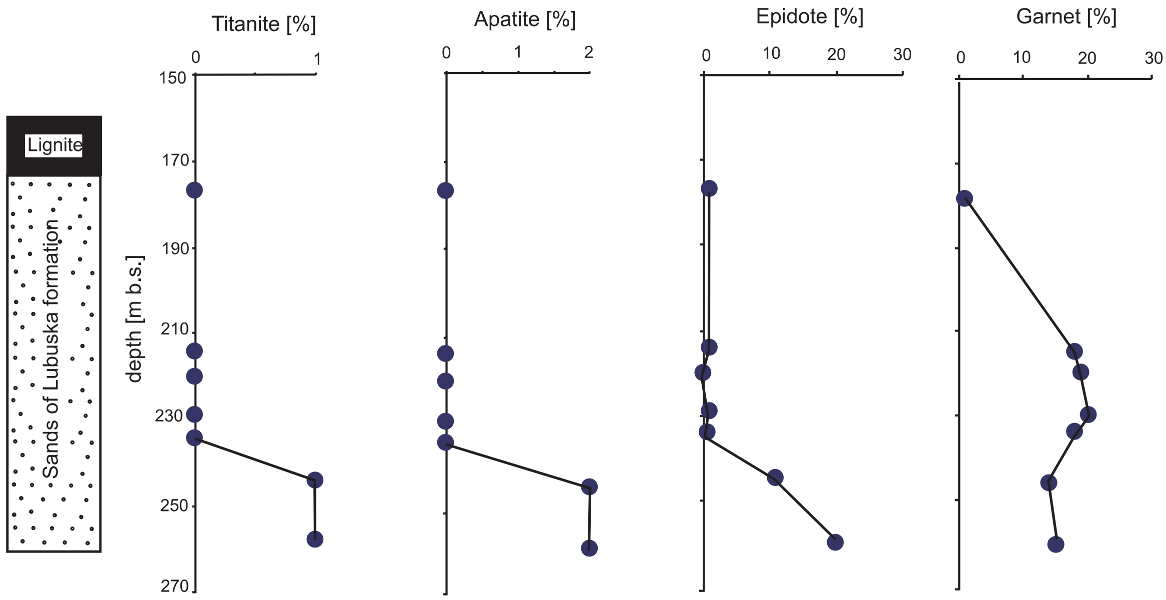

Fig. 6. Diagram showing the variation in the content of some heavy minerals with depth in the sands of the Lubuska formation (B section).

that the upper part of the Lubuska formation is also impoverished in some heavy minerals.

By marked contrast, the lower part of the Lubuska formation and the Mużakow formation contain more diverse mineral assemblages, including semi-stable apatite, titanite and biotite. These formations are interpreted as marine/brackish in origin, which confirms the observation of Friis (1974, 1978) that, as far as heavy minerals are concerned, marine sediments have a higher preservation potential that terrestrial ones; the latter undergo more intensive weathering processes due to their longer exposure to weathering agents. In the studied case, however, the source rocks underwent such deep weathering that all the pyroxene and amphibole grains were destroyed and are missing even from the marine sediments. This is the significant difference in comparison with the Tertiary sediments coming from the denudation of the Fennoscandian shield, for which amphibole is a typical mineral (Morton *et al.*, 1988; Kosmowska-Ceranowicz, 1979). In the Palaeogene, and possibly even earlier, the Sudetes Mts. must have undergone much more intensive weathering than the Fennoscandian area.

Weathering and diagenesis did not exclusively lead to mineral dissolution: anatase grains present in the majority of the studied samples exhibit features that indicate crystallization from pore-fluids in the sediments; they are composed of small anatase crystals (ca. 10 μm in size) of euhedral habits grouped in several in separate grains. The highest amount of anatase (25.5%) was found in the kaolinite clays of the Żary formation. Such anatase grains could be both redeposited from the Tertiary soils and directly formed in the studied sediments. Investigations of present-day soil profiles show that under strong tropical weathering conditions titanium may be mobile, and when released from primary minerals (ilmenite, pseudorutile, anatase, rutile), it precipitates as anatase (e.g. Berrow *et al.*, 1978; Cornu *et al.*, 1999). As demonstrated by Weaver (1976), the most common forms of titanium in kaolinite clays are residual rutile, inherited from weathering of the bedrock, and neoformed anatase. Accordingly, in addition to the lack of semi-stable minerals and the high ZTR index, a high content of neoformed anatase may be treated as another indicator of weathering intensity.

