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High (ultrahigh) pressure metamorphic terrane rocks as the source of the detrital garnets from the Middle Jurassic sands and sandstones of the Cracow Region (Cracow-Wieluń Upland, Poland)

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ABSTRACT:

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The Middle Jurassic (Upper Bathonian/Lower Callovian) sands and sandstones of the Cracow–Wieluń Upland contain detrital garnets with high contents of the pyrope molecule (30–73 mol %). The predominance of detrital pyrope garnets, and inclusions represented mainly by omphacite and kyanite, show that the garnets were derived from high (ultrahigh) pressure (H/UHP) metamorphic terrane rocks (garnet peridotites, eclogites and granulites). Their source is unknown. The Moldanubian Zone of the Bohemian Massif is closely comparable. However, the terranes between this zone and the Cracow–Wieluń Upland are dominated by almandine garnets. The relatively low proportion of almandine garnets in the examined samples indicates that transport of the detrital material could not have been from a far distant source as the garnet assemblage would otherwise be strongly dominated by almandine. A less distant possible source could have been the Góry Sowie Mts., which incorporate UHP/HP metamorphic rocks, but the exposed areal extent of these rocks is too small. It is possible that larger portions of these metamorphic rocks are buried beneath the Cenozoic cover and might have earlier represented a larger source area. Reworking of the entire heavy mineral spectra from older clastics is improbable because of the low maturity of the heavy mineral assemblages (higher proportion of less stable minerals). The source area therefore remains unknown. Most probably it was formed by primary crystalline complexes of lower crust to mantle origin, outcrops of which were not far distant from the area of deposition. Similar detrital garnet compositions were also recorded in the Outer Western Carpathians (Flysch Zone, Pieniny Klippen Belt), i.e. the crustal segments which formed the Silesian and Magura cordilleras; the Czorsztyn Swell was also formed by similar rocks.

Key words: Detrital garnets; Provenance analysis; Jurassic; Polish platform.

INTRODUCTION

Heavy mineral study is a tool of palaeogeographic research that complements facies and palaeobiogeographic data. Middle Jurassic sands and sandstones in the southern part of the Cracow–Wieluń Upland were analysed for heavy minerals to compare the assemblages with those published from the Tethyan Jurassic of the

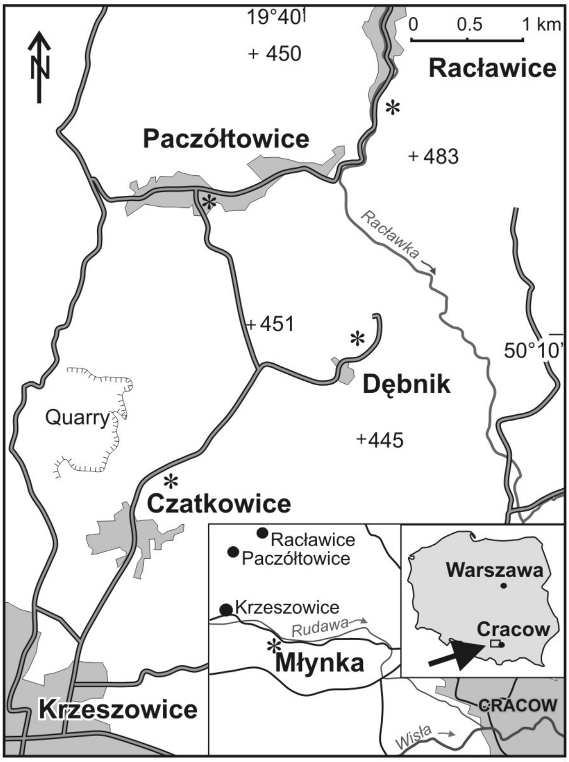
Western Carpathians (Łoziński 1956, 1957, 1966; Aubrecht 1993, 2001), Eastern Alps (Faupl 1975) and from the Tethyan margin of the Bohemian Massif (Štelcl *et al.* 1972, 1977). The crucial problem to be solved by the previous research was the provenance of the individual crustal blocks of the Tethyan units before the Jurassic rifting.

The results from the Western Carpathian Jurassic summarized from the above-mentioned literature show big differences in the heavy mineral spectra between the internides and the externides. The externides are dominated by garnet, accompanied by zircon, rutile and tourmaline, with subordinate amounts of other minerals. The internides are characterized by a predominance of tourmaline and apatite, accompanied by zircon and rutile. The results from the margin of the Bohemian Massif correlate well with the results from the externides.

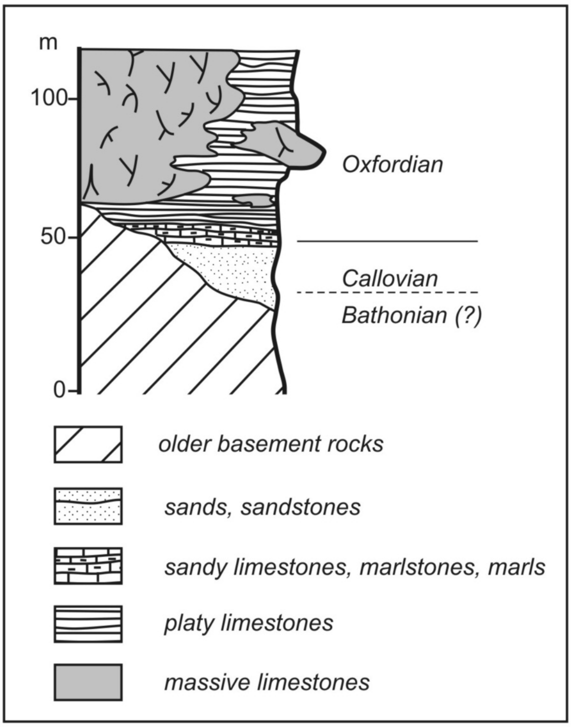
GEOLOGICAL SETTING

Transgressive Middle Jurassic sediments of the Cracow region (Cracow–Wieluń Upland, Poland) rest on the erosion surface formed on older Palaeozoic and Mesozoic rocks. In some places older Middle Jurassic continental clays (mainly lacustrine) are preserved (Kopik 1997). The Middle Jurassic commences with basal arenites (quartz sands and sandstones; Text-fig. 2), including some conglomeratic horizons. The basal arenites do not contain any fossils and are most probably of fluvial origin (Dżułyński 1950). The uneven basement topography is reflected by variable thicknesses of the arenites, from 0 to around 10 m (Hoffmann and Gradziński 2004). The arenites grade up into sands, sandstones and sandy limestones with marine faunas. The overlying marine clastics represent the Lower Callovian (Giżejewska and Wieczorek 1976; Ogg *et al*. 1991; Dembicz *et al*. 2006). Thus, the underlying basal arenites are most probably of Bathonian or earliest Callovian age.

