Geological Quarterly, 2006, **50** (2): 265–280

New data on heavy minerals from the Upper Cretaceous-Paleogene flysch of the Beskid Śląski Mts. (Polish Carpathians)

Justyna GRZEBYK and Stanisław LESZCZYŃSKI

Grzebyk J. and Leszczyński S. (2006) — New data on heavy minerals from the Upper Cretaceous-Paleogene flysch of the Beskid Śląski Mts. (Polish Carpathians). Geol. Quart., **50** (2): 265–280. Warszawa.

The types, abundance and origin of non-opaque heavy minerals from 17 samples of sandstones and granule conglomerates of the Godula Beds, Upper Istebna Sandstone, Ciężkowice and Cergowa Sandstone (Upper Cretaceous–Paleogene) of the Beskid Śląski Mts. are described in this study. The descriptions are based on standard optical petrographic investigations and on scanning electron microscope (including electron microprobe) analysis. Garnet, rutile, zircon and tourmaline are the most common types of heavy minerals. Monazite and apatite occur subordinately, whereas epidote and spinel are sporadic. The heavy minerals from the Middle and Upper Godula Beds and the Upper Istebna Sandstone indicate original derivation mainly from metamorphic rocks of granulite and partly eclogite facies. Metasediments were significant constituents, with subordinate granitoids and hornfelses. Granitoids and corresponding pegmatites and aplites, as well as metapelites and metapsammites, appear to be the primary crystalline parent rocks of the Lower Godula Beds and the Ciężkowice Sandstone. Garnet-mica schists with subordinate granitoids and their pegmatites are interpreted as the main crystalline parent rocks of the Cergowa Sandstone. Sporadic chromian spinels and chromian pyrope indicate derivation from mafic and ultramafic rocks. Co-occurrence of rounded and fresh unabraded grains (sometimes euhedral) suggests a mixed provenance for the clastic material, both from crystalline and older sedimentary rocks.

Justyna Grzebyk and Stanisław Leszczyński, Institute of Geological Sciences, Jagiellonian University, Oleandry 2a, PL-30-063 Kraków, Poland, e-mails: jjjustynaaa@yahoo.co.uk, stan@geos.ing.uj.edu.pl *(received: April 15, 2005; accepted: November 11, 2005).*

Key words: Poland, Carpathians, Paleogene, Upper Cretaceous, heavy minerals, provenance.

INTRODUCTION

The source rocks of the Tithonian-Early Miocene flysch facies sediments of the Outer Carpathians seem to be quite well recognized at a general level. This recognition is based upon investigations of gravelly components and heavy minerals contained in these sediments. Different magmatic, metamorphic and sedimentary rocks, derived mainly from continental crust, have been shown to be the chief or only source of these deposits (see Winkler and Ślączka, 1992; Salata, 2004). Ultrabasic rocks indicative of oceanic crust played a more significant role in supplying material to the rocks of the southern part of the Magura Nappe only (Winkler and Ślączka, 1992, 1994). Notably, the significance of siliciclastic source rocks appears to be subordinate in all nappes. However, the predominance of crystalline rocks as the direct source of clastic material in such a thick and stratigraphically short-ranged sediment pile as that of the Outer Carpathian Flysch seems to be unlikely. Very intense weathering would be necessary for the production of such huge amounts of clastic material. One cannot exclude the possibility that this inference is flawed, due to difficulties in recognizing provenance from older non-lithified and poorly lithified sedimentary rocks by means of heavy mineral investigations.

Provenance studies based on heavy mineral assemblages have become considerably more sophisticated recently, with the advent of single-grain geochemical analysis. The chemical composition of heavy minerals can be now readily determined using electron microprobe analysis (EPMA). This method provides sensitive information on the mineralogical composition of sediment source rocks (Morton, 1991; Morton and Hallsworth, 1999) and compared to the methods used before, allows us a more precise recognition of the type and geotectonic provenance of the source rocks.

This paper presents the results of investigations of non-opaque heavy minerals, with particular reference to garnets, by means of conventional optical method together with scanning electron microscopy, including electron microprobe analysis, in one transect of the Upper Cretaceous–Paleocene part of the Silesian Series and from one outcrop of the Lower Oligocene part of the Fore-Magura Series in the Beskid Śląski Mts. (Western Polish Carpathians). Electron microprobe analysis has been applied to garnets, tourmalines and chromian spinels. The results of these investigations are compared to those of Krysowska-Iwaszkiewicz and Unrug (1967) from the same sections with conventional optical methods exclusively. Our paper provides new data concerning both the heavy mineral assemblages and the mineralogy of garnets, zircons, tourmaline and spinels. The petrographic significance of these data is also discussed here.

STUDY AREA

The samples were collected from sandstones and conglomerates representing the Godula Beds (Turonian–Santonian; 7 samples) outcropping in the valley of Vistula River in the town of Wisła, from sandstones and conglomerates representing the Upper Istebna Beds (Lower Paleocene; 3 samples) and the Ciężkowice Sandstone (Upper Paleocene; 1 sample), outcropping in the valley of the Janoska Stream on the northwestern outskirts of the village of Kamesznica and from sandstones assigned either to the Krosno Beds or the Cergowa Sandstone (Lower Oligocene; 6 samples), outcropping in a quarry on the eastern outskirts of Kamesznica (Fig. 1; Table 1). The entire area is located in the western part of the Polish Carpathians, close to the boundary with the Czech Republic.

The Godula Beds, Istebna Beds and the Ciężkowice Sandstone constitute the middle part of the sedimentary succession called the Silesian Series whereas the Cergowa Sandstone forms the upper part of the sedimentary succession called the Fore-Magura Series or Dukla Series (see Paul *et al*., 1996; Fig. 2). The Silesian Series in the entire area of its occurrence is considered to form one of the chief tectonic units of the Outer Carpathians, termed the Silesian Nappe. The Fore-Magura Series forms a separate tectonic unit called the Fore-Magura Slice, which is thrust from the south on to the Silesian Series. The petrography, facies and sedimentary development of the studied units have been described in many papers, particularly by Unrug (1963; 1968) and Słomka (1995).

As in other sedimentary successions of the Outer Carpathian Flysch, the successions in question comprise deep-water sediments deposited mainly by mass gravity flows, and particularly by turbidity currents *sensu* Lowe (1982). The facies distribution and palaeocurrent data indicate derivation of clastic material of all sampled lithostratigraphic units from an intrabasinal ridge termed the Silesian Cordillera (Książkiewicz, 1956, 1960). The Silesian Series was deposited to the north of the ridge, according to recent studies, whereas the Fore-Magura Series accumulated to the south of it. Unfortunately, the only record of this ridge is contained within the Upper Cretaceous-Paleogene flysch. Moreover, the entire basement of the Outer Carpathian Flysch is not known since flysch was detached from it and thrust onto the European Platform, whereas the basement itself was deeply subducted to the south.

LABORATORY METHODS

The samples were prepared according to the standard laboratory methods described by Mange and Maurer (1992). First of all, the samples were disaggregated by five-fold crushing in a mechanical crusher and then sieved. The 63 and 250 µm size fractions were selected for further analysis. A slightly greater range of size fraction was taken for heavy mineral separations in this study comparing to that normally used (63–125 µm), due to the rich population of garnets that frequently occur in the rocks investigated in grains larger than 125 µm. Material of these size fractions was cleaned in an ultrasonic cleaner, to remove clay mineral coatings from the heavy mineral grains. Afterwards, the samples were dried and then heavy minerals were extracted by gravity settling in LST heavy liquid (s.g. 2.85±0.02 g/cm^3).

The heavy-mineral residue of each sample was divided into three parts according to the requirements of the investigation methods planned, i.e. by polarized light microscope (petrographic microscope), scanning electron microscope analysis of grain morphology, and electron microprobe analysis. Grains from one part of the residue of each sample were mounted in canadian balsam and analysed by petrographic microscope. Non-opaque heavy minerals (except for micas, glaucony and chlorite) were identified and their optical features were recorded using standard petrographic procedures. The abundances of particular mineral types were then determined by counting at least 200 grains in each mount (Fig. 3).

Grains of all distinct morphologic types recognized using a petrographic microscope were selected for additional analysis of morphology by scanning electron microscope. Grains for the analysis by scanning electron microscope were picked with a needle during optical examination from the respective part of the heavy mineral residue. The grains were placed on double-sided adhesive tape, coated with carbon, and analysed using a *JEOL 5410* scanning electron microscope at the Institute of Geological Sciences, Jagiellonian University.

The electron microprobe analysis was performed using polished mounts of garnet, tourmaline and chromian spinel grains by using on the scanning electron microscope equipped with a *Voyager 3100* (*Noran*) energy dispersive spectrometer (EDS). The grains were mounted in araldite resin and then ground and polished with 1A diamond paste. Accelerating voltage, specimen current and counting time for each grain were kept at 20kV, 10nA and 100 s respectively.

Garnet, the most common mineral in most of the samples, was examined by electron microprobe analysis in 50 to 100 grains in each sample except for the sample wo1-1 where only 15 grains were analysed. 800 garnet grains were analysed in total. The garnet analyses, except for a few grains in each sample, were performed exclusively in grain centres as grains of the sizes analysed in this study do not show zoning (see Atherton and Edmunds, 1966; Lopez Ruiz, 1976). The garnet end-members (pyrope, almandine, spessartine, andradite and grossular) were calculated according to Deer *et al.* (1992).