Hydrodynamic sorting

Although heavy mineral analysis is restricted in this study to a narrow sediment fraction (3–4 phi), the effects of hydrodynamic sorting of minerals by density may be locally recognized. The most conspicuous example is the relatively high concentration of tourmalines, heavy minerals of relatively low density, in the sediments of the L section, which is located furthermost from the source area. Another example is discussed below.

Provenance history

Even taking all the above limitations and simplifications into account, there are still some provenance indicative mineral assemblages, which allow the study of the directions of detritus transport in the Oligocene and Miocene. It is worth noting that the marked dominance of fine-grained sediments in all the studied sections (Tab. 3) suggests relatively low relief and a lack of significant differences in altitude in the study area during that time.

The sands and silts of the Oligocene Lubuska formation contain the most characteristic heavy mineral assemblage, composed of fresh and non-rounded minerals that

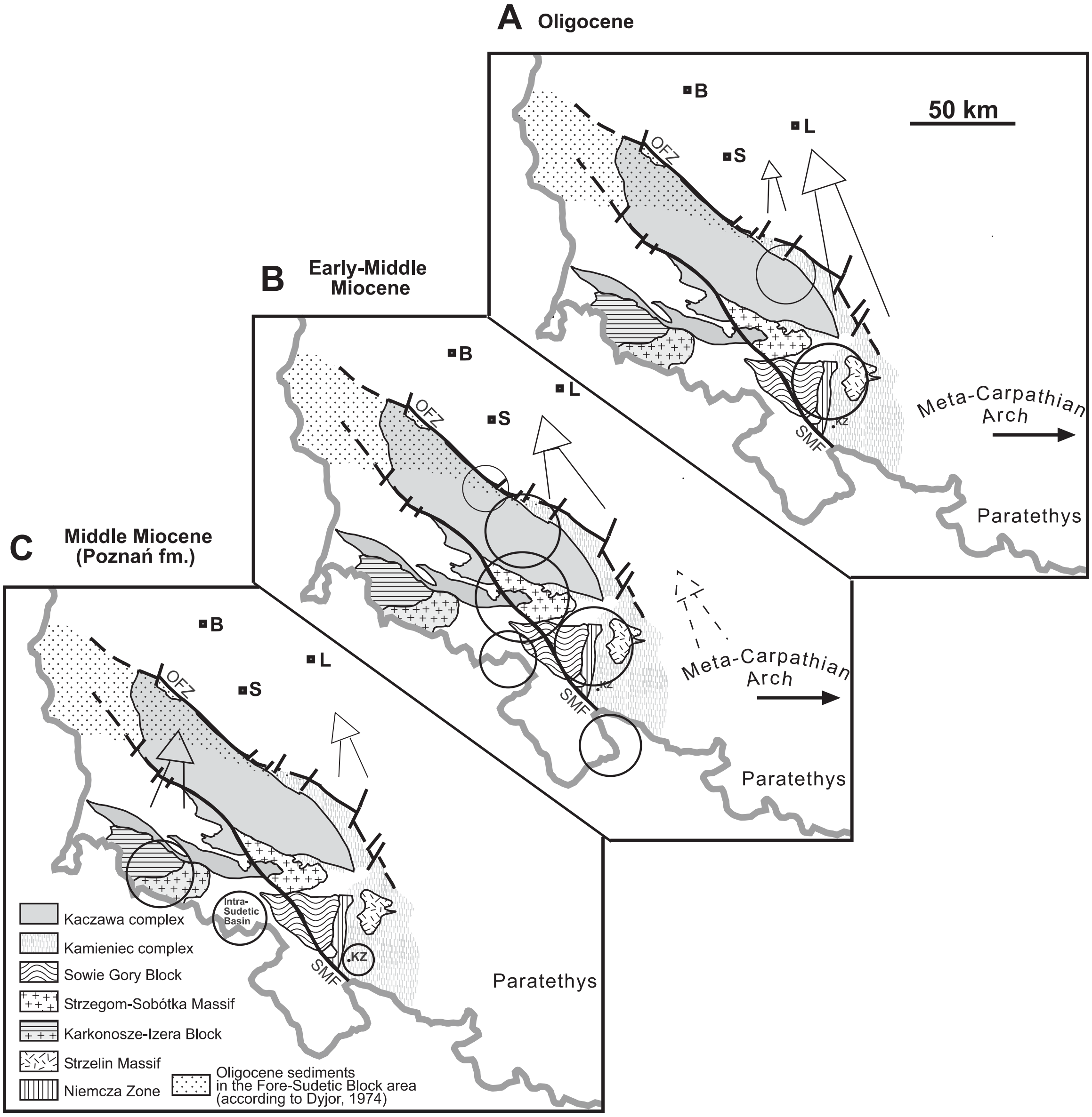

Fig. 7. Probable source areas (in circles) for the Oligocene–Miocene sediments of the Fore-Sudetic Monocline. Sketch geological map (only selected units) of the Sudetes Mts. and the Fore-Sudetic Block after Sawicki (1965), Grocholski (1982), and Cwojdziński & Żelaźniewicz (1995). OFZ – Odra Fault Zone; SMF – Sudetic Marginal Fault; KZ – Kamieniec Ząbkowicki.

were delivered from high-grade metamorphic rocks. Not only sillimanites (up to 19%) and kyanites (up to 26%) but also garnets, biotites and at least a part of the zircons, tourmalines and rutiles could have derived from the same source rocks, i.e. granulites, syllimanite gneisses, etc. The whole suite strongly points to the central part of the Fore-Sudetic Block, i.e. the Góry Sowie Block, Strzelin Massif and Niemcza Zone (Fig. 7A). Although the studied sections are situated in the direct foreland of the Kaczawa complex, epidote, a typical mineral, is not predominant. This suggests that this area did not supply the majority of the detrital material. Moreover, the presence of apatite and titanite, i.e. minerals of lower chemical stability than epidote, excludes weathering as the agent modifying the original proportions. Chlorite is another index mineral of the Kaczawa complex; its content is locally significant (Tab. 4), but the mineral, together with muscovite, is distinctly concentrated in the finer sediments. A negative correlation between the content of chlorite, and zircon and rutile, heavy minerals of high density, has been observed in the sands of the Lubuska formation (Fig. 8). This is probably not a provenance signal, but an example of the hydrodynamic sorting of minerals, a process effectively operating in the nearshore zones of seas. The epidote and chlorite disappear upwards in the section, which has been interpreted as an effect of weathering and discussed in the previous section. Summing up, in the Oligocene, the central part of the Fore-Sudetic Block, i.e. the western prolongation of the Meta-Carpathian Arch, was undoubtedly the dominant land providing the surrounding basins with detrital mate-

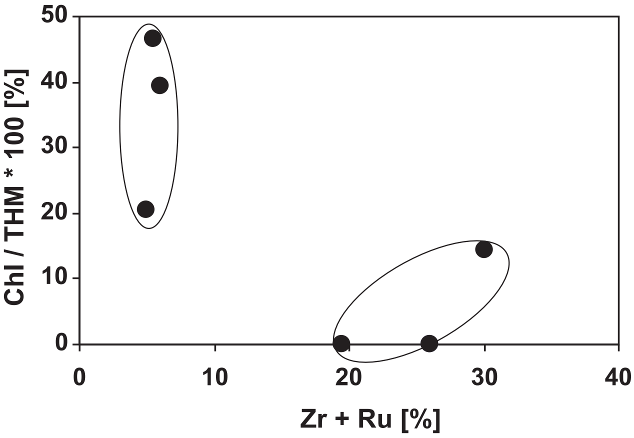

Fig. 8. Diagram showing the relationship between the zircon + rutile and chlorite content in the sands of the Lubuska formation (B section). Zr – zircon, Ru – rutile, Chl – chlorite, THM – translucent heavy minerals. The negative correlation is probably caused by hydrodynamic sorting of minerals.

rial. Moreover, this territory functioned as a source area during the sedimentation of successive formations up to the Mużaków formation. Only the sediments of the Poznań formation lack syllimanite and kyanite grains, although they contain chemically less stable garnets.

