

Heavy minerals as detritus provenance indicators for the Jurassic pre-Callovian palaeokarst infill from the Czatkowice Quarry (Kraków–Wieluń Upland, Poland)

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Heavy mineral assemblages from the infill of Jurassic pre-Callovian palaeokarst in the Czatkowice Quarry, in the Kraków–Wieluń Upland, are zircon dominated. They contain also garnet, tourmaline, rutile and scarce grains of kyanite, staurolite and single chromian spinel. The textural features of the heavy minerals suggest that certain types of source rocks supplied the clastic material infilling in the karst studied. Most of the heavy minerals were derived from sedimentary or metasedimentary rocks as suggested by the high degree of roundness of the grains and also by high ZTR (zircon–tourmaline–rutile) index values. Rounded minerals may derive from Carboniferous, Permian and Triassic clastic rocks occurring in the area surrounding the Czatkowice Quarry. The chemical compositions of rounded detrital garnet and tourmaline grains suggest metamorphic and igneous rocks as initial sources, perhaps located in the Bohemian Massif. However, a hypothetical landmass located south of the Kraków–Wieluń Upland might have been an additional source area. The euhedral zircon and garnet grains were transported directly from crystalline rocks, which may have been Carboniferous–Permian volcanic rocks and crystalline basement elevations of Brunovistulicum exposed during Jurassic pre-Callovian sedimentation in the Czatkowice area.

Key words: heavy minerals, sedimentary provenance, palaeokarst, Jurassic, Czatkowice, Kraków–Wieluń Upland.

INTRODUCTION

The karstification that affected the Kraków–Wieluń Upland has long attracted interest (e.g., [Lis and Wójcik, 1960](#); [Gradziński, 1962](#); [Gradziński and Wójcik, 1966](#); [Madeyska-Niklowska, 1969](#); [Madeyska, 1977](#); [Głazek, 1989](#) and references therein). More detailed description in the Czatkowice area followed the discovery there of bone breccias, initially at waste heaps of the working Czatkowice Quarry and then within palaeokarsts in the quarry itself (see [Paszowski and Wieczorek, 1982](#)). Investigations focused mainly on detailed palaeontological examination of the bone remnants occurring in sedimentary fillings in order to establish more fully the stages of karstification in the area ([Paszowski and Wieczorek, 1982](#); [Paszowski, 2000](#); [Borsuk-Białynicka and Evans, 2009](#) with references therein).

The provenance of the detritus that infills Late Triassic–mid Jurassic cave systems was briefly discussed based on one heavy mineral sample ([Paszowski and Wieczorek, 1982](#)). Material from the Jurassic pre-Callovian palaeokarst was exposed as a result of quarry exploration and were sampled again in

2005. From these deposits, heavy mineral assemblages were separated. The heavy mineral fraction, not treated with HCl solution, was briefly described and some qualitative analyses were made using an Energy Dispersive Spectrometer (EDS) ([Kałkol, 2011](#)). These investigations and the few EDS analyses gave only generalized data, providing the groundwork for more detailed analyses.

Heavy minerals are a very useful tool for determining the provenance of detritus in sedimentary rocks. Results may be obtained using standard optical techniques and advanced scanning microscopy in order to examine textural features of the heavy minerals and to study their detailed chemical composition. The latter allow determination of the primary rocks in which the minerals crystallised, which enables tracking the original source areas even for recycled sedimentary material. Garnet and tourmaline groups are particularly useful in primary rock determination. They are resistant to transport and burial processes and retain their original chemical composition that reflects the nature of their parent rocks (e.g., [Mange and Wright, 2007](#)).

The present paper provides detailed information on heavy mineral assemblages occurring in remnants of Jurassic pre-Callovian palaeokarst forms in the Czatkowice Quarry. The work is based on new data obtained from detailed chemical analyses and microscopic observations. The data obtained shed light on the origin of the heavy minerals, and thus of the detrital material, occurring in the karst sampled, supporting previous ideas on the mineral provenance and also generating new insights.