Tourmaline was examined by electron microprobe analysis in 85 grains only. Nearly half of these grains belonged to the sample wo1-2 where this mineral is particularly common. The low number of grains examined was due to the lower amount of

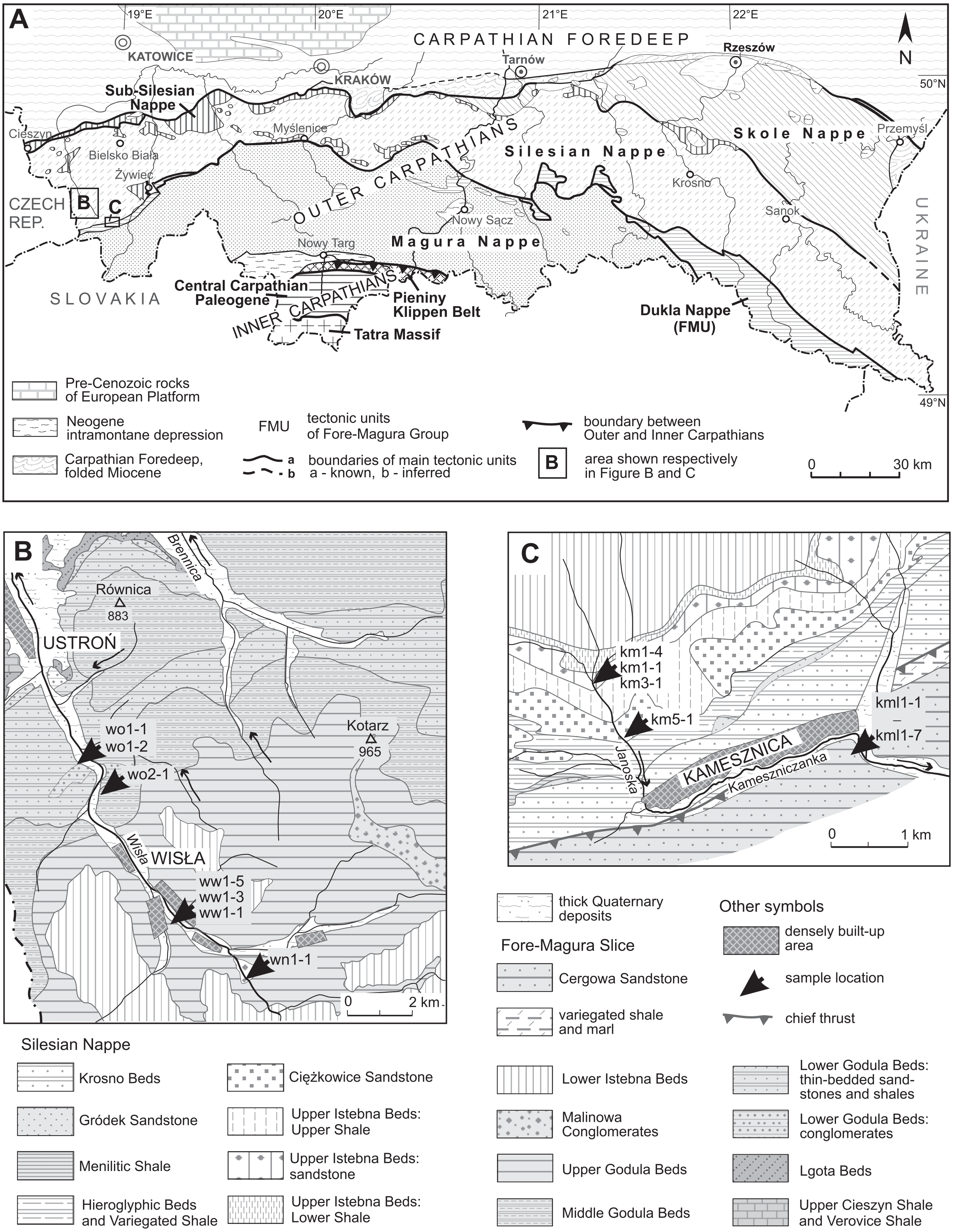

Fig. 1. Location of the sections and samples studied

Geological maps after Książkiewicz (1972) and Unrug (1979) with some modifications by S. Leszczyński based on different sources

Table 1

Main petrographic features of the samples examined

Sample no.	Lithostratigraphic unit	Rocks in the outcrop	Macroscopic features of sample
wo1-1	Lower Godula Beds	thin- to medium-bedded sandstones (Tc, Tbc, Ta-c) interbedded with dark grey muddy shales	dark grey, fine-grained, hard, horizontally laminated sandstone composed of quartz, rich in dark-coloured components, mainly biotite
wo1-2			light grey, fine-grained, hard sandstone composed of quartz, subordinately cream-yellow feldspars, subordinately light-coloured mica and glaucony
wo2-1	Middle Godula Beds	thin- to thick-bedded glauconitic sandstones interbedded with grey-green muddy shales	greenish-grey, medium-grained, hard sandstone composed of quartz, subordinately cream-yellow feldspars, light- and dark-coloured mica
ww1-1	Upper Godula Beds	thick-bedded, normally-graded sandstone interbedded with grey-green muddy shale layers up to 20 cm thick	coarse-grained, beige-coloured, hard sandstone, composed of quartz subordinately cream-yellow feldspars, light and dark-coloured mica, and glaucony
ww1-3			fine-grained, beige-coloured, faintly laminated, hard sandstone composed of quartz, subordinately cream-yellow feldspars, light and dark-coloured mica
ww1-5			pebbly sandstone, light-grey, composed of quartz, subordinately cream-yellow and pinkish feldspars, and dark-coloured mica
wn1-1	Upper Godula Beds: Malinowa Conglomerate	massive, quartzose pebble conglomerate occurring in several metres thick beds, with clasts of quartzose sandstone	pebble conglomerate (maximum pebble size 1 cm), poorly lithified, composed of quartz, subordinately cream-yellow feldspars and light-coloured mica
km3-1	Upper Istebna Beds: Upper Istebna Sandstone	poorly lithified pebble conglomerate intercalated with coarse-grained sandstone	coarse-grained, grey, hard sandstone composed of quartz, subordinately cream-yellow feldspars, dark-coloured components, and light-coloured mica
km1-1			medium-grained, light grey, hard sandstone composed of quartz, subordinately cream-yellow feldspars, and light coloured mica
km1-3			pebble conglomerate (maximum pebble size 1 cm) rusty-coloured, poorly lithified, consisting mainly of quartz, subordinately light-coloured mica
km5-1	Ciężkowice Sandstone	thick-bedded, light-grey pebbly sandstone overlain by thin-bedded, grey sandstone interbedded with greenish-grey muddy shale	fine pebbly sandstone, beige-coloured, medium hard, graded, composed of quartz, subordinately cream-yellow feldspars, unidentified dark-coloured components and mica
kml1-1	Cergowa Sandstone	thick-bedded sandstone with thin muddy shale intercalations	coarse-grained sandstone, light grey, medium hard, composed of quartz, subordinately mica and unidentified dark-coloured components
kml1-2			fine-grained sandstone, light grey, medium hard, laminated, composed of quartz, subordinately mica
kml1-3			fine-grained sandstone, light grey, medium hard, laminated, composed of quartz, subordinately mica and cream-yellow feldspars
kml1-5			fine-grained sandstone, light grey, medium hard, laminated, composed of quartz, subordinately mica
kml1-6			fine-grained sandstone, grey-coloured, poorly lithified, horizontally laminated, composed of quartz, coalified plant fragments, subordinately mica
kml1-7			very fine-grained sandstone, light-grey, medium hard, composed of quartz, subordinately mica