The Late Oligocene/Early Miocene Żary formation from the S section is the most conspicuous lithologically. It is composed of poorly sorted kaolinite clays, 38 m thick (Fig. 2), with subordinate gravels. The latter contain quartz and potassic feldspar grains, with minor amounts of crystalline shales, phyllites and rhyolites (Fig. 9). The petrographic and sedimentological features suggest redeposited weathered crust on the slope of an alluvial fan. Such sediments, up to 100 m thick, commonly occur along the southern periphery of the Fore-Sudetic Monocline in the area between Głogów, Lubin and Bytom Odrzański (Frankiewicz, 1982); they are probably related to one of the fault scarps which functioned during that time on the border between the Fore-Sudetic Block and Monocline. In other words, they are evidence of morphological differentiation in the Odra Fault Zone during the Late Oligocene/Early Miocene. The presence of K-feldspars and the high content of andalusite (up to 34%) among the heavy minerals suggest granitoids and their cover, *inter alia*, as source-rocks. The nearest rocks of such composition are located in the Odra Fault Zone (40 km to the north) and in the Strzegom-Sobótka Massif (~ 70 km away). Since the former constitute only small bodies (Grocholski, 1982), the latter probably fed the Tertiary basins with sediments. Kural (1979), in a detailed study devoted to the kaolins of the Strzegom Massif, concluded that a kaolinite cover of a substantial thickness (>100 m) must have been spread over the whole area of the Strzegom Hills before their upthrust in the Late Oligocene/Early Miocene. Weathered material must have been transported on the Fore-Sudetic Block, and thence was again redeposited in alluvial fans further to the north. The radii of alluvial fans typically do not exceed 10–15 km (Blair & McPherson, 1994). The Fore-Sudetic Block would thus have been a transit area for sediments. Nevertheless, this territory itself was the source of weathered material, as suggested by the phyllite contribution. Moreover, the weathered Wądroże Wlk. granitogneisses could also have delivered kaolinite clays. Furthermore, a part of the detrital material came from what is now the Sudetes Mts.: the rhyolite clasts, although present in minor quantities, are a very sensitive indicator of transport from that direction. Non-metamorphosed acid volcanic rocks occur in the Intra- and North Sudetic Basins. This hypothesis is also supported by the relatively high content of staurolite in the remaining rocks subsumed under the Żary formation; this mineral is common in schists from the Orlica-Śnieżnik Dome (e.g. Smulikowski, 1979), and was probably transported from there. The fine-grained sands and muds from the lower part of the S section and from the L and B sections (Żary formation) comprise a diverse mineral assemblage, and in addition to staurolite, they contain Al_2SiO_5 minerals, epidote, and even garnet (ZTR < 20%). The suite probably did not come from a deeply weathered residuum of crystalline rocks, but from their slightly altered weathered cover, which was the reason that less stable minerals survived. The variable heavy mineral composition does not point to one source area but rather to a number of territories of different lithologies, from the epimetamorphic Kaczawa complex to the high-grade rocks of the central part of the Fore-Sudetic Block

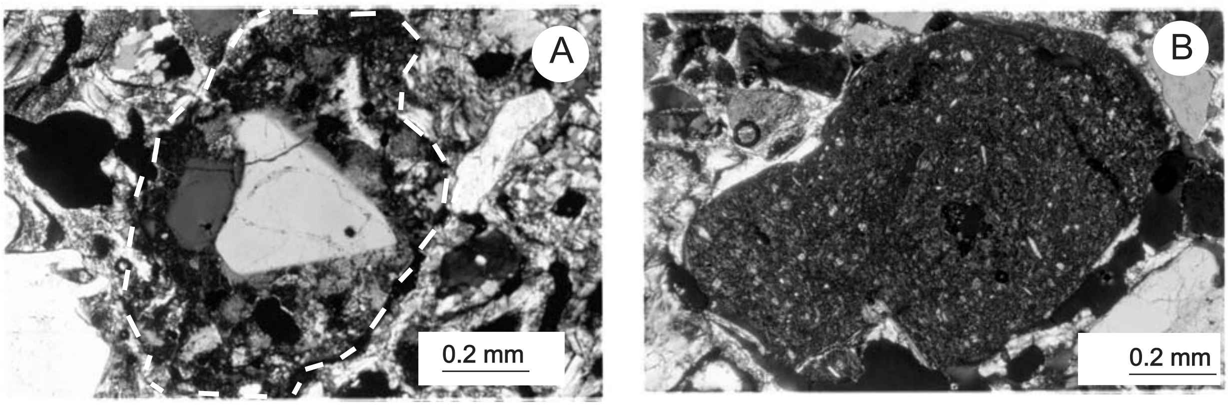

Fig. 9. Photomicrographs of non-metamorphosed acid volcanic rock fragments. Żary formation, A – sample S208, B – sample S219.