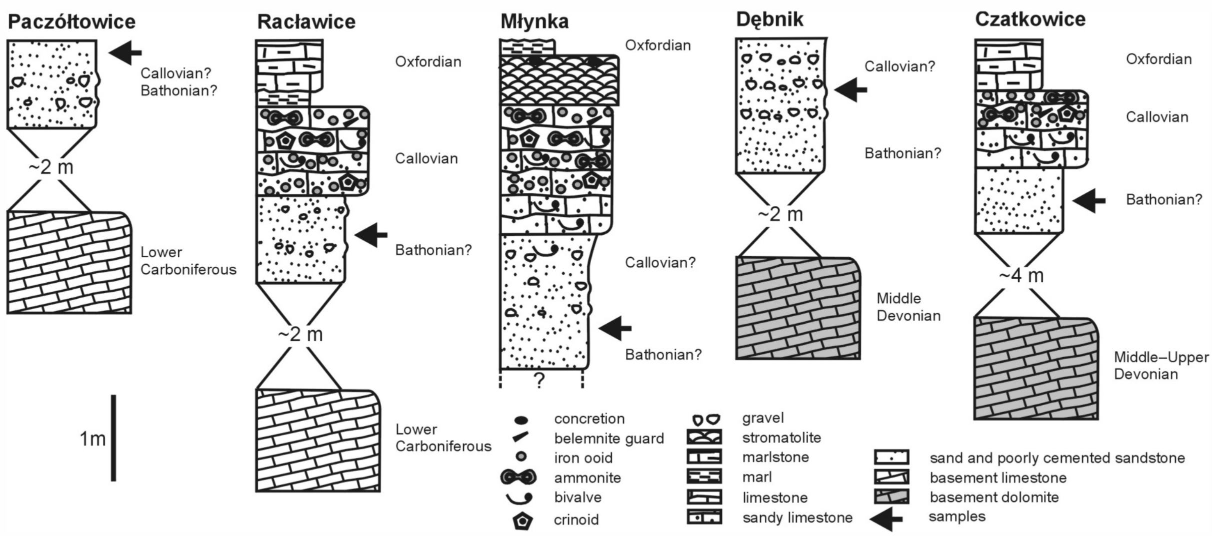
Results of heavy mineral analysis of Middle Jurassic sediments of the Cracow region were published by Przybyłowicz (1958) and Krysowska (1960, 1962). Przybyłowicz (1958) reported heavy mineral spectra with variable amounts of garnet, tourmaline, rutile and zircon, with subordinate amounts of other minerals; Krysowska (1960, 1962) mentioned similar heavy mineral spectra but mostly dominated by garnet. This paper focuses on the provenance of the detrital garnets in these assemblages. The following localities were studied (Text-fig. 1): quarry near Czatkowice beside the road to Dębnik (N 50°13’16.5”, E 19°47’41.3”),



Text-fig. 1. Positions of the sampled sites (indicated by asterisks)



Text-fig. 2. Jurassic deposits of the Cracow Region. General geological section; after Matyszkiewicz and Krajewski (2007)



Text-fig. 3. Studied sections – Młynka simplified and modified after Dembicz et al. (2006); Czatkowice based on Mariusz Hoffmann unpublished data; Racławice based on Andrzej Górny unpublished data

Dębnik Quarry (N 50°09'52.1", E 19°40'17.4"), Paczółtowice (N 50°10'33", E 19°39'22.9"), Młynka (N 50°06'33.5", E 19°41'16.4") and Racławice (N 50°11'7.8", E 19°40'34.5"). In the Czatkowice and Dębnik localities the arenites overlie Devonian carbonates whereas in Paczóltowice and Racławice they overlie Lower Carboniferous (Mississippian) limestones (Text-fig. 3). The basement to the Middle Jurassic deposits in Młynka is not known but it probably consists of Carboniferous rocks. The samples were taken from structureless yellowish sands to poorly lithified sandstones, free of any faunal relics (most probably the fluvial part of the formation).

MATERIALS AND METHODS

From each locality, one 2–3 kg sand (to sandstone) sample was taken. The sandstones are soft and only some crushing by hammer was needed. The heavy minerals were separated in heavy liquids (bromoform, density ca 2.8). The 0.08–0.25 mm fraction was studied by transmitted light; the whole fraction was also examined under a binocular microscope. Percentage ratios of the heavy mineral assemblages were determined by ribbon point counting. The opaque minerals in all samples were dominated by diagenetic Fe-minerals – limonite and pyrite, which are insignificant from the point of view of clastic provenance. Therefore, the results presented in this paper are based only on the translucent heavy minerals.

The chemical compositions of the garnets and their inclusions (Tables 2, 3) were determined using a CAMECA SX-100 electron microprobe at the State Geological Institute of Dionýz Štúr in Bratislava, Slovakia. The analytical conditions were as follows: 15 kV accelerating voltage and 20 nA beam current, with a peak counting time of 20 seconds and a beam diameter of 2–10 µm. Raw counts were corrected using a PAP routine.

RESULTS

Percentage ratios of the heavy minerals

The heavy mineral spectra are slightly dominated by garnet but the contents of zircon, rutile and tourmaline are also high, which slightly contradict the previous results of Krysowska (1960, 1962) but are in accordance with those of Przybyłowicz (1958). These four minerals were accompanied by lesser amounts of staurolite, apatite, kyanite, titanite, hornblende and epidote (Table 1, Text-figs 4, 5). The heavy mineral spectra show variable ZTR indexes (Table 1), from 39% in the Młynka sample to 86% in the Dębnik sample. This index represents the percentage of the ultrastable trinity zircon-tourmaline-rutile in the heavy mineral spectrum (Hubert 1962). It reflects the overall maturity of the sediment and also indicates a possible redeposition from older sediments. The higher the index, the more mature is the sedimentary material. The index increases with longer transport and abrasion of the detrital grains, but intrastratal dissolution also plays a significant role. Intrastratal dissolution is influenced by burial depth (Morton 1987) as well as by organic acids present in the sediment (Hansley 1987).

locality	minerals %										ZTR index
	Grt	Zrn	Rt	Tur	Ap	Hbl	Ttn	St	Ky	Ep	
Czatkowice	21	35	12	24	1	0	0	4	+	2	71
Paczółtowice	36	13	18	23	1	0	0	5	+	3	54
Racławice	28	20	36	7	5	0	0	1	0	3	63
Dębnik	3	19	26	41	1	1	0	6	0	3	86
Młynka	56	20	14	5	1	0	2	2	+	0	39