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GEOLOGICAL OUTLINE

The Czatkowice Quarry is a working quarry located in the western part of the Dębnik Anticline (Fig. 1), along the eastern edge of the post-Hercynian tectonic structure termed the Sławków Graben. The central part of the anticline is built of Givetian to Famennian dolomites and limestones followed by Upper Tournaisian to mid Visean carbonate rocks towards its western part (e.g., Siedlecki, 1954; Bogacz, 1980; Paszkowski, 2009). To the west of the Czatkowice Quarry the Carboniferous deposits are successively followed by continental and marine Triassic and Jurassic strata, while further towards the west (in the area of Miękinia and Karniowice) the Carboniferous rocks are overlain by Lower Permian continental deposits that fill the Sławków Graben, where a variety of Permian volcanic and volcanoclastic rocks are present (e.g., Harańczyk, 1989; Żaba, 1999; Nawrocki et al., 2008). In contrast, towards the east of the Czatkowice area the Cambrian to Lower Carboniferous rocks are directly covered by Middle Jurassic strata (Fig. 1; Siedlecki, 1954; Bogacz, 1980; Paszkowski and Wieczorek, 1982; Paszkowski, 2000, 2009). As a result of the Variscan movements the Upper Paleozoic deposits were in part removed. Lower Permian, Lower Triassic, Upper Triassic and Lower–Middle (up to Callovian) Jurassic sediments were preserved exclusively in the infills of palaeokarstic depressions occurring in the area (see Paszkowski and Wieczorek, 1982; Głazek, 1989; Paszkowski, 2000, 2009).

An obvious effect of the Variscan tectonics in the Czatkowice area is the steep, up to almost vertical, orientation of the Carboniferous strata. This allowed the formation of pronounced karst forms (Paszkowski and Wieczorek, 1982; Paszkowski, 2000, 2009), which attain up to 150 m in depth (Paszkowski, 2000). In the Krzeszowice area, karsts formed during the inter-

val spanning from the Early Carboniferous to the Callovian, in which three main phases may be distinguished (Paszkowski, 2000):

- synsedimentary, Early Carboniferous;
- continental, starting after removal of the Upper Carboniferous cover and ending before Early Triassic transgression;
- Mesozoic phase, lasting from the Late Triassic to the Callovian transgression.

The karstification developed mainly in Lower Carboniferous limestones or in infills of older karsts (Paszkowski, 2000). Palaeokarst forms were filled with clayey to sandy sediments, breccias, pyroclastic rocks and speleothems (Paszkowski, 2000). Bone breccias, with fossils of fishes, reptiles and amphibians, were found in some karsts, enabling the establishing of age constraints (see Paszkowski and Wieczorek, 1982; Paszkowski, 2000; Borsuk-Białynicka and Evans, 2009 and references therein).

One of the palaeokarst forms (now no longer available for investigation), was filled with sediment resembling the Middle Jurassic sandstone occurring at the top of the quarry; it included pieces of vertebrate bone, fish scales and *Ceratodus* teeth, determined as *Ceratodus phillipsi* Agassiz (Paszkowski and Wieczorek, 1982; Paszkowski, 2000). This places the karst as formed during the third stage of karstification in the area, hence representing the remnants of a Jurassic pre-Callovian cave (see Paszkowski, 2000).

SAMPLED MATERIAL

The material filling the Jurassic palaeokarst was sampled by M. Gradziński and M. Paszkowski in 2005, in part of the palaeokarst shown in Figure 2, exposed as a consequence of