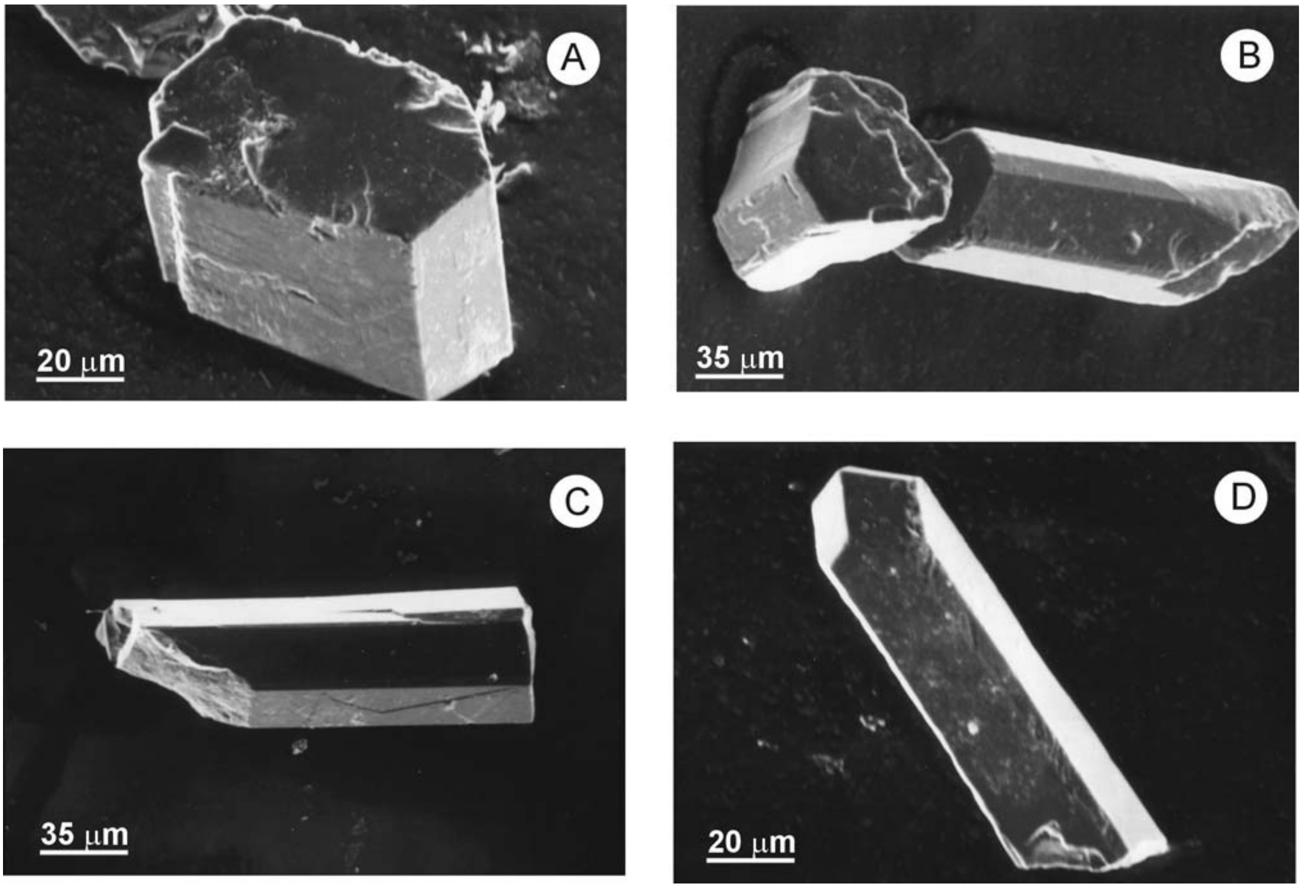

Fig. 10. SEM microphotographs of euhedral apatite (**A–C**) and zircon (**D**) grains, probably of pyroclastic origin. Mużaków formation, samples L123 (A, B, D) and S92 (C).