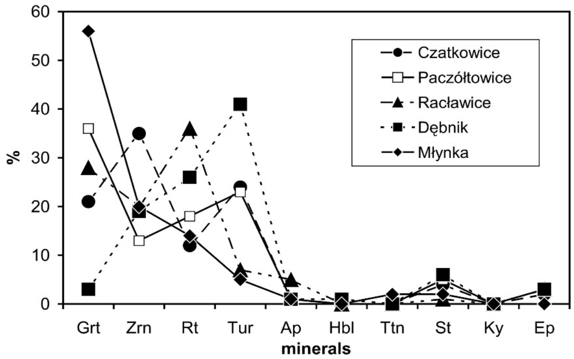
Explanations: Grt – garnet, Zrn – zircon, Rt – rutile, Tur – tourmaline, Ap – apatite, Hbl – hornblende, Ttn – titanite, St – staurolite, Ky – kyanite, Ep – epidote. All symbols for rock-forming minerals in this paper were used according to Kretz (1983)

Table 1. Percentages of heavy minerals in the examined samples

Composition of the detrital garnets

Garnets are important in the interpretation of the genesis of igneous and metamorphic rocks as (1) they are used for the pressure-temperature-time history of the host rock; (2) they are very good indicators of the parental rock type; and (3) they are useful for defining the metamorphic facies. "Pyrope-almandine-grossular" and "pyrope-almandine-spessartine" triangular diagrams (Méres 2008, 2009 – see Text-figs 6, 7) provide a good classification of garnets from the UHP/HP, granulite and amphibolite metamorphic facies, according to their chemical compositions.

To construct the original triangular diagrams, the compositions of garnets from various metamorphic conditions were plotted (Aubrecht *et al.* 2009; Méres 2008, 2009). Representative analyses of the garnets from various rocks (kimberlites, garnet peridotites, UHP eclogites, eclogites, HP granulites, LP granulites, retrograde eclogites), were taken from the following papers: garnets from HP granulites in the Góry Sowie Mts. (O'Brien *et al.* 1997); garnets from peridotites, eclogites and granulites from the Bohemian Massif (Messiga and Bettini 1990; Nakamura *et al.* 2004; Seifert and Vrána 2005; Vrána *et al.* 2005; Medaris *et al.* 2006a,b; Janoušek *et al.* 2006, 2007; Racek *et al.* 2008); garnets from HP and UHP eclogites and



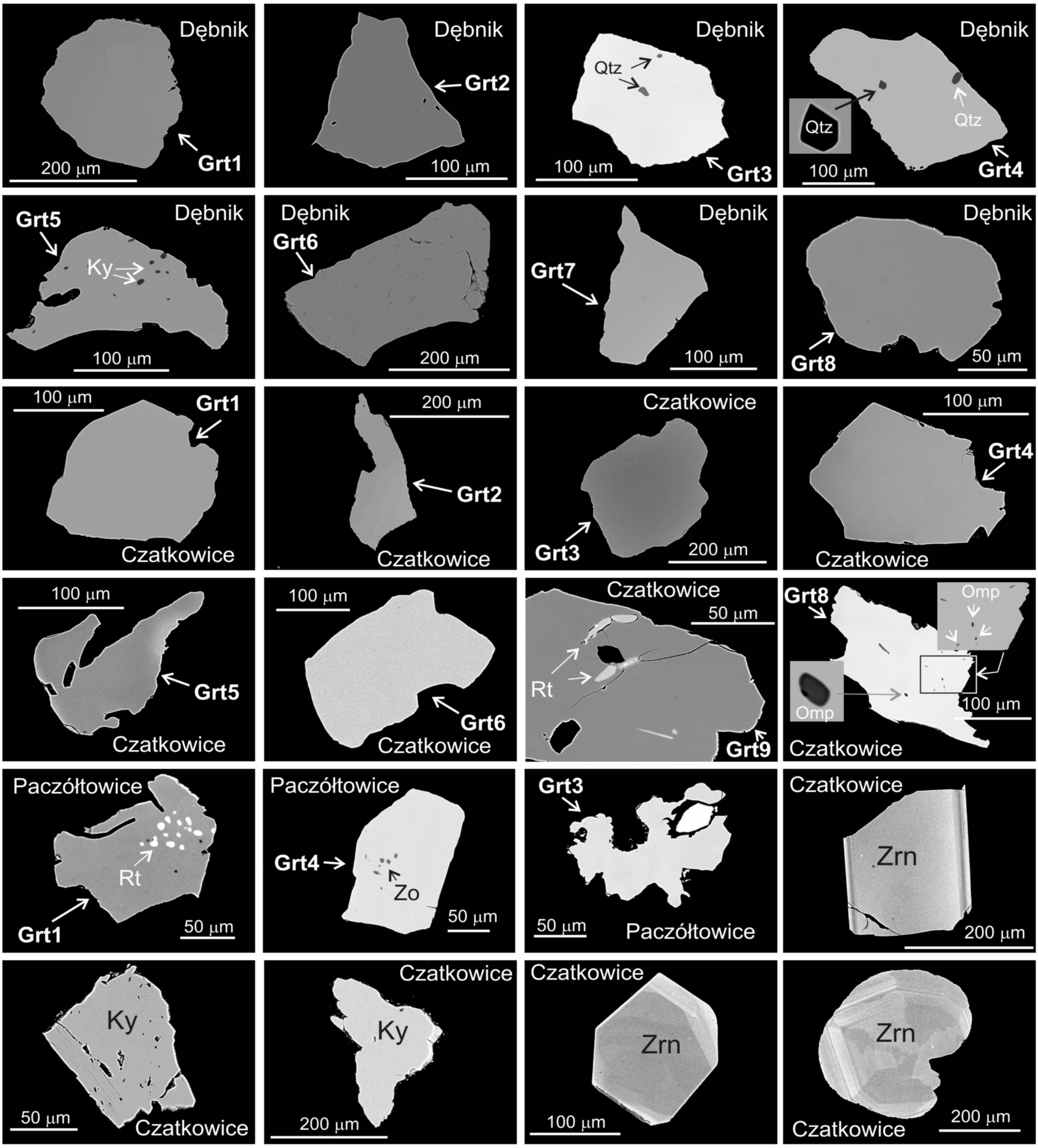
Text-fig. 4. Line diagram showing percentages of heavy minerals in the examined samples

garnet peridotites from the Norway Western Gneiss Region (Krogh Ravna and Terry 2004); garnets from kimberlites (Schulze 1997); garnets from eclogites with inclusions of diamond (Schulze 1997); garnets from HP granulites, from UHP eclogites with inclusions of coesite and from garnet peridotites from the Saxonian Erzgebirge and Granulitgebirge (Massonne and Bautsch 2004). The resulting triangular diagram was divided to three sectors – A, B, C, with the latter subdivided into the sectors C1 and C2 (see Text-figs 6, 7, white fields): (A) garnets from high pressure (HP) and ultrahigh pressure (UHP) conditions; (B) garnets from HP eclogite and HP granulite facies conditions; and (C) garnets from amphibolite facies conditions: Subsector C1 represents a transitional subgroup metamorphosed under transitional P-T conditions between the granulite and amphibolite facies conditions and Subsector C2 represents a subgroup of amphibolite facies conditions.