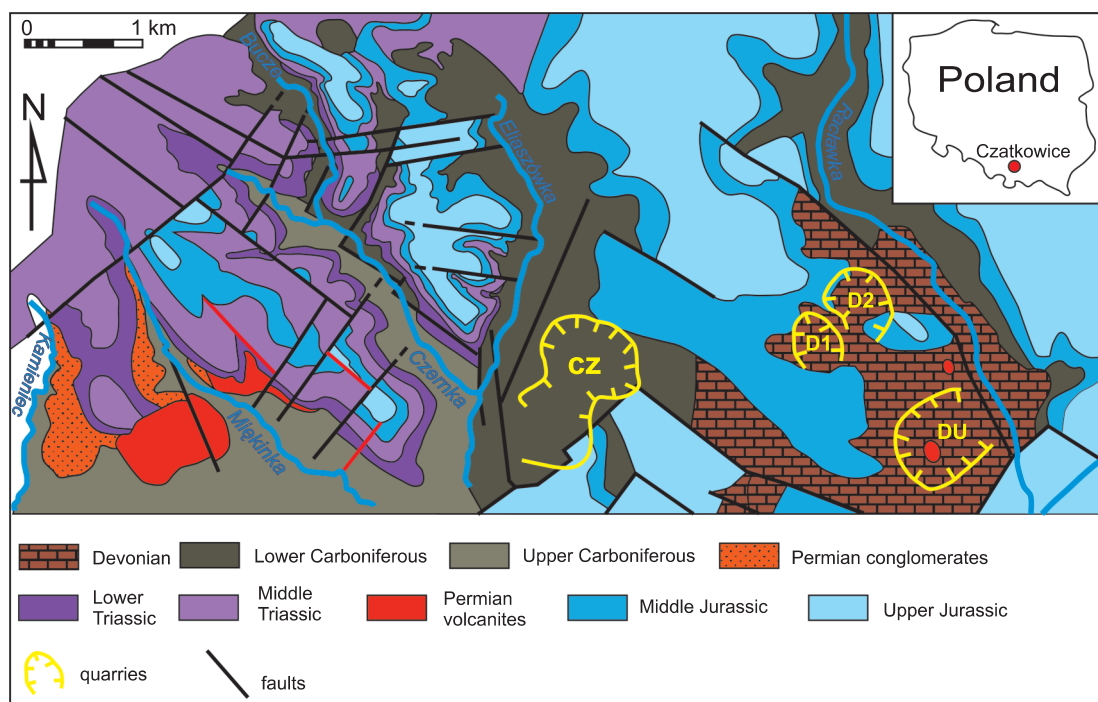


Fig. 1. Location of the Czatkowice Quarry on a geological map of the Dębnik Anticline area (Paszkowski, 2009, modified according to Gradziński, 1993)

CZ – Czatkowice, D1 – Dębnik (old), D2 – Dębnik (new), DU – Dubie



Fig. 2. View of the pre-Calloviaian Jurassic cave studied (pink solid lines) developed within Lower Carboniferous limestones (C₁) in the Czatkowice Quarry

Dashed lines indicate bedding of cave loam deformed by compaction (according to Paszkowski, 2000; phot. M. Gradziński, 1997)

the progressive exploitation of the quarry. The presence of *Ceratodus* teeth was confirmed (M. Gradziński pers. comm., 2012) in the deposits filling the sampled karst, indicating that it represents the same system of Jurassic karsts as described by Paszkowski and Wieczorek (1982). The deposits investigated represent sandy to gravely limestones. The detritus, cemented by calcite, is chaotically dispersed and composed mainly of well-rounded or broken quartz grains. White, rounded quartzitic sandstone clasts are also present. Locally, siliceous concretions are developed in the carbonate cement. The heavy fraction separated from the sandy material, not treated with the hydrochloric acid solution, was dominantly of opaque minerals represented mainly by Fe-oxides, hydroxides and Fe-Ti oxides. Among transparent grains, tiny pieces of bone and authigenic apatite minerals dominate. Besides these, zircon, tourmaline, rutile, garnet and scarce grains of staurolite and chromian spinel were identified (Kałkol, 2011).

ANALYTICAL METHODS

The rock samples were crushed to about 1 cm pieces and then were disintegrated in 10% HCl solution for 24 hours at room temperature, to remove carbonate cement and tiny pieces of bone. During the treatment all apatite particles were dissolved but no damage was caused to other constituents. Zircon, tourmaline, rutile, garnet, staurolite and chromian spinel, previously determined also by Kałkol (2011) in the material not treated with HCl are, according to Deer et al. (1992), not soluble in this acid. Then the loose sandy material was split into fractions. Heavy minerals were separated from the 63–250 μm fraction using sodium polytungstate of 2.9 g/cm³ density as the heavy liquid. Heavy mineral assemblages were mounted in Canada balsam, described and counted using a polarising microscope. For each sample 300 grains of transparent, non-micaceous minerals were counted according to the ribbon method. Mineral frequencies were calculated as number percents. Grain morphology was additionally studied by means of a Scanning Electron Microscope (SEM) Hitachi S-4700 in the Laboratory of Field Emission Scanning Electron Microscopy and Microanalysis at the Institute of Geological Sciences,