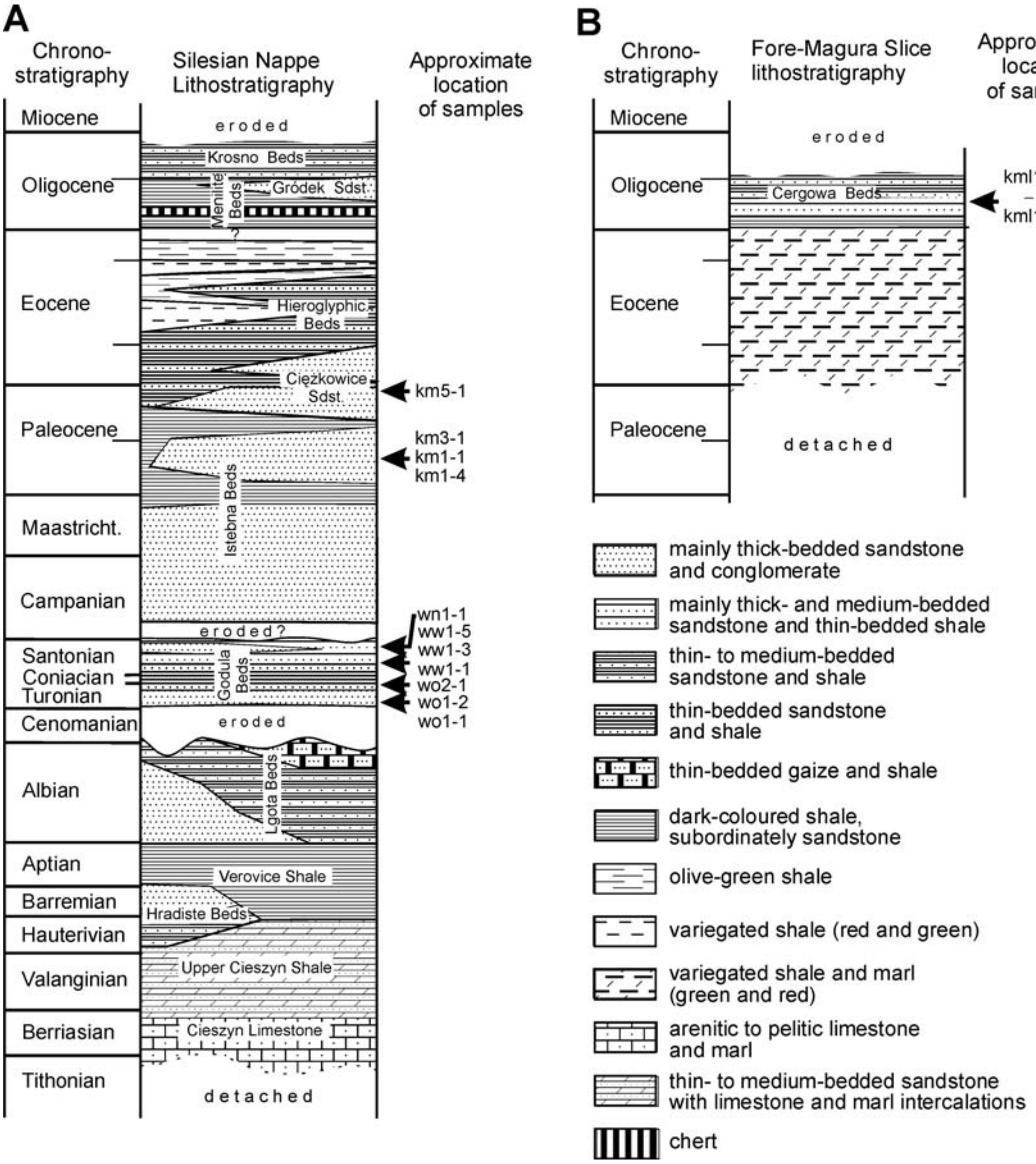

Fig. 2. Stratigraphy of the Silesian Nappe (A) and Fore-Magura Slice (B) of the Beskid Śląski range based on Unrug (1979) and Paul *et al*. (1996) with some modifications by S. Leszczyński

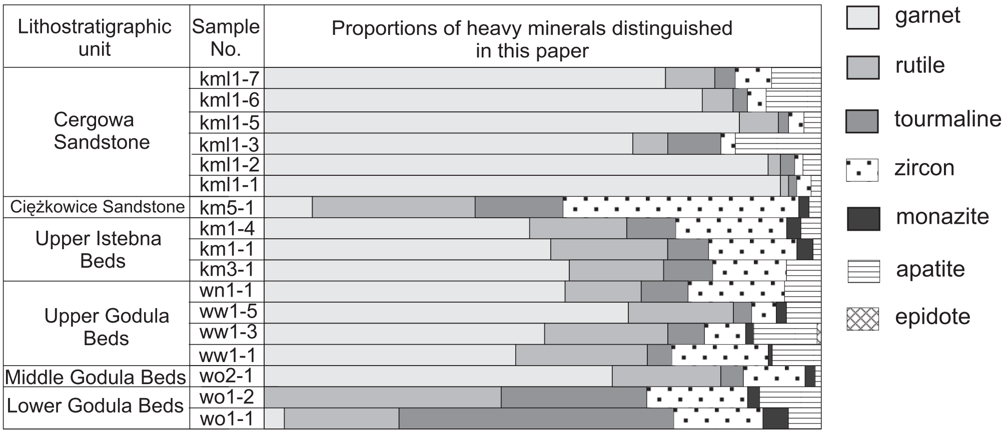

Fig. 3. Assemblages and proportions of non-opaque heavy minerals recorded with optical microscopy in the samples investigated

this mineral in the samples investigated compared to the garnet grains. Moreover, the low precision in determining B and Li, which frequently occur in this mineral, together with the frequent variability of chemical composition of individual grains, made the analysis less useful to this study. The analyses were always performed on grain cores, therefore the data acquired refer to the original, and not necessarily to the immediate source material of the grains investigated.

Chromian spinel was examined by electron microprobe analysis in 28 grains only because of rarity of this mineral in the samples studied. The analyses were performed on both cores and margins of grains.

RESULTS

OPTICAL MICROSCOPY

Garnet, rutile, tourmaline, zircon, monazite, apatite and epidote were identified in the samples studied (Fig. 3). These minerals occur in four distinct assemblages with differing proportions of particular minerals. Assemblages dominated by rutile, tourmaline and zircon occur in two samples taken from the Lower Godula Beds. Assemblages dominated by garnet with common rutile and zircon occur in samples from the remaining part of the Godula Beds and in the Upper Istebna Beds (8 samples). An assemblage dominated by zircon, with common rutile and frequent tourmaline, occurs in sample km5-1, taken from the Ciężkowice Sandstone. Assemblages where garnet constitutes 70–90% of the non-opaque heavy minerals, with correspondingly low proportions (<10%) of other species occur in all samples from the Cergowa Sandstone.

Garnet is present in all samples except for wo1-2 taken from the Lower Godula Beds. Apatite or, in some samples from the Silesian Series, monazite occur subordinately in all samples. In some samples, the number of apatite grains is comparable or even slightly higher than that of zircon and/or tourmaline. Some samples from the Cergowa Sandstone (kml1-2, kml1-3, kml1-5, kml1-6, kml1-7) contained more apatite grains than rutile, tourmaline and/or zircon. Epidote is the rarest non-opaque heavy mineral in all samples studied. It was recorded only by means of optical microscope in sample ww1-3 (2 grains) and in sample kml1-3 (1 grain).

Garnet in all samples is predominantly colourless, angular, etched, with rare, irregularly distributed inclusions. The most intense etching occurs in garnets from the Silesian Series. Non-etched, euhedral grains were sporadically recorded in the samples from the Cergowa Sandstone. Some grains display slight rounding. Garnets rich in inclusions concentrated at the grain core were rarely recorded in samples from the Upper Istebna Beds and in two samples (kml1-6, kml1-7) from the Cergowa Sandstone. Coloured garnets were rarely noted. Salmon-pink, pink, brownish-pink and rusty-brown species were recorded in the samples from the Silesian Series and salmon-pink to brownish-pink varieties in the samples from the Cergowa Sandstone.

Rutile occurred nearly exclusively as rounded grains showing yellowish-brown to dark brown colour. Euhedral grains were found in both samples from the Lower Godula Beds and sporadically in those from the Cergowa Sandstone. In the samples from the Lower Godula Beds, euhedral rutile constituted nearly half of the population of rutile grains.

Tourmaline occurred as non-abraded, euhedral or angular grains and as rounded grains showing mainly pale yellow to yellowish-brown and variable, aquamarine, green to dark green colours. Colourless, blue and pleochroic grains showing greenish-brown, pale yellow to achromatic coloration as well as grains showing zoned coloration occurred rarely. Moreover, tourmalines showing variable, brownish-pink to turquoise coloration and zoned, dark brown to turquoise coloration occurred rarely in samples from the Cergowa Sandstone. Euhedral grains prevailed in samples from the Silesian Series whereas subangular to rounded grains were commonly found in samples from the Cergowa Sandstone. Zoned and yellowish-brown tourmalines occurred here as well rounded grains.

Brown and dark green tourmalines containing numerous black inclusions occurred in samples from the Upper Godula Beds, Istebna and Ciężkowice Sandstone. In the samples from the Cergowa Sandstone, spot-like black inclusions were found in variously-coloured tourmalines.

Zircon occurred mainly as rounded grains in all samples. Euhedral grains were very rarely found. The grains were either colourless, frequently rich in inclusions or yellow, semi-transparent, metamict. Mainly yellow zircon occurred as well-rounded grains in the samples from the Cergowa Sandstone. Some grains in all samples showed distinctive growth zones around their core. Strongly elongated grains of colourless zircon were occasionally found in samples from the Upper Godula Beds and the Cergowa Sandstone. The grains were euhedral to slightly rounded in the former unit and usually slightly rounded in the latter. Some of the elongated crystals, in both lithostratigraphic units, show resorption borders.

Monazite was found in all samples, mainly as rounded, pale yellow grains, frequently containing dark inclusions. Apatite was found as euhedral, non-abraded to slightly rounded, colourless and pale yellow grains. Epidote occurred as angular, yellowish-green splinters. Spinels were recorded as irregular, reddish-brown, angular splinters.

SCANNING ELECTRON MICROSCOPY

ELECTRON MICROPROBE ANALYSIS

Garnets: the chemical composition of the garnets analysed was found to be highly variable even within individual samples. However, no significant differences were found in the proportions of particular elements between the centres and margins of individual grains. The dominant molecule in the grains analysed is almandine, comprising over 50% in most grains. The amount of pyrope ranges mainly between 5 and 50 mol%, whereas the content of other molecules is lower (Figs. 4 and 5). Spessartine usually does not exceed 10 mol%. Eleven garnet types differing in the content of pyrope, spessartine and grossular+andradite molecules were distinguished (Table 2). The chemical composition of individual types is shown in Table 3. Some differences were found in the assemblage of garnets and proportion of individual garnet types between individual lithostratigraphic units (Fig. 6).