(Fig. 7B). Moreover, the successive Silesian-Lusatian formation (in the less altered part) and the lower part of the Mużaków formation exhibit a similar pattern of heavy mineral distribution. This means that since the sedimentation of the Żary formation, the central part of the Fore-Sudetic Block had not been the more dominant area, although it still supplied detrital material.

A dramatic change in heavy mineral composition occurs in the upper part of the Middle Miocene Mużaków formation, which was deposited in a marine environment. The main differences are expressed in the low Al_2SiO_5 mineral content, the exceptionally high garnet content (up to 55%) and significant apatite grain content (up to 14%). The Al_2SiO_5 minerals are so scarce that their redeposition from the older Tertiary sediments is not ruled out. In turn, enrichment in garnets may have been caused either by the peculiar provenance of the sediments or very effective hydraulic sorting. The present-day local placer concentrations of garnets on the Baltic beaches are an example of the latter process. However, a consistantly high garnet content in the sediments of the S and L sections, at least 10 m thick, preferably indicates the impact of provenance rather than hydrodynamic sorting. Kosmowska-Ceranowicz & Bühmann (1982) documented similar enrichment in garnets in the equivalent sediments from the vicinity of Poznań, i.e. in the sediments situated 70 km further north. Among the Sudetic crystalline rocks, garnet-bearing shales from the Izera Metamorphic Unit or from the Kamieniec Ząbkowicki complex are the most probable source of considerable amounts of garnets. Götze & Blankenburg (1994), in their study devoted to the equivalent Hohenbocka quartz sands, suggested that during that time, the Izera Mts. were denudated and delivered detritus to the Lusatian basin. A detailed study of garnet chemical composition might help determine the influence of the two source areas. However, the described heavy mineral suite is impoverished in some typical minerals for the two areas, such as andalusite, staurolite, and topase. This does not exclude the Izera Mts. and Kamieniec Ząbkowicki complex as source areas but suggests an additional source for the detrital material. For example, the Carboniferous sedimentary rocks of the Intra-Sudetic Basin (Felicka, 2000) and the crystalline rocks of the East Sudetes Mts. (e.g. Godlewski & Wierchowiec, 2004) could also supply garnets to the basin. Moreover, the Upper Silesian Triassic rocks that occur in the western part of the Meta-Carpathian Arch also contain abundant garnets in their heavy-mineral suites (M. Kowal – personal communication). Their contribution is not excluded.

The significant apatite content in the Tertiary sediments is most striking. The mineral could have come from the granitoid rocks, but the long-prism, colourless and euhedral crystals of apatite (Fig. 10) may also indicate that they originate from volcanic ashes that fell directly into the basin or its surrounding. Such an interpretation is suggested not only by the crystal shape (apatite grains from the granitoids would have been more weathered and rounded) but also by the presence of biotite plates (some of euhedral, pseudohexagonal habit), and by the fact that the highest amount of apatite occurs in the sediments of the L section, the farthest from the Sudetes Mts. Kosmowska-Ceranowicz (1979), who examined heavy minerals from the Tertiary sediments of northern and central Poland, which were mainly delivered from the less weathered Fennoscandian area, reported a maximum of 9% apatite in the form of rounded grains. Apatite and biotite indicate acid volcanic rocks, which are known outside the Sudetes Mts.; the Tertiary volcanic rocks in the Sudetic area have a basic composition. In turn, several tonstein horizons were described from central Poland (Wagner, 1981, 1984; August *et al.*, 1985; Matl & Wagner, 1986; Lorenc & Zimmerle, 1993) and from the Paratethys Basin (Parachoniak, 1954; Gabzdyl & Kapuściński, 1972; Alexandrowicz & Pawlikowski, 1978, 1980). The tonsteins from the Paratethys were dated for the Badenian (*op. cit.*). The Mużaków formation was also deposited during that time (Dyjor *et al.*, 1977; Sadowska, 1995). Therefore, it is quite probable that volcanic ashes directly fell or were washed out from the Meta-Carpathian Arch to the marine basin, where the volcanic glass was destroyed leaving behind these characteristic heavy minerals. Apatite, biotite and zircon were also reported from the tonsteins of central Poland (Matl & Wagner, 1986; Lorenc & Zimmerle, 1993).