Jagiellonian University. Additionally, surface features of minerals not treated and after HCl treatment were compared by SEM, to reveal any damage to minerals. The chemical composition of garnets and tourmalines was determined in carbon-coated polished thin sections with a Cameca SX-100 electron microprobe (EMP) operated in wave length dispersion (WDS) mode at the Joint-Institute Analytical Complex for Minerals and Synthetic Substances at Warsaw University. The WDS analyses conditions were: 15 kV accelerating voltage, 20 nA beam current and focused beam. Synthetic and natural mineral standards were used for analytical calibration: Si (wollastonite in tourmalines and diopside in garnets), Al and K (orthoclase), Cr (Cr₂O₃), Ti (rutile), Mg (diopside), Fe (Fe₂O₃), Mn (rhodonite), Ca (wollastonite), Na (albite), F (phlogopite). The detection limits of elements measured are: Ca – 0.02%, Fe – 0.07%, Mn – 0.07%, Ti – 0.03%, Cr – 0.03%, Si – 0.02%, Al – 0.02%, Mg – 0.01% in garnet and K – 0.05%, Ca – 0.05%, Fe – 0.12%, Mn – 0.14%, Ti – 0.05%, Cr – 0.08%, Na – 0.05%, F – 0.31%, Mg – 0.03%, Al – 0.03%, Si – 0.04% in tourmaline. Garnet and tourmaline grains for analyses were chosen randomly. Garnet grains were analysed mostly in their centres. Additionally, 15 garnet grains of various compositions were analysed in traverses to detect changes in element proportions. Tourmaline grains were mostly analysed in one spot per grain. If any lighter or darker zones were noticed in the back-scattered electron (BSE) images of tourmalines, analyses were made in each zone. Additionally, 15 tourmaline grains were analysed in traverses. The tourmaline calculations were normalized to 31 anions. The boron content in tourmalines was not measured directly but three boron atoms were assumed to be present in the tourmaline formula. Therefore, the weight percents of B₂O₃ necessary to produce 3 boron atoms were calculated for the analyses on stoichiometry assuming OH + F = 4 apfu (atoms per formula unit) and that all iron is Fe²⁺.

RESULTS AND INTERPRETATION

HEAVY MINERAL ASSEMBLAGES

Zircon, tourmaline, rutile, garnet, staurolite and single grains of kyanite and chromian spinel were identified among the transparent heavy minerals (Fig. 3A and Table 1). Scanning microscopic investigations revealed also very rare rounded monazite grains. Zircon is most frequent in the heavy mineral assemblages studied, reaching 69%. Tourmaline, rutile and garnet occur in similar quantities in most samples, comprising from about ten to several percent. Only in one sample the tourmaline population analysed slightly exceeds 2%. Staurolite amounts reach 3%, while kyanite rarely reaches 1%. A singular chromian spinel grain was determined only in one sample (Fig. 3A and Table 1). The rough heavy mineral fraction, not treated with HCl solution, contained also euhedral apatite (most probably authigenic) and apatite pieces (fragments of bone). However, due to the large amount of apatite bone fragments the real content of detrital apatite was impossible to establish (Kałkol, 2011). Apatite and its fragments were dissolved during rock disintegration in the current study, therefore the heavy mineral fraction is impoverished in this mineral.