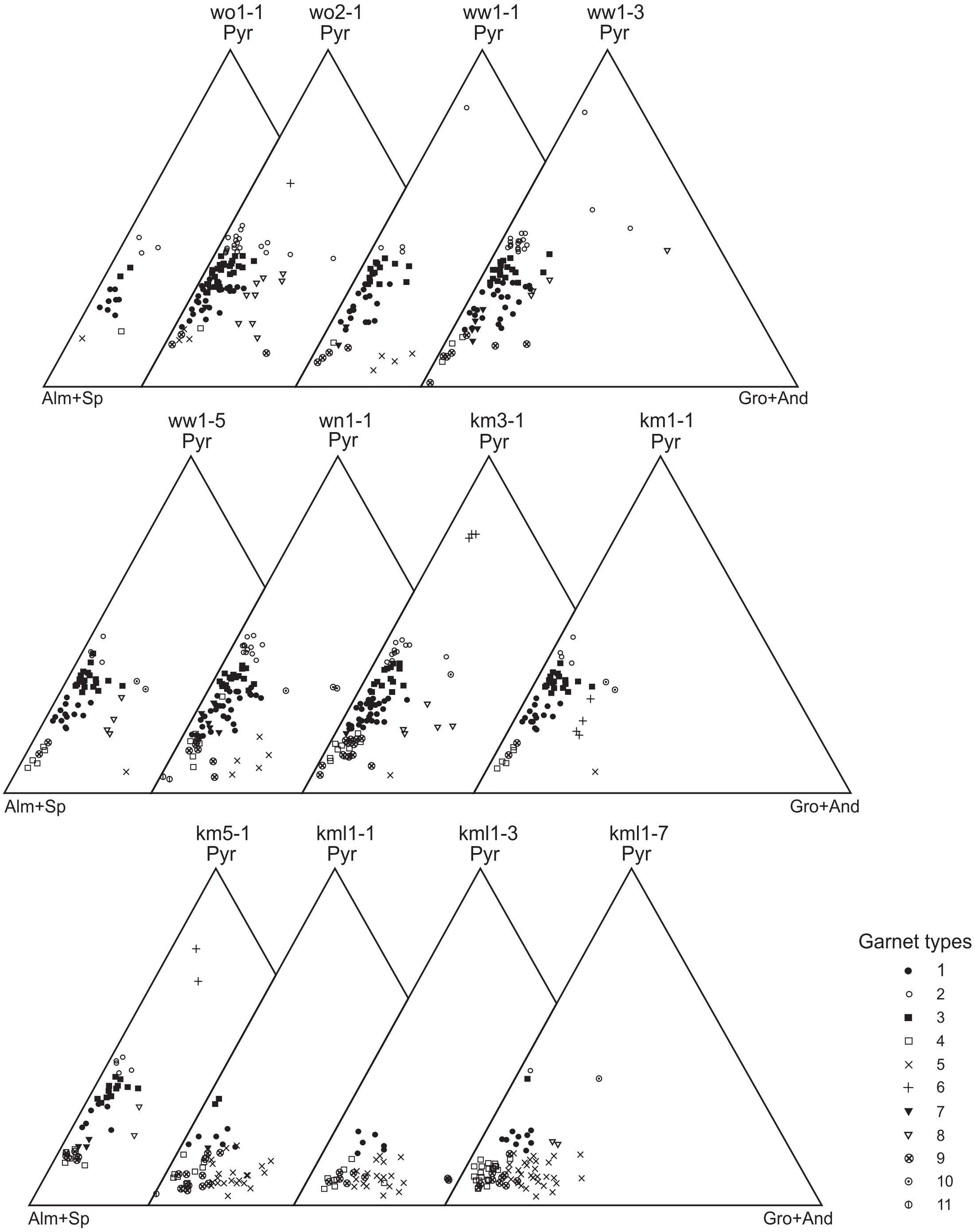

Fig. 4. Garnet compositions in individual samples

Pyr = pyrope, Alm+Sp = almandine + spessartine, Gr+And = grossular + andradite; garnet types explained in Table 1

Ca-poor garnets rich in almandine and medium-rich to rich in pyrope (types 1–3) prevail in the samples from the Silesian Series. Proportions of these particular groups in the samples are different. Garnet types 7, 8 and particularly 9 participate here in subordinate amounts. Samples from the higher part of the Silesian Series show increasing amounts of garnet type 4 (almandines poor in other molecules). Individual grains of chromian pyrope occur in samples wo2-1 and km5-1. Samples wn1-1 and km1-1 contain garnets rich in Ca-rich pyrope (Ca up to 30%). Moreover, garnets containing above 25% spessartine molecule (type 11) occur in sample wn1-1.

Pyrope-rich garnets are scarce or absent in the Cergowa Sandstone. Garnets showing different amounts of andradite+grossular and spessartine molecules (type 4 and 5) dominate in these samples. Admixtures of other elements are rare. TiO_2 occurs most commonly, although amounts never exceed 1 wt.%. Traces of Zr, Y and Zn are present in some grains.

Tourmaline: the tourmalines examined showed a distinct variability in the content of Fe(tot) and Mg, and, to a lesser extent, in the Al content (Fig. 7). Tourmalines of particular samples seem to differ slightly as regards their chemical composition (comp. Fig. 7A and 7B). Tourmalines from one sample

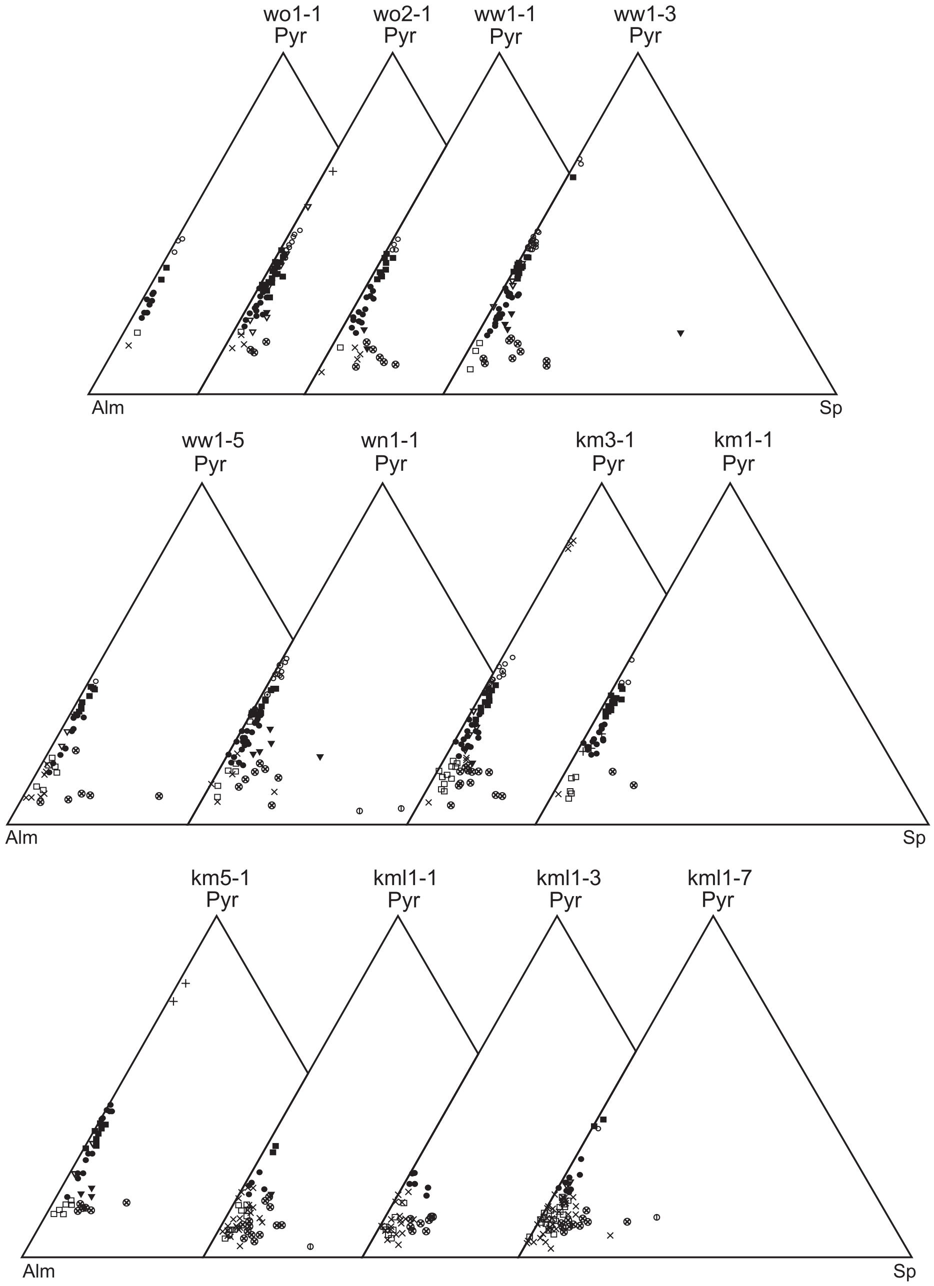

Fig. 5. Garnet compositions in individual samples

Alm = almandine, Sp = spessartine; for other explanations see Figure 4

seem to show less variable compositions than those from different samples. Admixtures of TiO_2 never exceeding 1.5 wt.%, as well as Cr_2O_3 never exceeding 0.5 wt.%, are present in the grains examined.

Chromian spinel: the spinels measured show significant variability with respect to the main cation contents. However, no systematic change in chemical composition was recorded between the different lithostratigraphic units sampled (Figs. 8 and 9). The atomic ratios of Cr/(Cr+Al) range between 0.28 and 0.79. Only three of grains measured showed a ratio of <0.30. The atomic ratios of Mg/(Mg+Fe^{2+}) ranged between 0.25–0.7. Fe^{3+} concentration was consistently low. Core-to-rim variations are minor. Ti, Mn, V and Zn are present in only trace amounts. ZnO is the most abundant; its concentrations reached up to 1.65 wt.%. TiO_2 concentrations reached 1.46 wt.%, whereas the concentration of V_2O_5 did not exceed 0.57 wt.%.