Electron microprobe analyses of the detrital garnets from Młynka (9 analyses from the grain cores), from Dębnik Quarry (9 analyses from the cores and rims), from Czatkowice (10 analyses from the cores), from Racławice (11 analyses from the cores) and from Paczółtowice (9 analyses from the cores) show significant variation in chemistry. Variation of garnet composition is mainly in the relative proportions of the pyrope, almandine, grossular, spessartine and uvarovite end-member components (Text-figs 6, 7; Table. 2). Chemical zoning across the profiles of the detrital garnets was not recognized; the garnets are homogenous (Text-fig. 5; Table 2).

The detrital garnets can be divided to six groups (within the previously defined sectors A, B and C) according to their composition (Text-figs 6, 7; Table 2):

(1) Detrital garnets with the highest contents of the pyrope molecule (> 70 mol %), with relatively low contents of almandine (~ 15 mol %) and grossular (~ 12 mol %) and a very low spessartine component (< 1 mol %). Typical of this group is the presence of uvarovite (0.7–1 mol %). These types of garnets were

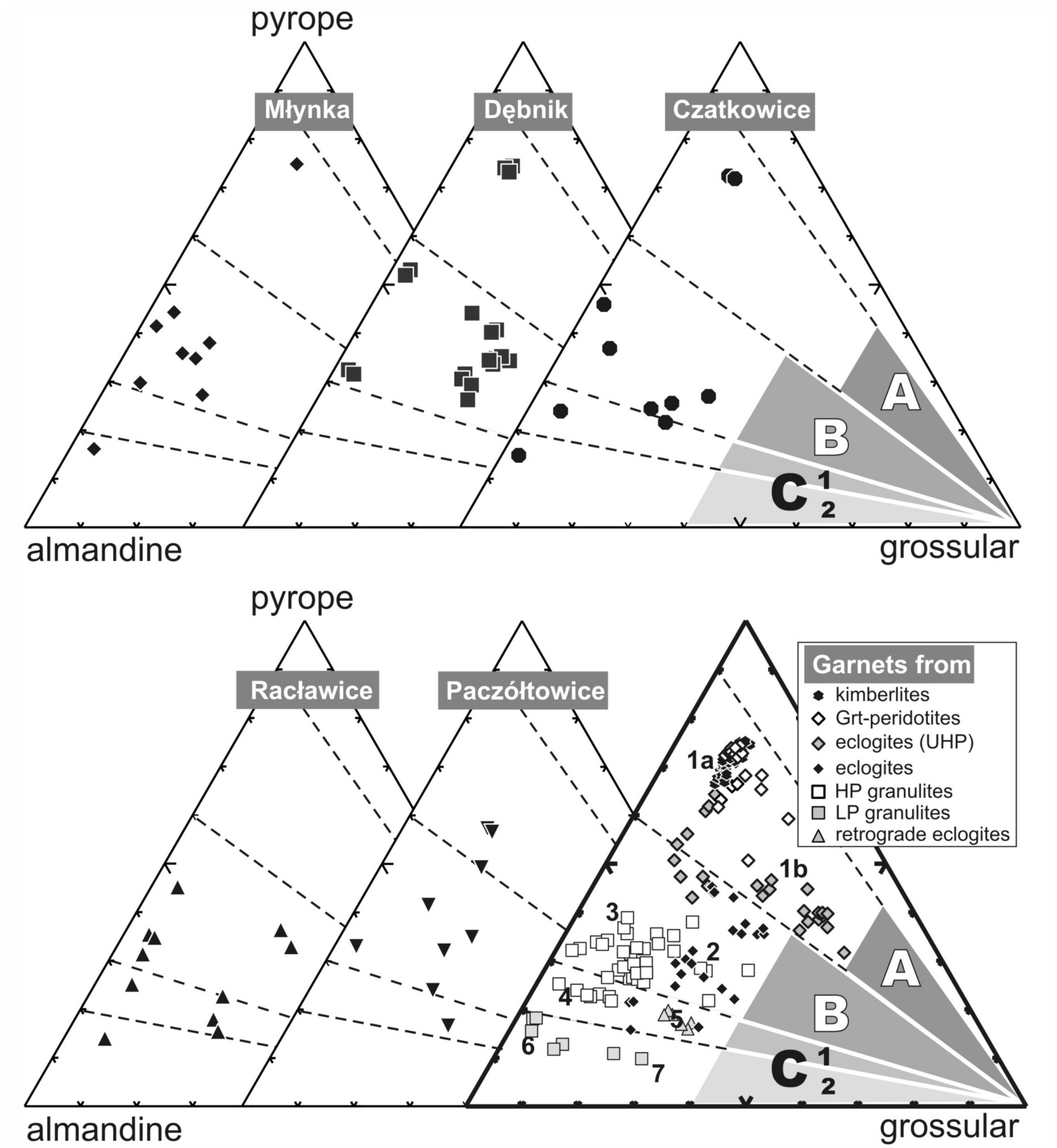


Text-fig. 5. Back-scattered electron (BSE) images of the detrital garnets, their inclusions, detrital kyanites and detrital zircons from sands and sandstones of the Cracow Region

identified at Młynka, Dębnik Quarry and Czatkowice (Text-figs 6, 7, A sector).

(2) Detrital garnets with high contents of the pyrope molecule (40–56 mol %), high almandine contents (35–45 mol %) and with high proportions of the grossular molecule (15–31 mol %). The spessartine content is less than 1 mol %. These garnets were identified at all the localities studied (Text-figs 6, 7, B sector, position around No. 2).

(3) Detrital garnets with lower contents of the pyrope molecule (30–52 mol %) than the previous groups, but with higher contents of almandine (50–60 mol %), a low proportion of grossular (~ 5 mol %) and very low contents of spessartine (< 2 mol %) molecules. This type of garnet was found at all the localities studied (Text-figs. 6, 7, B sector, position around No. 3).