Among the zircon population, mostly colourless but also pinkish and yellowish varieties are typical. Colourless grains often contain numerous inclusions, while the yellowish and pinkish zircons occasionally display distinct oscillatory zonation patterns. The tourmaline population is dominated by olive-brown varieties, whereas blue-green and pink grains are in the minor-

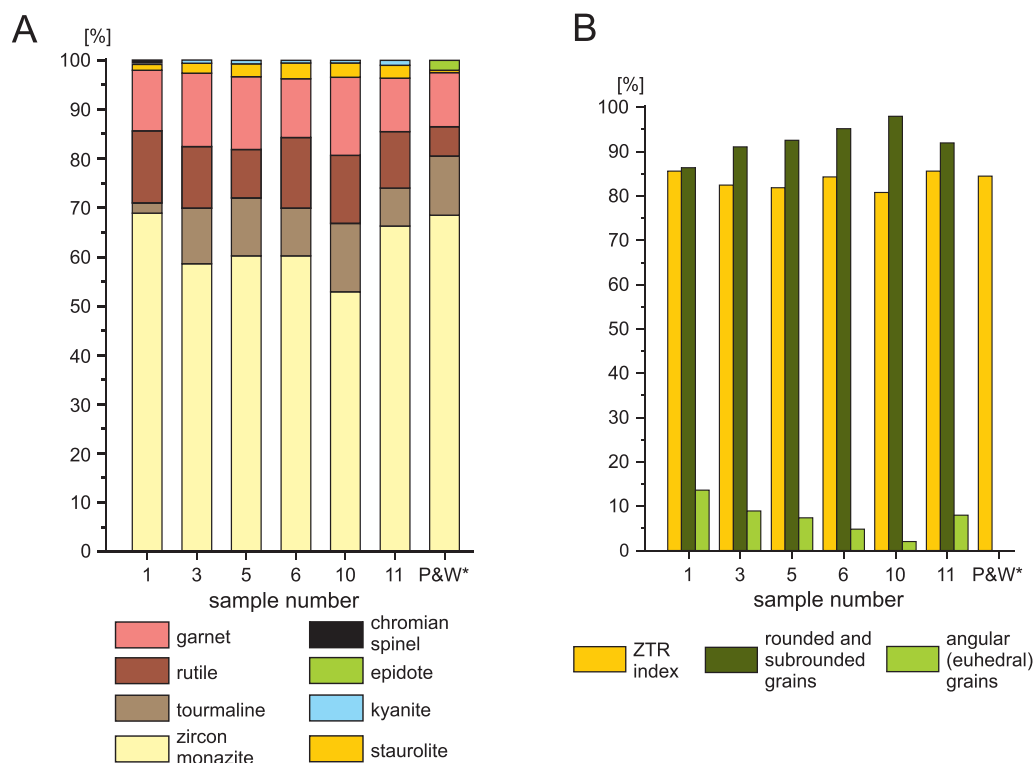


Fig. 3A – heavy mineral composition in the samples studied; B – ZTR index values and content of rounded, subrounded and angular (including euhedral) grains

P&W* – data according to [Paszowski and Wieczorek \(1982\)](#)

Table 1

Heavy mineral compositions of the samples studied [%]

No.	Zrn + Mnz	Tur	Rt	Grt	St	Ky	Ep	Cr-sp	ZTR	R + S	A
1	68.9	2.1	14.7	12.3	1.2	0.3	–	0.6	85.6	86.4	13.6
3	58.6	11.3	12.6	14.9	2.0	0.7	–	–	82.5	91.1	8.9
5	60.2	11.8	9.9	14.8	2.6	0.7	–	–	81.9	92.6	7.4
6	60.2	9.7	14.4	12.0	3.2	0.5	–	–	84.3	95.2	4.8
10	52.9	13.9	13.9	15.9	2.9	0.5	–	–	80.8	98.0	2.0
11	66.3	7.7	11.5	10.9	2.6	1.0	–	–	85.6	92.0	8.0
P&W*	68.5	12.0	6.0	11.0	0.5	–	2.0	–	84.5	–	–

Cr-sp – chromian spinel, Ep – epidote, Grt – garnet, Ky – kyanite, Mnz – monazite, Rt – rutile, St – staurolite, Tur – tourmaline, Zrn – zircon, ZTR – zircon–tourmaline–rutile index, R – rounded grains, S – subrounded grains, A – not rounded (angular, euhedral) grains; for other explanations see [Figure 3](#)

ity. Rutile is represented by brown-red and orange to yellow grains. Garnet is mostly colourless but pink and salmon-pink grains are also present. Staurolite displays yellow to orange colours.