ANALYSIS OF GRAIN MORPHOLOGY

The commonly observed etching of garnet grains (mainly facets, rarely pits and hacksaw terminations; Fig. 10A–D), differ in intensity depending on the chemical composition of the grain. The intensity is greater in grains showing an increased proportion of pyrope molecule. At the same time, grains rich in

Table 2

Classification of garnets according to the content of pyrope, grossular+andradite and spessartine molecules*

Type No.	Percentage of end-member molecules			Groups of types
	Pyrope	Grossular +andradite	Spessartine	
1	15–30%	<15%	<5%	garnets with intermediate content of pyrope molecule
8	15–30%	>15%	<5%	
7	15–30%	<15%	>5%	
2	>40%	–	–	garnets with high content of pyrope molecule
3	30–35%	–	–	
10	30–35%	>20%	–	
6	>50%	–	–	garnets with very high content of pyrope and >5% of uvarovite molecule
4	<15%	<10%	<5%	garnets with low content of pyrope molecule
5	<15%	>10%	<5%	
9	<15%	<10%	>5%	
11	<10%	–	>25%	

* — empty fields denote highly variable contents of a molecule

Table 3

Selected EPMA analyses of particular types of garnets distinguished in this study

Oxides	Percentage of oxides in particular garnet type										
	1	8	7	2	3	10	6	4	5	9	11
SiO_2	38.04	38	37.66	39.7	38.54	39.16	41.84	36.69	37.01	37.41	36.36
Al_2O_3	20.52	21.04	19.53	21.08	21.16	21.52	21.17	19.62	20.25	19.9	19.8
MgO	6.76	5.83	4.93	11.21	9.05	8.13	20.2	2.62	1.66	3.44	0.95
CaO	2.42	6.56	2.28	1.46	1.53	6.81	4.61	1.97	6.5	2.43	0.98
FeO	31.88	27.84	33.02	25.9	28.64	23.9	9.53	38.36	34.2	31.92	24.04
MnO	0.38	0.73	2.58	0.65	1.08	0.48	nd	0.74	0.38	4.9	17.36
Cr_2O_3	nd	nd	nd	nd	nd	nd	1.92	nd	nd	nd	0.51
TiO_2	nd	nd	nd	nd	nd	nd	0.71	nd	nd	nd	nd
Amounts of cations calculated by adjusting for 24 oxygen atoms											
Si	6.01	5.97	6.04	6.06	5.99	6.02	5.99	5.99	5.99	6.04	5.99
Al	3.81	3.89	3.7	3.79	3.87	3.9	3.57	3.78	3.87	3.79	3.84
Mg	1.59	1.36	1.18	2.55	2.09	1.86	4.31	0.64	0.4	0.83	0.23
Ca	0.41	1.1	0.39	0.24	0.25	1.12	0.7	0.34	1.12	0.42	0.17
Fe	4.21	3.66	4.43	3.31	3.72	3.07	1.14	5.24	4.63	4.31	3.31
Mn	0.05	0.1	0.35	0.08	0.14	0.06	nd	0.1	0.05	0.67	2.42
Cr	nd	nd	nd	nd	nd	nd	0.21	nd	nd	nd	nd
Ti	nd	nd	nd	nd	nd	nd	0.07	nd	nd	nd	0.06
Percentage of individual end-members											
pyrope	26.2	22.4	19.5	42.7	34.5	31	71.9	10.5	6.6	13.8	3.8
almandine	66.2	57.9	68.3	51.9	59.1	49.4	16.4	82.3	74.1	68.1	38.4
spessartine	0.8	1.6	5.8	1.3	2.3	1	–	1.6	0.8	11.1	55
andradite	4.8	3.5	6.4	4	3.5	2.5	4	5.6	3.5	5.3	2.8
grossular	2	14.6	nd	nd	0.6	16.1	2.4	nd	15	1.7	nd
uvarovite	nd	nd	nd	nd	nd	nd	5.3	nd	nd	nd	nd

nd — below detection level

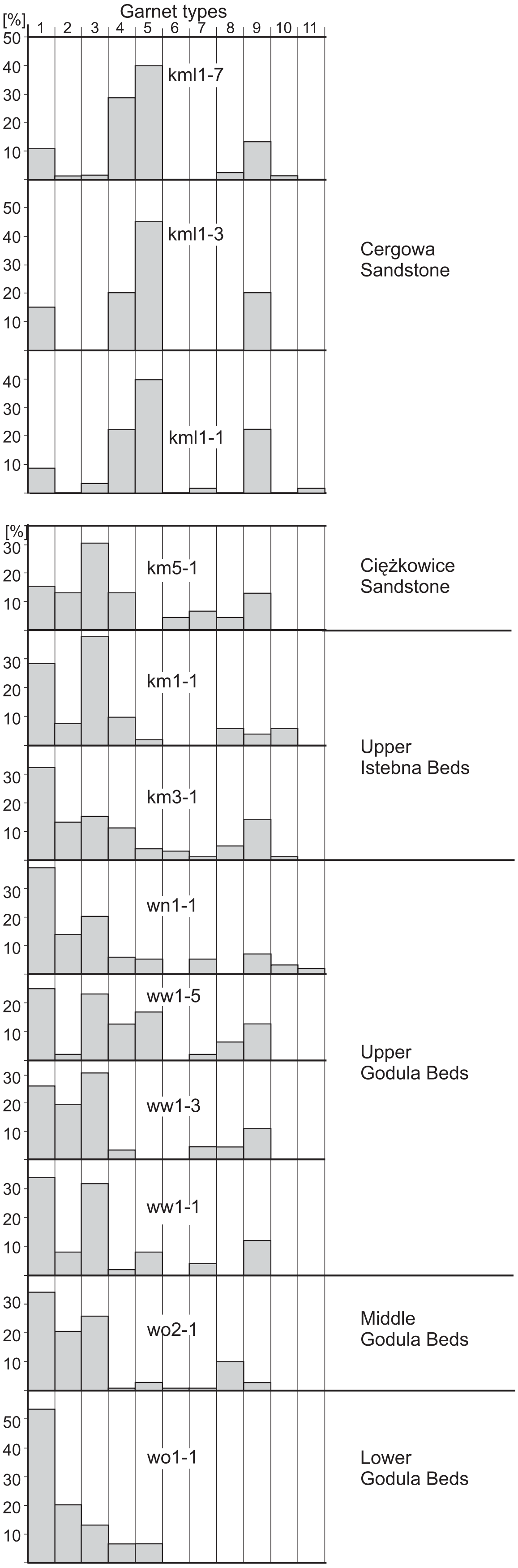

Fig. 6. Garnet types and their proportions in individual samples

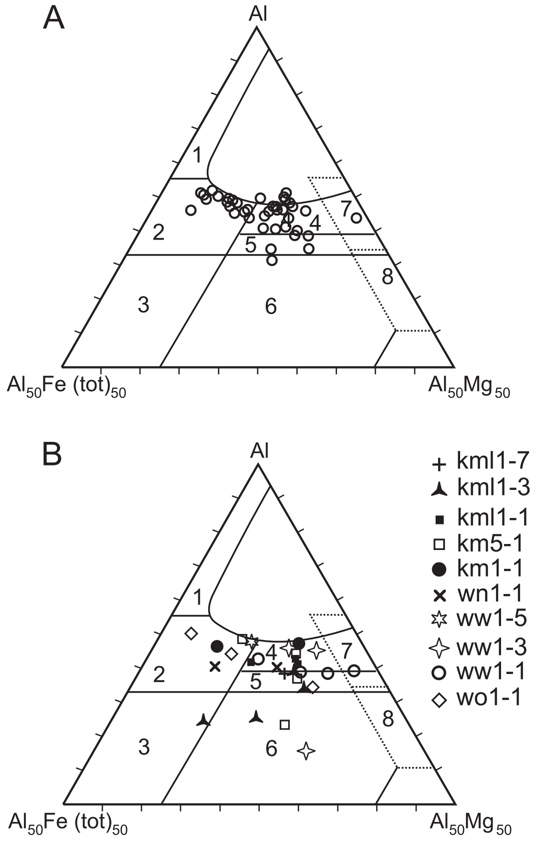

Fig. 7. Compositions of tourmalines from the samples investigated and fields of composition of tourmalines from different parent rocks according to Henry and Guidotti (1985); A — tourmalines from sample wo1-2; B — tourmalines from different samples as explained

1 — Li-rich granitoid pegmatites and aplites, 2 — Li-poor granitoids and their associated pegmatites and aplites, 3 — Fe^{3+}-rich quartz-tourmaline rocks (hydrothermally altered granites), 4 — metapelites and metapsammites coexisting with an Al-saturating phase, 5 — pelites and psammites not coexisting with an Al-saturating phase, 6 — Fe^{3+}–rich quartz-tourmaline rocks, calc-silicate rocks and pelites, 7 — low-Ca metaultramafics and Cr, V-rich metasediments, 8 — metacarbonates and meta-pyroxenites