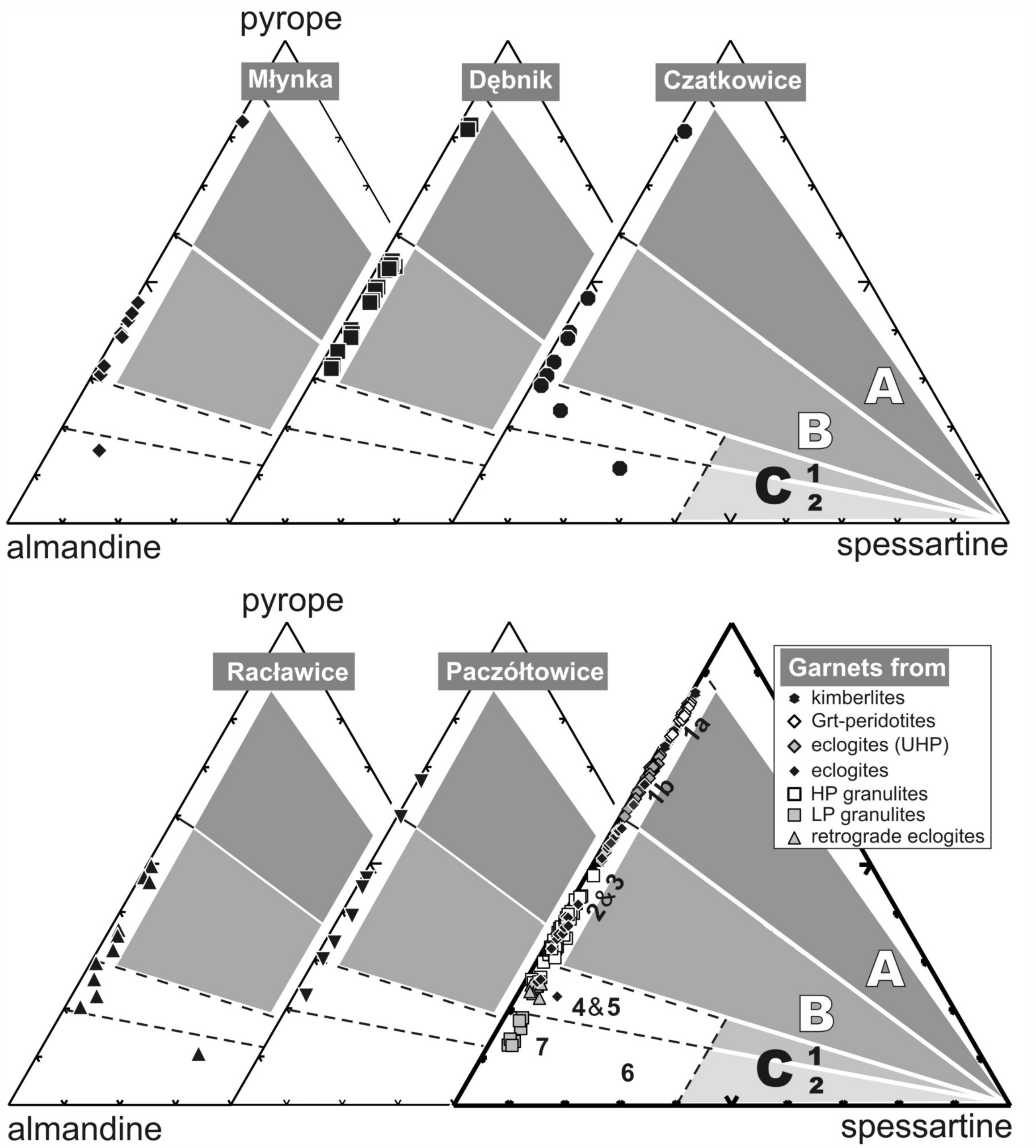


Text-fig. 6. Composition of the detrital garnets from the Middle Jurassic sands and sandstones of the Cracow Region and garnets from UHP/HP metamorphic rocks in the "pyrope-almandine-grossular" classification diagrams (Méres 2008, 2009): Explanations: **Sector A.** White field – garnets from UHP/HP conditions. Position around No. 1a – Grt derived from UHP eclogites, garnet peridotites and kimberlites. Position around No. 1b – Grt derived from UHP eclogites; **Sector B.** White field – garnets from eclogite and granulite facies conditions. Position around No. 2 – Grt derived from HP eclogites and HP mafic granulites. Position around No. 3 – Grt derived from HP felsic and intermediate granulites; **Sector C.** White field – garnets from amphibolite facies conditions: Sector C1 – transitional subgroup between granulite and high amphibolite facies conditions. Position around No. 4 – Grt derived from gneisses metamorphosed under P–T transitional to granulite and amphibolite facies conditions. Position around No. 5 – Grt derived from amphibolites metamorphosed under transitional P–T granulite to amphibolite facies conditions. Sector C2 – subgroup amphibolite facies conditions. Position around No. 6 – Grt derived from gneisses metamorphosed under amphibolite facies conditions. Position around No. 7 – Grt derived from amphibolites metamorphosed under amphibolite facies conditions. In the C2 subgroup Grt from many other sources integrate, e.g. Grt from igneous rocks (granitoids, syenites), Grt from HP/LT metamorphic rocks, Grt from contact-metamorphosed rocks. Grey fields – immiscibility gap of Grt end-members composition: A – from UHP/HP conditions, B – from eclogite and granulite facies conditions, C – from amphibolite facies conditions

(4) Detrital garnets with high almandine contents (60–75 mol %), low pyrope contents (~ 20 mol %) and low contents of spessartine (< 10 mol %). Contents of grossular were less than 6 mol %. A few garnets of this type were identified at the Czatkowice and Racławice localities (Text-figs. 6, 7, C 1sector, position around No. 4).

(5) Detrital garnets with high almandine contents (40–60 mol %), relatively low pyrope contents (20–30 mol %) and very low contents of spessartine (< 3 mol %). Contents of grossular were 6–26 mol %. Only a few garnets of this type were identified at the Paczółtowice and Racławice localities (Text-figs. 6, 7, C1 sector, position around No. 5).

(6) Detrital garnets with high almandine contents (40–60 mol %), low pyrope contents (10–15 mol %) and high contents of spessartine (9–28 mol %). Contents of grossular were less than 6 mol % (Text-figs 6, 7, C 2 sector, position around No. 6). Only three such detrital garnets grains were found, at the Młynka, Czatkowice and Racławice localities.



Text-fig. 7. Composition of the detrital garnets from the Middle Jurassic sands and sandstones of the Cracow Region and garnets from UHP/HP metamorphic rocks in the "pyrope-almandine-spessartine" classification diagrams (Méres 2008, 2009). For explanations see Text-fig. 6