The characteristic feature of all the heavy minerals listed above is their high degree of roundness ([Fig. 4](#)). They are mostly well-rounded, seldom subrounded, while euhedral grains occur exceptionally ([Fig. 4B–F](#)). The rounded and subrounded grains comprise up to 98% of the heavy mineral assemblages studied, among which rounded grains of zircon comprise the majority. Furthermore, all the minerals studied of-

ten occur in the form of irregular fragments with uneven fractures. Among the infrequent euhedral mineral population, comprising mostly below 10% of transparent heavy minerals ([Fig. 3B and Table 1](#)), elongated zircon is most common ([Fig. 4C](#)), but short prismatic zircon was also found ([Fig. 4D](#)). Less frequently, euhedral garnet ([Fig. 4F](#)) and rutile ([Fig. 4B](#)) are present. The large quantity of rounded grains is accompanied by high values of the ZTR ([Hubert, 1962](#)) reaching 86 ([Fig. 3B and Table 1](#)).

The surfaces of garnet, tourmaline, rutile and kyanite grains display microtextures such as etch-pits, facets and hacksaw

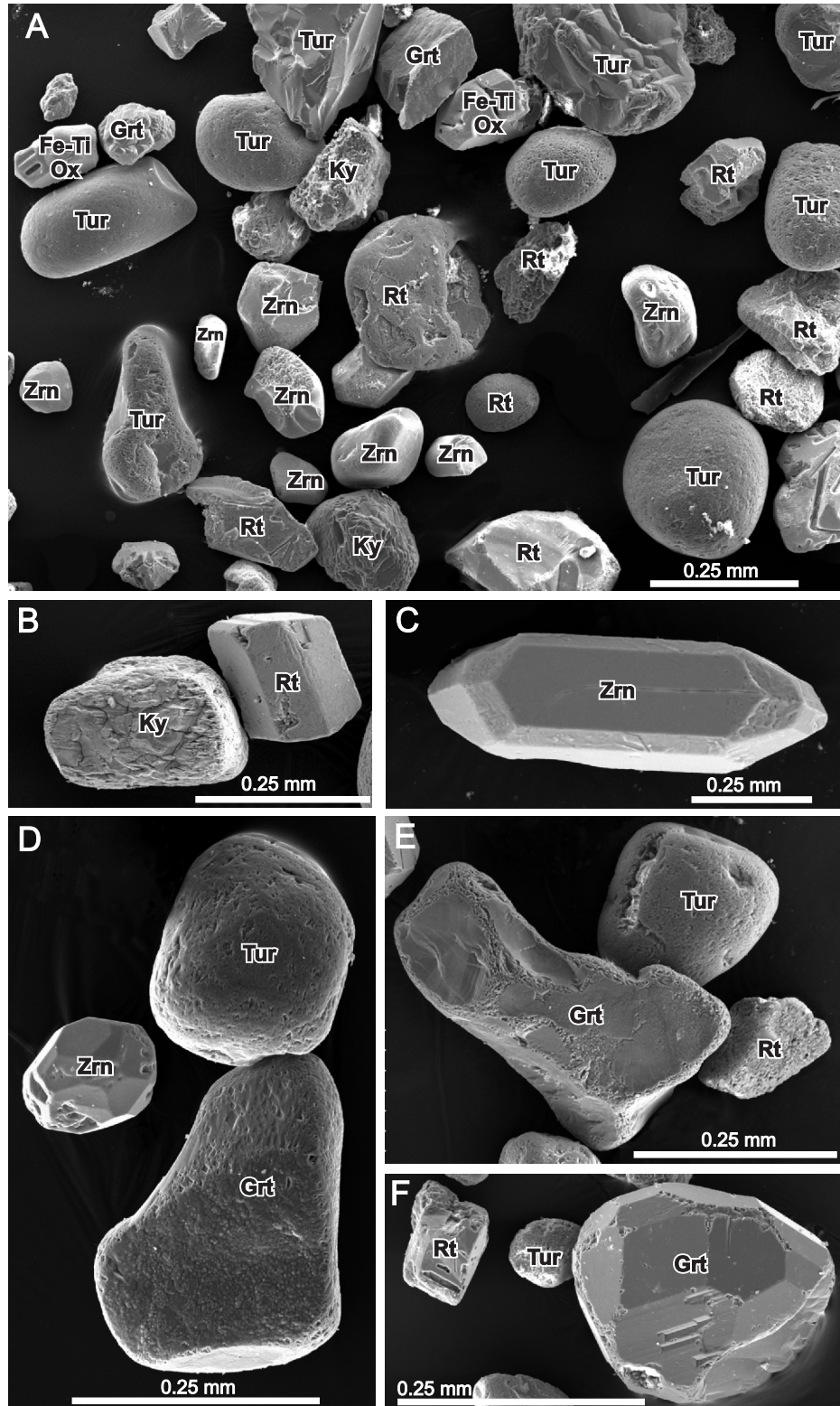


Fig. 4. Heavy minerals occurring in the palaeokarst studied in the Czatkowice Quarry

A – general view of rounded randomly scattered heavy minerals; **B** – euhedral rutile and rounded kyanite; **C** – euhedral elongated zircon; **D** – euhedral short prism of zircon and rounded tourmaline and grossular-rich pyrope-almandine garnet; **E** – rounded grains of tourmaline, rutile and pyrope-rich almandine garnet; **F** – euhedral spessartine-almandine garnet and rounded rutile and tourmaline; Fe-Ti Ox – Fe-Ti oxide, Grt – garnet, Ky – kyanite, Rt – rutile, Tur – tourmaline, Zrn – zircon; SEM

terminations indicating intracrystalline dissolution of those minerals (Fig. 4). The microtextures are present only in rounded grains, often on their smoothed surfaces (Fig. 4A, B, D, E), while they are not visible on crystal faces of euhedral grains or on pre-depositional planes of mineral fractures (Fig. 4B, C, F).

GARNET AND TOURMALINE CHEMICAL COMPOSITION

The garnet population studied displays a large diversity in terms of chemical composition (Figs. 5, 6 and Table 2). Among them five compositional varieties may be distinguished (Fig. 6):

- 1 – pyrope slightly enriched in the uvarovite molecule (Prp 68–70 mol%; Uv 7–10 mol%);
- 2 – almandine-dominated garnet, sometimes enriched in spessartine (up to 24 mol%) or grossular (up to 32 mol%) molecules;