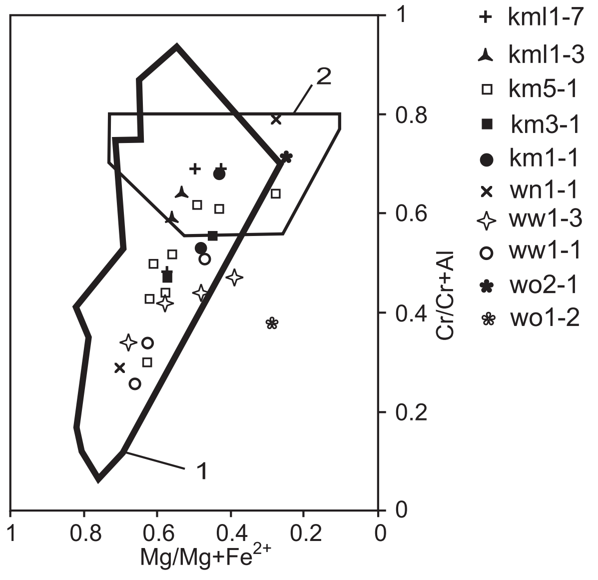

Fig. 8. Composition of spinels examined compared with Alpine-type peridotite (1) and stratiform complex ultramafic bodies (2); fields after Irvine (1974)

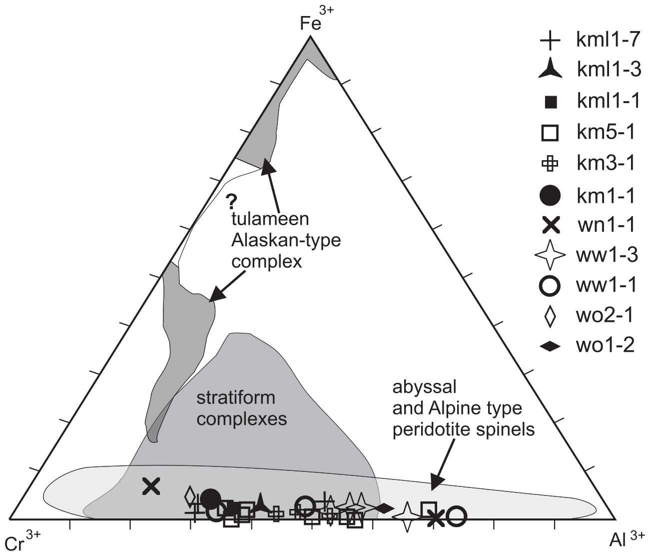

Fig. 9. Composition of spinels examined with respect to concentrations of the major trivalent cations; discrimination fields are from Cookenboo *et al.* (1997)

almandine molecule show nearly euhedral shapes with virtually non-etched to only slightly etched, well-preserved faces (Fig. 10C). These were particularly well-observed in samples from the Cergowa Sandstone.

The grains of zircons and monazite examined show mainly smooth, unetched surfaces (Fig. 10E–L). The rare euhedral grains of zircons show either well-preserved, non-etched faces and edges (Fig. 10E–H) or slightly abraded edges (Fig. 10I). The tourmalines occur mainly as grains of broken euhedral crystals locally showing slightly rounded edges (Fig. 10M–O).

DISCUSSION

HEAVY MINERALS

The heavy minerals identified in this study constitute relatively poor assemblages as regards the number of basic mineral types. The assemblages roughly correspond to those recorded in the same transect by Krysowska-Iwaszkiewicz and Unrug (1967). Both papers show reasonably similar lithostratigraphic distributions of garnets in proportion to the remaining heavy minerals. The highest difference between these two papers occurs in the relative contents of particular minerals and in their characterization. Moreover, staurolite, amounting up to 2% of the non-opaque heavy minerals, was recorded in samples from the Lower Godula Beds and the Ciężkowice Sandstone by Krysowska-Iwaszkiewicz and Unrug. These minerals have not been recorded in our study. In contrast, monazite, epidote, apatite and spinel were not recorded by Krysowska-Iwaszkiewicz and Unrug whereas they were identified in this study.

The difference in the heavy mineral assemblages recorded by Krysowska-Iwaszkiewicz and Unrug (1967) and those found in the present study reflects the methodology of investigation. The effects of different investigation methods are particularly well expressed by the data on the chemical differentiation of garnets, tourmalines and chromian spinels, an aspect first considered in the present paper.

The heavy minerals recorded in this study are mainly stable and ultrastable. In this sense, the assemblages are comparable to those recorded in the Upper Cretaceous-Paleogene deposits of other areas of the Polish Outer Carpathians (see Winkler and Ślączka, 1992, 1994; Salata, 2003, 2004). However, proportions of individual mineral species vary both geographically and stratigraphically. Notably, garnet is the dominant heavy mineral in the Upper Cretaceous-Paleogene deposits of the adjacent part of the Magura Nappe (see Krysowska-Iwaszkiewicz and Unrug, 1967). More distinctly, there are differences in the types and amounts of subordinate heavy minerals and in the varieties of individual minerals. The latter aspect is reflected in the variability of optical features and chemical compositions of these minerals. Still, garnets recorded in this study are similar to those from coeval sediments of the northern part of Magura Nappe (Salata, 2003, 2004). Moreover, garnets with lower amounts of spessartine and andradite are in both areas more frequent in the Lower Paleocene than in the Upper Cretaceous deposits. A similar distribution was recognized in the Hauterivian-Middle Eocene deposits of the outer part of the Magura Nappe in Southern Moravia (Otava *et al*., 1997, 1998). Garnets from the southern part of Magura Nappe are different. In contrast to these recorded in the present study and those reported from the northern part of the Magura Nappe, they are impoverished in pyrope and enriched in the grossular molecule (see Salata, 2004). One cannot exclude that the recorded variability of garnets as regards their chemical compositions is in part due to their derivation from larger zoned crystals.

The heavy mineral assemblage of the Cergowa Sandstone is entirely different from that in coeval deposits of the Silesian Series (*cf.* Krysowska-Iwaszkiewicz and Unrug, 1967). The dominance of garnet makes it comparable to the deposits of the neighbouring part of the Magura Series.

The coexistence of etched garnet grains and non-etched apatite in individual samples suggest that etching of garnets occurred during sediment burial (see Morton and Hallsworth, 1999). The highly variable intensity of corrosion of the grains in individual samples may result from variable susceptibility to dissolution of particular garnet types, to different histories of the garnet populations (reworked from older sediments versus derived directly from crystalline rocks), as well as from variable permeability of the parent sediment and therefore a variable influence of porefluids during burial. Unfortunately, our data do not allow us to interpret the relative modification of the heavy mineral assemblages determined in this study by diagenesis.

PROVENANCE OF HEAVY MINERALS

The heavy minerals recorded in this study indicate derivation from a diverse set of rocks. The vertical variability of the assemblages indicate changes of provenance through time and suggest a complex geology of the source areas. Of the minerals identified in the rocks sampled, zircon and tourmaline are typically derived from non-metamorphic to low grade metamorphic granitic continental crust. Rutile comes from

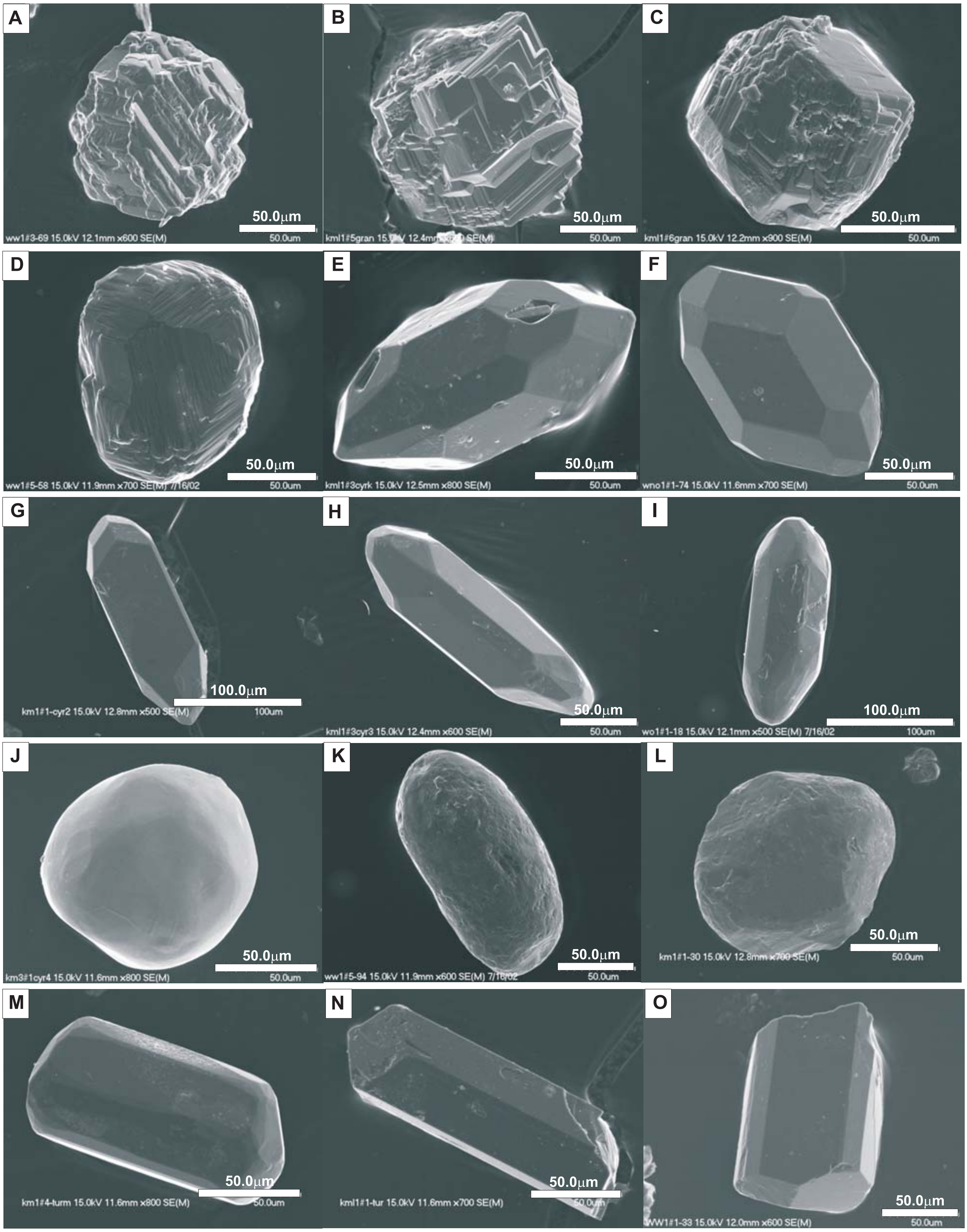

Fig. 10. SEM photomicrographs of characteristic forms of most common types of heavy minerals in the samples investigated