locality	Młynka				Dębnik				Czatkowice	
grain	Grt 2 c	Grt 3 c	Grt 4 c	Grt 7 c	Grt 2 r	Grt 4 c	Grt 5 c	Grt 6 r	Grt 2 c	Grt 6 r
Grt source	A	C 2-6	B 3	B 3	B 2	A	B 3	B 2	C 2-6	B 3
SiO_2	42.47	37.93	39.16	39.96	40.57	43.00	39.21	39.78	37.51	39.30
TiO_2	0.17	0.02	0.01	0.03	0.00	0.00	0.00	0.00	0.00	0.00
Al_2O_3	21.56	21.38	21.99	22.43	23.00	22.12	22.40	22.07	21.16	22.19
Cr_2O_3	2.82	0.02	0.00	0.07	0.06	2.21	0.00	0.00	0.00	0.01
Fe_2O_{3calc}	0.55	0.14	0.18	0.36	0.04	0.18	0.55	0.00	0.00	0.00
FeO_{calc}	7.06	32.92	29.78	24.30	16.76	7.59	20.45	20.75	27.78	25.19
MnO	0.41	4.00	0.72	0.42	0.43	0.45	0.54	0.49	10.34	0.46
MgO	20.92	3.71	7.66	11.73	10.77	20.96	13.67	7.64	2.80	9.48
CaO	4.81	1.40	2.08	1.69	9.46	4.68	1.19	9.59	0.86	3.07
Total	100.76	101.52	101.58	100.98	101.09	101.19	98.01	100.31	100.46	99.69
	formula normalization to 12 oxygens									
Si	3.000	2.998	3.001	2.996	2.996	3.019	2.981	3.025	3.015	3.014
Ti	0.009	0.001	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000
Al	1.795	1.992	1.986	1.981	2.002	1.831	2.007	1.977	2.004	2.005
Cr	0.158	0.001	0.000	0.004	0.004	0.123	0.000	0.000	0.000	0.001
Fe^{3+}	0.029	0.009	0.011	0.020	0.002	0.009	0.032	0.000	0.000	0.000
Fe^{2+}	0.417	2.176	1.909	1.523	1.035	0.446	1.300	1.320	1.867	1.616
Mn	0.024	0.268	0.047	0.027	0.027	0.027	0.035	0.031	0.704	0.030
Mg	2.203	0.437	0.876	1.311	1.185	2.194	1.549	0.866	0.335	1.084
Ca	0.364	0.119	0.171	0.136	0.749	0.352	0.097	0.781	0.074	0.252
	mol %									
almandine	13.9	72.6	63.6	50.8	34.5	14.8	43.6	44.0	62.6	54.2
pyrope	73.2	14.6	29.2	43.7	39.6	72.7	52.0	28.9	11.2	36.4
grossular	10.9	3.9	5.7	4.5	24.9	10.9	3.2	26.1	2.5	8.4
spessartine	0.8	8.9	1.6	0.9	0.9	0.9	1.2	1.0	23.6	1.0
uvarovite	1.0	0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.0	0.0
andradite	0.3	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0

Fe_2O_{3calc} and FeO_{calc} calculated from stoichiometry, c – core, r – rim, Grt source – position in classify diagrams (Text-figs 5 and 6)

Table 2. Representative microprobe analyses of detrital garnets from the Middle Jurassic sand and sandstones of the Cracow-Wieluń Upland

Inclusions in the detrital garnets

In many of the detrital garnets minute inclusions (~ 10 μm) of zoisite, quartz, rutile and ilmenite were recognized (Text-fig. 4). In the garnets with pyrope contents of 71.1 mol % (Grt 8, Table 2) from Czatkowice, omphacite inclusions with a high proportion of jadeite were recognized (Text-fig. 5, 8, Table 3). In the detrital garnets with 52 mol % of pyrope (Grt 5, Table 2) from Dębnik, kyanite inclusions were recognized (Text-fig. 5).

DISCUSSION AND INTERPRETATION

Interpretation of the source rocks

Comparision of the six groups of detrital garnets from the Middle Jurassic sands and sandstones of the Cracow Region and representative analyses of the garnets from various metamorphic rocks (Text-figs 6, 7) shows that the detrital garnets were derived from various HP (UHP) metamorphic rocks:

The first group of detrital garnets (A), located in the A-sector in the triangular diagrams, (Text-figs 6, 7) shows similar compositions to the garnets (with diamond and coesite inclusions) from UHP eclogites, garnet peridotites and kimberlites. Specific for these detrital garnet are high pyrope contents (~ 70 mol %), the presence of uvarovite (~ 1 mol %) and rare inclusions of omphacite (Text-fig. 5, Tables 2, 3). This indicates that the parental rocks of these detrital garnets were UHP eclogites or garnet peridotites.

The second group of detrital garnets (B2), located in the B sector around No. 2 in the triangular diagrams, was derived from HP (UHP) eclogites and HP mafic granulites.

The third group of detrital garnets (B3), located in the triangular diagrams around No. 3, were derived from HP

locality	Czatkowice		Racławice				Paczółtowice			
grain	Grt 7 c	Grt 8 c	Grt 1 r	Grt 2 c	Grt 3 c	Grt 8 c	Grt 1 c	Grt 3 c	Grt 4 c	Grt 7 c
Grt source	C 1-5	A	B 3	C 2-6	B 3	B 2	B 2	B 2	C 1-5	B 2
SiO_2	39.86	42.69	39.46	37.84	40.35	40.30	41.65	40.26	38.92	42.16
TiO_2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al_2O_3	22.27	21.90	21.98	20.94	22.54	22.30	23.12	22.45	21.23	23.65
Cr_2O_3	0.00	2.33	0.03	0.02	0.16	0.03	0.00	0.03	0.00	0.08
Fe_2O_{3calc}	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FeO_{calc}	19.69	7.92	27.44	25.41	23.44	16.98	15.76	21.35	24.61	13.21
MnO	0.46	0.39	0.82	12.10	1.09	0.31	0.29	0.39	0.73	0.32
MgO	7.05	20.36	8.88	2.54	11.87	8.71	13.33	10.80	4.18	15.45
CaO	11.34	5.02	1.89	1.85	1.75	11.47	6.87	4.59	10.00	6.28
Total	100.67	100.67	100.49	100.71	101.19	100.09	101.03	99.88	99.66	101.16
	formula normalization to 12 oxygens									
Si	3.019	3.021	3.027	3.033	3.013	3.032	3.041	3.040	3.050	3.033
Ti	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Al	1.988	1.826	1.988	1.978	1.984	1.977	1.990	1.998	1.961	2.006
Cr	0.000	0.130	0.002	0.001	0.009	0.002	0.000	0.002	0.000	0.005
Fe^{3+}	0.000	0.003	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Fe^{2+}	1.248	0.469	1.760	1.703	1.464	1.068	0.962	1.348	1.613	0.795
Mn	0.030	0.023	0.053	0.821	0.069	0.020	0.018	0.025	0.048	0.020
Mg	0.796	2.147	1.015	0.304	1.321	0.976	1.451	1.216	0.488	1.658
Ca	0.920	0.381	0.155	0.159	0.140	0.925	0.538	0.372	0.839	0.484
	mol %									
almandine	41.7	15.5	59.0	57.0	48.9	35.7	32.4	45.5	54.0	26.9
pyrope	26.6	71.1	34.0	10.2	44.1	32.7	48.9	41.1	16.3	56.1
grossular	30.7	11.7	5.2	5.3	4.6	30.9	18.1	12.5	28.1	16.3
spessartine	1.0	0.8	1.8	27.5	2.3	0.7	0.6	0.8	1.6	0.7
uvarovite	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
andradite	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 2. continue. Representative microprobe analyses of detrital garnets from the Middle Jurassic sand and sandstones of the Cracow-Wieluń Upland

felsic and intermediate granulites. HP metamorphic source rocks were also indicated by rare inclusions of kyanite (Text-fig. 5).

The fourth group of detrital garnets (C1–4), located in the triangular diagrams around No. 4, were derived from LP granulites or gneisses metamorphosed under transitional P–T conditions to granulite and amphibolite facies.