- 3 – pyrope-rich almandine (Prp 22–46 mol%; Alm 34–65 mol%);
- 4 – almandine-pyrope-grossular (Prp 22–43 mol%; Alm 34–45 mol%; Grs 20–34 mol%);
- 5 – spessartine-dominated (Alm 24–45 mol%; Sps 37–59 mol%).

Andradite and uvarovite molecules in almost all garnet varieties (except group 1) do not exceed 7 and 1 mol% respectively.

Among the garnet population studied spessartine- or pyrope-rich almandine grains belong to the most common garnet varieties, while other types are less widespread. Only two grains of garnet representing chromium-enriched pyrope were found (Fig. 5 and Table 2). There is one further distinctive feature of the detrital garnet group analysed: all of the garnet compositional varieties were established among the rounded set of garnet grains but only the spessartine-rich almandine was determined within the infrequent euhedral garnet population. The garnet population analysed prevalently displays internal homogeneity in terms of the elements measured. Only some of the grossular-rich varieties display weak differences between molecule contents (mainly pyrope, almandine and grossular), but the maximum differences between the marginal and internal parts of such garnets do not exceed 4 mol% (Table 2). However, this feature may be misleading as the irregular chemically homogenous fragments may represent pieces of larger zoned garnet grains.

Garnets with high almandine molecule content, with the grossular amount up to about 30 mol%, or with significant spessartine content, derive generally from metapelites of medium-grade metamorphic facies. Spessartine and spessartine-almandine with pyrope content comprising several percent is most typical of intermediate to acidic plutonic and volcanic rocks. Spessartine-dominated garnet may form in skarns where it occurs in assemblages with Mn-rich minerals. It may also occur in granite pegmatites and aplites. Almandine with elevated amounts of pyrope is frequently found in high-grade metamorphic rocks, such as granulites and eclogites, while almandine-pyrope with elevated contents of grossular may be found in ultramafic rocks such as pyroxenites and peridotites and their metamorphosed varieties. Pyrope-bearing garnet, with pyrope molecule exceeding 70%, including those with an elevated uvarovite amount, indicates origin from ultra-high pressure eclogites, garnet peridotites and kimberlites (Fig. 7; e.g., Deer et al., 1997; Morton et al., 2004; Dahlquist et al., 2007; Mange and Morton, 2007; Méres et al., 2012 and references therein).