A–**D** garnets (A, B — intensely etched grains; C — euhedral crystal with only slight etching; D — rounded grain); **E**–**K** — zircons (E–H — euhedral crystals; H–I — crystal showing slight rounding; J–K — well rounded grains); **L** — rounded grain of monazite; **M**–**O** — tourmaline (M — slightly rounded grain; N, O — broken euhedral crystals); sample numbers shown in lower left corners of photographs high grade metamorphic rocks. Garnet and epidote derive mainly from medium- to very high grade metamorphic rocks. Apatite may originally be derived from various igneous and metamorphic rocks, monazite from metamorphic rocks and granites, and chromian spinel from ultramafic igneous rocks (Morton, 2003). Accordingly, non-metamorphic to low grade metamorphic and granitic rocks could have been the chief parent rocks of the sampled parts of the Lower Godula Beds and the Ciężkowice Sandstone, whereas medium- to very high grade metamorphic rocks prevailed among the parent rocks of the remaining sampled units. However, all these minerals may also have been reworked from older deposits. This particularly concerns the material of the Lower Godula Beds and the Ciężkowice Sandstone that show a zircon-tourmaline-rutile index (Hubert, 1962) of between 86 and 87% (*cf.* Unrug, 1968). Similar conclusions as regards the parent rocks of the deposits investigated in this study were earlier inferred from petrographic investigations of clastic components, e.g. by Wieser (1948, 1985) and Unrug (1968) and from the heavy mineral investigations of Krysowska-Iwaszkiewicz and Unrug (1967).

Additional information on the possible provenance of the heavy minerals is yielded by the data on the chemical composition of the minerals, particularly the garnets. Garnets contained in the samples from the Silesian Series indicate derivation chiefly from high grade metamorphic rocks. The most common grains, i.e. those containing more than 20% pyrope molecule and poor in Ca and Mg (type 1 and 3), are characteristic of granulite facies rocks where metasediments and/or orthopyroxene charnockite rock types are significant constituents (Sabeen *et al.*, 2002). The slightly less frequent garnets, i.e. these containing above 40% pyrope molecule (type 2), poor in Mn and showing various amounts of Ca, are considered to be characteristic of metamorphic rocks of eclogite facies (Morton, 1985; Deer *et al.*, 1992). The other garnet types that are also quite frequent in the examined samples, i.e. those showing a predominance of almandine and very low pyrope contents (type 4 and 5), and those showing variable amounts of Ca and increased Mn (type 9) are derived from rocks corresponding to garnet-mica schists (Deer *et al.*, 1992). However, garnets rich in the almandine molecule and containing significant amounts of spessartine (type 9) can also form in metamorphic rocks within contact aureoles, mainly hornfelses (Deer *et al.*, 1992). The subordinate garnets, similar to those of types 1 and 3, although rich in Ca (type 8), recorded in 5 samples (most numerous in wo2-1), are known from mafic granulites and recently were described from two-pyroxene charnockites (Sabeen *et al.*, 2002). The chromian pyropes (type 6) recorded in a small number of grains in three samples (wo2-1, km3-1 and km5-1) are characteristic of peridotite xenoliths (Coleman *et al.*, 1965; Deer *et al.*, 1992). The almandine garnets rich in spessartine molecules (type 11), recorded in two grains from sample wn1-1, may be derived from low grade metamorphic rocks such as metapelites or from acid pegmatites (Morton, 1984; Deer *et al.*, 1992). The derivation of garnets type 7 and 10 is not clear.

Some enrichment in spessartine and andradite content recorded in garnets from the Upper Godula Beds (Santonian) relative to these from the Upper Istebna Beds (Paleocene) suggests the presence of increased amounts of low to medium grade metamorphic rocks (i.e. amphibolites, amphibolite and mica schists, and gneisses) in the source area (*cf.* Salata, 2004). In contrast, derivation basically from high to medium grade metamorphic rocks is suggested for the Upper Istebna Beds. These features support observations by Unrug (1967) who argued that different petrographic parameters indicate a decrease in the amount of material derived from sedimentary and metamorphic rocks from the Lower Godula Beds to the Upper Istebna Beds. This decrease he interpreted as due to a gradual reduction in the sedimentary and metamorphic cover of the source areas, i.e. in the Silesian Cordillera. A similar trend was recognized by Unrug in the Upper Senonian-Paleocene deposits of the neighbouring part of the Magura Nappe, which also are considered as derived from the Silesian Cordillera. The increased influence of sedimentary rocks in the clastic material of the overlying Ciężkowice Sandstone was interpreted by Unrug as due to supply from a new source area, also situated on the Silesian Cordillera but east of the area previously eroded.

The almandine garnets that show very low pyrope contents and variable amounts of Ca (type 4 and 5), and those showing increased Mn contents (type 9), predominating in the samples from the Cergowa Sandstone, are characteristic of garnet-mica schists (Deer *et al.*, 1992). Garnets rich in the spessartine molecule, being relatively numerous in samples from this lithostratigraphic unit, suggest that part of the clastic material could have been derived from hornfelses.

Tourmalines examined in this study indicate provenance mainly from rocks corresponding to different pelites and psammites as well as from Li-poor granitoids and their associated pegmatites and aplites (Fig. 7). Individual grains correspond to tourmalines from hydrothermally altered granites, calc-silicate rocks, and pelites. One tourmaline grain in sample wo1-2 and one in ww1-1 occur in the field of low-Ca meta-ultramafics and Cr, V-rich metasediments. Grains located on the diagram of Henry and Guidotti (1985) in the field of pelites and psammites, which coexist with an Al-saturating phase (Fig. 7), show small to intermediate contents of Ti and Ca. Such compositions suggest provenance from schists and gneisses of amphibolite to granulite facies.

The chemical composition of tourmalines in individual samples (e.g. Fig. 7A) indicates, as does the composition of the garnets, their original provenance from different parent rocks. Such origin is also indicated by the features of the tourmalines recorded optically.

Zircons in all the samples examined also show variability. The euhedral and subhedral shape of some grains suggests direct provenance from granitoid rocks (Speer, 1980). The rounded grains imply a polycyclic history, and could have been supplied from schists and gneisses formed from sedimentary protoliths (Deer *et al.*, 1992) and, at least in part, were reworked directly from older sedimentary rocks. The elongate, frequently euhedral grains showing resorption borders could have been derived from pyroclastic rocks (Mange and Maurer, 1992).

Chromian spinels are typical accessory minerals of mafic and ultramafic rocks. For a long time, detrital chromian spinels were considered as an ideal source of information on the lithology and geotectonic location of their parent rocks. These parameters were interpreted from diagrams proposed by Irvine (1967) and Dick and Bullen (1984). According to these diagrams (Figs. 7 and 8), the spinels examined in the present paper are associated with those characteristic of peridotites formed in mid-ocean ridges and island arcs (Alpine-type peridotites). The values of atomic ratios of $Mg/(Mg + Fe^{2+})$ ranging between 0.25–0.7 in the grains analysed together with the atomic ratio of $Cr/Cr + Al)$ ranging between 0.28–0.79 coincide with those of the spinels of a marginal basin lithosphere and island-arc-associated rocks (Cookenboo *et al*., 1997). However, according to Power *et al*. (2000), all interpretations of the origin of chromian spinels based on the diagrams of Irvine (1967) and Dick and Bullen (1984) are doubtful.

The heavy mineral assemblage of the Cergowa Sandstone indicates provenance of its clastic material from an entirely different source area to that of coeval deposits (Krosno Beds) of the neighbouring part of the Silesian Series. The close similarity of this assemblage to those recorded in the northern part of the Magura Nappe indicates also the similar geological character of their source areas (see Unrug, 1968).

CONCLUSIONS

Several heavy mineral assemblages, differing particularly in their content of garnet, rutile, tourmaline and zircon, have been recognized in the deposits examined. The assemblages and their stratigraphic distribution generally correspond to those recognized in these deposits by Krysowska-Iwaszkiewicz and Unrug (1967).

Apatite, monazite, chromian spinel and epidote were identified in the present study for the first time in this succession. Apatite occurs subordinately (a few to 15%) in all samples, monazite is present only in samples from the Silesian Series where it amounts 1–5%, whereas chromian spinel and epidote occurs only as sporadic grains in some samples of both the Silesian Series and the Cergowa Sandstone.

The heavy mineral suites recorded in the samples examined, together with the physical and chemical features of the mineral grains, indicate derivation of the clastic material from a variety of crystalline and sedimentary rocks. Metamorphic rocks of granulite and partly eclogite facies, with subordinate granitoids and hornfelses, appear to be the chief crystalline parent rocks of the Middle and Upper Godula Beds and Upper Istebna Sandstone sampled. Non-metamorphic to low grade metamorphic rocks of granitic continental crust (granitoids and corresponding pegmatites and aplites as well as pelites and psammites) were the primary crystalline parent rocks of the Lower Godula Beds and the Ciężkowice Sandstone sampled.