The fifth group of detrital garnets (C1–5), located in the triangular diagrams around No. 5, were derived from retrograde eclogites or amphibolites, metamorphosed under transitional P–T conditions to granulite and amphibolite facies.

The sixth group of detrital garnets (C2–6), located in the trianglar diagrams around No. 6, were derived from gneisses metamorphosed under amphibolite facies conditions. Such a detrital garnet composition was relatively rare.

Most of the detrital garnets from all the localities generally contain high contents of the pyrope molecule (30–73 mol %) and, according to their chemical compositions, are classified in the triangular diagrams as garnets coming from HP/UHP conditions and garnets coming from HP eclogite and HP granulite facies conditions (Text-figs. 6, 7).

The inclusions in the detrital pyrope garnets also provide useful evidence of their provenance. The associated minerals in eclogites include pyrope garnet, omphacite, quartz (coesite), rutile, kyanite, phengite, and lawsonite (e.g. Carswell 1990; Best 2003; Liou *et al*. 2004). Omphacite is stable only in relatively high pressure metamorphic facies and is a major mineral component of UHP metamorphic rocks. It is therefore diagnostic of eclogite facies metamorphism (Desmons and Smulikowski 2004; Schmid *et al*. 2004).

UHP/HP source rocks are indicated mainly by occurrences of omphacite inclusions with high jadeite contents (Text-fig. 8) in the detrital pyrope garnets with high pyrope contents (~ 70 mol %). Such pyrope contents are

grain	Omp 1	Omp 2	Omp 3	Omp 4
SiO_2	55.99	52.66	55.89	52.89
TiO_2	0.09	0.12	0.08	0.10
Al_2O_3	12.18	14.03	12.37	13.93
Cr_2O_3	0.00	0.00	0.00	0.00
FeO	4.24	7.77	3.84	7.17
MnO	0.02	0.14	0.01	0.12
MgO	7.97	7.46	7.82	7.65
CaO	13.48	12.71	13.64	12.82
Na_2O	6.25	5.11	6.55	5.61
K_2O	0.00	0.00	0.00	0.00
Total	100.24	100.01	100.22	100.30
	formula normalization to 6 oxygens			
Si	1.981	1.896	1.977	1.897
Al^{IV}	0.019	0.104	0.023	0.103
Al^{VI}	0.489	0.492	0.493	0.486
Fe^{3+}	0.000	0.000	0.000	0.002
Cr	0.000	0.000	0.000	0.000
Ti	0.002	0.003	0.002	0.003
Fe^{2+}	0.126	0.235	0.114	0.214
Mn	0.001	0.004	0.000	0.004
Mg	0.421	0.400	0.413	0.409
Ca	0.511	0.490	0.517	0.493
Na	0.429	0.357	0.449	0.391
K	0.000	0.000	0.000	0.000
Total	3.978	3.982	3.988	4.001

Fe^{3+} and Fe^{2+} calculated from stoichiometry

Table 3. Representative microprobe analyses of omphacite inclusions in the detrital garnets (Czatkowice locality, Grt8, Text-fig. 5) from the Middle Jurassic sand and sandstones of the Cracow-Wieluń Upland

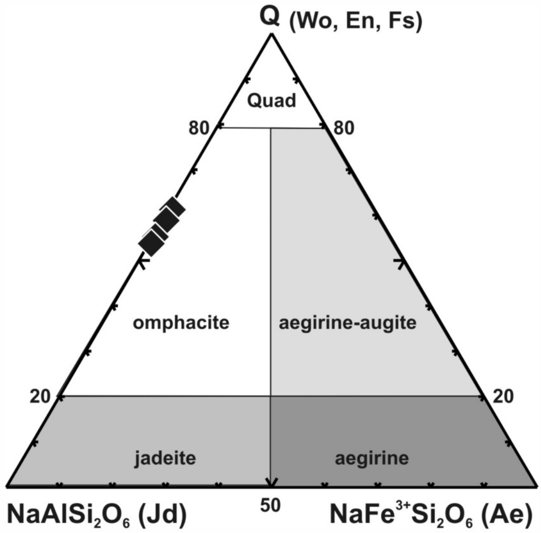
typical only of garnets from garnet peridotites, kimberlites and UHP eclogites with inclusions of coesite and diamond (Text-figs 6, 7). The presence of kyanite and rutile inclusions (Text-fig. 5) in the detrital garnets with high pyrope contents also indicate their high pressure origin.

Interpretation of the possible source area

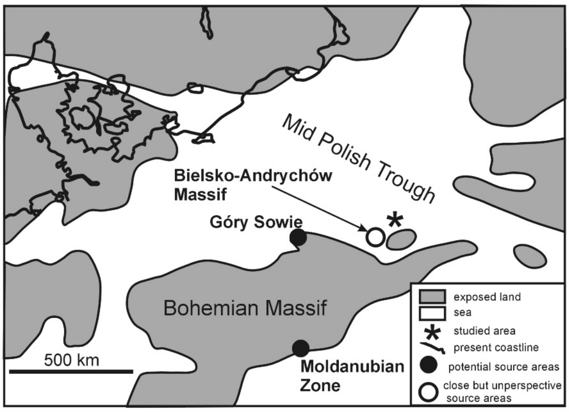
UHP metamorphic terranes consist of UHP continental gneiss, country-rock eclogite and lenses of mantle-derived peridotite. This HP/UHP rock association requires that slices of continental crust be subducted deeply into the mantle so that fragments of the overlying mantle-wedge can become entrained in the crust as peridotite lenses. The UHP terranes are subsequently exhumed and erosion exposes deeper levels of the orogen (Ernst and Liou 2000; Liou *et al*. 2004). Such metamorphosed complexes are known in the European Variscides (e.g. Dora Maira Massif of the Western Alps, Moldanubian Zone of the Bohemian Massif, Massif Central) and in the Western Gneiss Region of the Norwegian Caledonides (e.g. Liou *et al*. 2004).