The heavy mineral composition of the Poznań formation is similar to that of the upper part of the Mużaków formation, except for the absence of apatite. Although the heavy mineral composition is known from only two samples from the L section, it may be treated as representative, as Kosmowska-Ceranowicz & Bühmann (1982) documented very similar mineral diversity in the Poznań formation sediments from the vicinity of Poznań. Moreover, enrichment in garnets and scarcity of Al_2SiO_5 minerals are also documented in numerous papers by Czerwonka & Krzyszkowski (e.g. 1992, 1994), who studied a great number of samples from Lower Silesia. The small amounts of Al_2SiO_5 minerals and the low content of epidote grains suggest that the central part of the Fore-Sudetic Block and the Kaczawa complex were not strongly denudated. This is consistent with the results of regional studies (Dyjor, 1968, 1970; Oberc & Dyjor, 1969), which showed that the Poznań formation had reached the Sudetes Mts. edge and even covered the Meta-Carpathian Arch (Głazek & Szynkiewicz, 1987). The relatively high content of zircon (up to 17.5%), partly of euhedral habit, and garnets (up to 21.5%) may point to the Karkonosze-Izera Block. However, the lack of andalusite and topase, typical minerals for that area (Wieser, 1958) suggests that the contact rocks of the Karkonosze granite did not exist in outcrop at that time, and thus, that the Karkonosze-Izera Block was not strongly uplifted. The significant enrichment in garnets might also suggest detritus delivery from the Kamieniec Ząbkowicki complex or the Intra-Sudetic Basin (Fig. 7C).

The reconstruction of the provenance of the Oligocene–Miocene sediments presented in this study is approximate. A detailed study of some mineral species and more data about heavy mineral suites from a larger area may verify the conclusions. Krzyszkowski & Karanter (2001), Krzyszkowski (2001) and Czerwonka & Krzyszkowski (2001), on the basis of the diversity of the frequencies of selected minerals in the heavy mineral assemblages, reconstructed a drainage pattern for Lower Silesia in the Miocene. They recognized six major river systems that formed during the Early Miocene. However, they did not subdivide the Neogene sediments that underlie the Poznań formation, so a comparison with their results is difficult. Moreover, the results obtained in the present study indicate that heavy minerals from the Tertiary sediments were influenced by weathering and hydrodynamic sorting. Therefore, in terms of palaeogeographical reconstruction, the frequencies of minerals should be interpreted with caution, otherwise they may be misleading.

CONCLUSIONS

1. Different heavy-mineral assemblages have been recognized in the Oligocene–Miocene sediments of the Fore-Sudetic Monocline. Their composition is the result of their provenance, the intensity of the chemical weathering they underwent and, locally, their hydrodynamic sorting by density.

2. All the heavy mineral suites lack unstable heavy minerals, such as olivines, pyroxenes and amphiboles. Epidote, garnet, staurolite and syllimanite locally exhibit traces of dissolution. The most impoverished mineral suites were found in terrestrial sediments. Heavy minerals were destroyed during the deep weathering of the source rocks as well as during transport and diagenesis.

3. In the Oligocene and Miocene, the Sudetic land did not possess the features of a mountainous area, and the whole territory was not significantly uplifted relative to the Fore-Sudetic Monocline.

4. In the Oligocene and Early Miocene, the central and eastern part of the Fore-Sudetic Block (Góry Sowie Block and Strzelin Massif), constituting the western prolongation of the Meta-Carpathian Arch, was the predominant land supplying detrital material to the adjacent part of the Northwest European Basin. The contribution of the epimetamorphic Kaczawa complex, located close to the Fore-Sudetic Monocline, was not major, although considering the low chemical resistance of its typical minerals, it may be under-estimated.

5. At the end of the Late Oligocene/Early Miocene, the uplifted Strzegom-Sobótka Massif, as well as other rocks of the Fore-Sudetic Block, delivered kaolinite regoliths with highly stable minerals (ZTR + anatase + andalusite) to the then-lowered Fore-Sudetic Monocline. A part of the detritus was probably supplied from the area of what are now the Sudetes Mts.

6. A distinct shift in source areas took place in the Middle Miocene. Material was not supplied from the central part of the Fore-Sudetic Block, but from other areas (e.g. from the Karkonosze-Izera Block, Kamieniec Ząbkowicki horst, Intra-Sudetc Basin, east Sudetes, and probably, from the areas located further to the east).

7. Heavy minerals recorded a pyroclastic fall to the basin where the Middle Miocene Mużaków formation was deposited.

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