Garnets contained in the samples from the Silesian Series indicate derivation chiefly from metamorphic rocks of granulite facies where metasediments and/or orthopyroxene charnockites were significant constituents, together with rocks of eclogite facies, garnet-mica schists, rocks of contact aureoles and to a lesser extent from mafic granulites, two-pyroxene charnockites, peridotite xenoliths and pelites.

Mica-garnet schists, subordinate granitoids and their pegmatites were probably the main crystalline parent rocks of the Cergowa Sandstone. The rare chromian pyropes and spinels suggests provenance of a small part of the clastic material of these units from mafic and ultramafic rocks. Peridotite xenoliths appear to be their most probable crystalline parent rocks.

The co-occurrence of rounded and fresh, unabraded grains (including euhedral crystals) suggests a mixed provenance of the clastic material, both from crystalline and older sedimentary rocks. The unabraded grains suggest that outcrops of crystalline rocks lay in close proximity to the sites of deposition of the deposits examined.

The vertical distribution of the heavy mineral assemblages is generally consistent with the earlier observations by Unrug (1968) suggesting progressive unroofing of the source area (Silesian Cordillera).

The similarity of garnets recorded in the Upper Cretaceous-Paleogene deposits of the Silesian Nappe to those of coeval sediments of the northern part of Magura Nappe, both considered as derived from the Silesian Cordillera, supports the idea of an intrabasinal ridge.

Acknowledgments. This work was supported by the State Committee for Scientific Research (KBN grant 6 P04D 083 21 to J. Grzebyk) and the Jagiellonian University grant DS/V/ING/3 to S. Leszczyński. D. Salata is thanked for discussion. Special thanks are extended to reviewers Drs A. C. Morton and R. Aubrecht for their valuable remarks. A. C. Morton is additionally thanked for linguistic corrections.

REFERENCES

ATHERTON M. P. and EDMUNDS W. M. (1966) — An electron microprobe study of some zoned garnets from metamorphic rocks. Earth Planet. Sc. Let., **1**: 185–193.

COLEMAN R. G., LEE D. E., BEATTY L. B. and BRANNOCK W. W. (1965) — Eclogites and eclogites: their differences and similarities. Bull. Geol. Soc. Am., **76**: 483–580.

COOKENBOO H. O., BUSTIN R. M. and WILKS K. R. (1997) — Detrital chromian spinel compositions used to reconstruct the tectonic setting of provenance: implication for orogeny in the Canadian Cordillera. J. Sedim. Res., **67** (1): 116–123.

DEER W. A., HOWIE R. A. and ZUSSMAN J. (1992) — An introduction to the rock-forming minerals. 2nd ed., Longman Sc. Technic. Harlow.

DICK H. J. B. and BULLEN T. (1984) — Chromian spinel as petrogenetic indicator in abyssal and alpine-type peridotites and spatially associated lavas. Contr. Miner. Petrol., **86**: 54–76.

HENRY D. J. and GUIDOTTI C. V. (1985) — Tourmaline as a petrogenetic indicator mineral: an example from the staurolite-grade metapelites of NW Maine. Am. Miner., **70**: 1–15.

HUBERT J. F. (1962) — A zircon-tourmaline-rutile maturity index and the interdependence of the composition of heavy mineral assemblages with the gross composition and texture of sandstones. J. Sedim. Petrol., **32**: 440–450.

IRVINE T. N. (1967) — Chromian spinel as a petrogenetic indicator. Part 2, Petrologic applications. Canad. J. Earth Sc., **4**: 71–103.

IRVINE T. N. (1974) — Petrology of the Duke Island ultramafic complex, southeastern Alaska. Geol. Soc. Am., Memoir, **138**.

KRYSOWSKA-IWASZKIEWICZ M. and UNRUG R. (1967) — Heavy minerals in the flysch of the Polish Western Carpathians. Bull. Acad. Pol. Sc., Série Sc. Géol. Géogr., **15**: 57–64.

KSIĄŻKIEWICZ M. (1956) — Geology of the Northern Carpathians. Geol. Runds., **45**: 369–411.

KSIĄŻKIEWICZ M. (1960) — Pre-orogenic sedimentation in the Carpathian Geosyncline. Geol. Runds., **50**: 8–31.

KSIĄŻKIEWICZ M. (1972) — Budowa Geologiczna Polski. v. 4. Wyd. Geol.

LOPEZ RUIZ J. (1976) — The zoning of garnets as an indicator of the P-T history of their host rocks. Ann. Soc. Géol. Belg., **99**: 337–346.

LOWE D. R. (1982) — Sediment gravity flows: II. Depositional models with special reference to the deposits of high-density turbidity currents. J. Sed. Petrol., **52**: 279–297.

MANGE M. A. and MAURER H. F. W. (1992) — Heavy Minerals in Colour. Chapman and Chall, London.

MORTON A. C. (1984) — Stability of detrital heavy minerals in Tertiary sandstones from the North Sea Basin. Clay Miner., **19**: 287–308.

MORTON A. C. (1985) — A new approach to provenance studies: electron microprobe analysis of detrital garnets from Middle Jurassic sandstones of the northern North Sea. Sedimentology, **32**: 553–566.

MORTON A. C. (1991) — Geochemical studies of detrital heavy minerals and their application to provenance studies. In: Developments in Sedimentary Provenance Studies (eds. A. C. Morton, S. P. Todd and P. D. W. Haughton). Geol. Soc. London, Spec. Publ., **57**: 31–45

MORTON A. C. (2003) — Heavy Minerals. In: Encyclopedia of Sediments and Sedimentary Rocks (eds. G. V. Middleton, M. J. Church, M. Coniglio, L. A. Hardie and F. J. Longstaffe): 356–358. Kluwer Acad. Publ., Dordrecht.

MORTON A. C. and HALLSWORTH C. R. (1999) — Processes controlling the composition of heavy mineral assemblages in sandstones. Sediment. Geol., **124**: 3–29.

OTAVA J., KREJČI O. and SULOVSKÝ P. (1997) — První výsledki studia chemismu gránatů pískovců račanské jednotky magurského flyse. Geol. Výz. Moravy a Slezska (Brno), **4**: 29–31.

OTAVA J., SULOVSKÝ P. and KREJČI O. (1998) — Výsledki studia detritýckich gránatů křidových sedimentů račanské jednotky magurské skupiny. Geol. Výz. Moravy a Slezska (Brno), **4**: 29–31.

PAUL Z., RĄCZKOWSKI W., RYŁKO W. and TOMAŚ A. (1996) — Budowa geologiczna zachodniej części Karpat polskich. Przewodnik LXVII Zjazdu Polskiego Towarzystwa Geologicznego (67th Annual Meeting of Polish Geological Society): 8–31. Państ. Inst. Geol., Kraków.

POWER M. R., PIRRIE D., ANDERSON J. C. Q. and WHEELER P. D. (2000) — Testing the validity of chrome spinel chemistry as a provenance and petrogenetic indicator. Geology, **28**: 1027–1030.

SABEEN H. M., RAMANUJAM N. and MORTON A. C. (2002) — The provenance of garnet: constraints provided by studies of coastal sediments from southern India. Sediment. Geol., **152**: 279–287.

SALATA D. (2003) — Charakterystyka mineralogiczno-geochemiczna frakcji ciężkiej górnokredowo-paleoceńskich piaskowców środkowej części płaszczowiny magurskiej. Unpub. Ph.D. Thesis, Jagiel. Univ., Kraków.

SALATA D. (2004) — Detrital garnets from the Upper Cretaceous–Paleocene sandstones of the Polish part of the Magura Nappe and the Pieniny Klippen Belt: chemical constraints. Ann. Soc. Geol. Pol., **74** (3): 351–364.

SŁOMKA T. (1995) — Deep-marine siliciclastic sedimentation of the Godula Beds, Carpathians (in Polish with English summary). Prace Geol. Oddział PAN w Krakowie, **139**.

SPEER J. A. (1980) — Zircon. Min. Soc. Amer. Rev. Mineral., **5**: 67–112.

UNRUG R. (1963) — Istebna Beds — a fluxoturbidity formation in the Carpathian Flysch. Rocz. Pol. Tow. Geol., **33** (1): 51–92.

UNRUG R. (1968) – The Silesian cordillera as the source of clastic material of the flysch sandstones of the Beskid Śląski and Beskid Wyspowy ranges (Polish Western Carpathians). Rocz. Pol. Tow. Geol., **38**: 81–164.

UNRUG R. ed. (1979) — Karpaty Fliszowe między Olzą a Dunajcem. Wyd. Geol., Warszawa.

WIESER T. (1948) — Crystalline exotic blocks in the Silesian Cretaceous of the Wadowice area. Rocz. Pol. Tow. Geol., **18** (1): 109–150.

WIESER T. (1985) — Fundamental researches in the western part of the Polish Carpathians. Guide to Excursion 1, Carpatho-Balkan Geol. Assoc., XIII Congress, Poland, Geol. Inst., Warszawa.

WINKLER W. and ŚLĄCZKA A. (1992) — Sediment dispersal and provenance in the Silesian, Dukla and Magura flysch nappes (Outer Carpathians, Poland). Geol. Rundschau, **81**: 371–382.

WINKLER W. and ŚLĄCZKA A. (1994) — A Late Cretaceous to Paleogene geodynamic model for the Western Carpathians in Poland. Geol. Carpath., **45** (2): 71–82.