The provenance of the studied detrital garnets is interesting in the context of the position of the Cracow–Wieluń Upland. It is situated in the Brunovistulian Zone, which is a terrane consolidated in Neoproterozoic time and only weakly metamorphosed in the Hercynian orogeny (Żelaźniewicz *et al.* 2009). Most of this terrane is covered by younger sediments but there are no borehole or outcrop data to provide evidence of the presence of UHP/HP rocks (e.g. granulites and eclogites). The nearby Bialsko-Andrychów Massif (see Text-fig. 9) does not contain any granulites or eclogites. (fig. 9)

The only known potential primary sources occur in Hercynian zones west of the Brunovistulian Zone, e.g. the Moldanubian Zone and the Lugic Zone (Western Sudetes). Metamorphic rocks in the Moldanubian Zone of the Bohemian Massif (garnet peridotites, garnet pyroxenites, kyanite eclogites and granulites) commonly contain pyrope-rich garnets (Medaris *et al.* 1995a, b, 1998, 2005, 2006a, b; Nakamura *et al.* 2004; O'Brien and Vrána 1995; O'Brien *et al.* 1997; Scharbert and Carswell 1983). There are also two more proximal occurrences of granulites and eclogites – the Góry Sowie Block and the Śnieźnik area complex in the Western Sudetes (Oberc 1972; Smulikowski 1967; Kryza *et al.* 1996; O'Brien *et al.* 1997). These are, ho-



Text-fig. 8. Composition of omphacite inclusions (Table 3) in the detrital garnets (Grt8, Text-fig. 5) from the Czatkowice locality. Nomenclature of the Ca-Mg-Fe and Na pyroxenes with accepted names according to IMA classification (Morimoto *et al.* 1989). Quad represents the Ca-Mg-Fe pyroxene area



Text-fig. 9. Potential source areas on palaeogeographical map of Middle Callovian (Thierry and Barrier 2000)

wever, too small to be a regionally important source of clastic material in the Cracow–Wieluń Upland. Nevertheless, Biernacka and Józefiak (2009) considered the granulitic block of Góry Sowie as the main source of pyrope-almandine garnets in Turonian sandstones in the North Sudetic Basin. They argued that the areal extent of this unit in the Mesozoic was larger, as a large part of it is covered with younger, Cenozoic sediments.

In order to evaluate a possible reworking of the detrital material, it is necessary to mention that exotic pyrope-almandine garnets were also reported from the Carboniferous of the Moravo-Silesian Culm basin (Otava and Sulovský 1998; Otava *et al.* 2000; Čopjaková *et al.* 2001, 2005; Hartley and Otava 2001). Some granulitic pebbles were also found in the Carboniferous sediments of the Upper Silesia Coal Basin (Paszkowski *et al.* 1995). In the Carboniferous clastics of the Moravo-Silesian Zone, the authors invariably derive the clastic material from the Moldanubian Zone of the Bohemian Massif (Paszkowski *et al.* 1995; Hartley and Otava 2001). The Upper Carboniferous clastics of the Upper Silesia Coal Basin cannot be completely excluded from consideration, since Łydka (1955) claims that some sandstones from the Libiąż Beds contain 4.3 vol. % of garnets, of which some are high-pyrope garnets (personal communication Mariusz Paszkowski, 2010). Przybyłowicz (1958) interpreted her results from the Jurassic of the Cracow–Wieluń Upland as indicating resedimentation from the "Buntsandstein" (Lower Triassic sandstones of the Germanic Triassic Basin). We consider the probability of complete reworking of our material from older clastics as low, albeit the ZTR index of some samples shows relative depletion in less stable minerals. Moreover, all the possible sources known to date (Moldanubian Zone, Góry Sowie, Carboniferous sediments of Silesia) are surrounded by crystalline complexes in which almandine garnets are dominant (e.g. in the Góry Sowie Mts. only a restricted part of the crystalline complexes contains pyrope-almandine garnets. The rest is almandine-dominated – see Biernacka and Józefiak 2009). Heavy mineral spectra transported from these distal sources would be enriched in almandine. The source rocks were then most probably primary crystalline complexes of lower crust to mantle origin, outcrops of which were not very far distant from the area of deposition. Perhaps verification of the subsurface extent of the Góry Sowie Massif would shed more light on this problem (cf. Biernacka and Józefiak 2009).

In the context of the presence of the pyrope-almandine garnets in the Polish Jurassic platform cover, it is important to note its relationship with the Tethyan realm rimming the platform to the south. Pyrope-rich garnets are absent in the crystalline rocks of the West Carpathian internides (Central and Inner Western Carpathians. (Aubrecht and Méres 2000) but they are ubiquitous in the Outer Western Carpathians, which are very close to the Polish Platform. Pyrope-almandine garnets are typical of the Jurassic of the Pieniny Klippen Belt (Aubrecht and Méres 1999, 2000). Similar garnets were reported from the Cretaceous to Paleogene sediments of the Carpathian Flysch Zone (Otava *et al.* 1997, 1998; Salata 2004; Oszczypko and Salata 2005; Grzebyk and Leszczyński 2006). The data from the Flysch Zone are not restricted solely to heavy minerals; exotic granulitic pebbles (one of the potential source rocks) were also reported from the Silesian Unit by Wieser (1985). Based on the exotic pebbles from the Silesian Cordillera, it was inferred that it was composed of Hercynian crystalline complexes: granulites with eclogites in the west and weakly metamorphosed Neoproterozoic complexes in the east (Paszkowski *et al.* 1995; Poprawa *et al.* 2006), i.e. it was most probably derived from the Moldanubian/Brunovistolian contact area. It is also consistent with the earlier interpretations of Aubrecht and Méres (1999, 2000) who derived the Pienidic (Oravic) crustal segment from the Moldanubian Zone.

CONCLUSIONS

(1) Heavy mineral analysis of the Middle Jurassic sands and sandstones of the Cracow Region shows a predominance of garnets and high amounts of zircon, rutile and tourmaline. These main heavy minerals are accompanied by subordinate amounts of staurolite, apatite, kyanite, titanite, hornblende and epidote.

(2) The majority of the detrital garnets contain high contents of the pyrope molecule and their composition shows that they were derived mainly from a high- (ultrahigh-) pressure metamorphic rocks (garnet peridotite, eclogite and granulite). This is also supported by inclusions of omphacite and kyanite.

(3) Similar rocks most probably formed the original crustal segments of the Outer Carpathians (Czorsztyn Ridge, Magura Cordillera, Silesian Cordillera).

(4) The Cracow–Wieluń Upland is situated upon the Brunovistulian Zone, which was only weakly metamorphosed in the Hercynian orogeny and there are no data to provide evidence of the presence of UHP/HP rocks. The nearby Bialsko-Andrychów Massif does not contain any granulites or eclogites.

(5) The terrane which seems to be most similar to the inferred source area is the Moldanubian Zone of the Bohemian Massif but this is too distant from the Cracow–Wieluń Upland to be considered. Between the Moldanubian potential sources and the Cracow–Wieluń Upland there are terranes which contain predominantly almandine garnets. Any pyrope-almandine garnet-rich material would be diluted by almandine garnets, when transported from such a distance. Less distant are the Góry Sowie Mts., which incorporate UHP/HP metamorphic rocks, but the exposed areal extent of these rocks is too small. However, it is possible that larger portions of these metamorphic rocks are buried beneath the Cenozoic cover and might represent the source area.

(6) Although similar garnets were also reported from younger deposits (e.g. Carboniferous, Cretaceous), the possibility of complete reworking of the exotic garnets from older sediments is very low.

(7) The source area therefore remains unknown. Most probably it was formed by primary crystalline complexes of lower crust to mantle origin, outcrops of which were not far distant from the area of deposition.

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