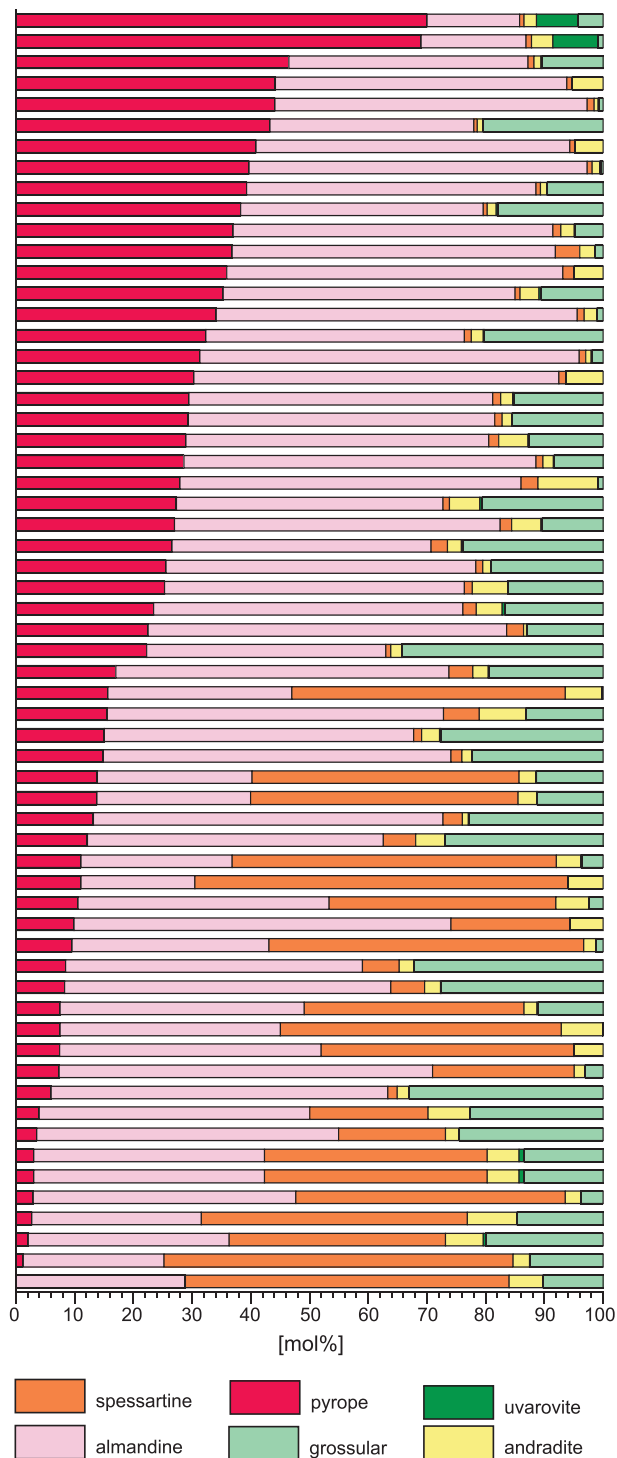


Fig. 5. Garnet end-member amounts in the detrital garnet population analysed

Garnet analyses are arranged in order of decreasing pyrope amount

The tourmaline population studied mostly displays X-site vacancy (X_{vac}) values lower than 0.50 and very low contents of Ca, mostly below 0.20 apfu, which allow classification of the tourmalines to the alkali group, although some grains have X_{vac} values close to 0.50, what places them at the boundary between alkali and X-vacant groups. (Fig. 8A and Table 3; Henry et al., 2011). The X-site is occupied mainly by Na mostly ex-

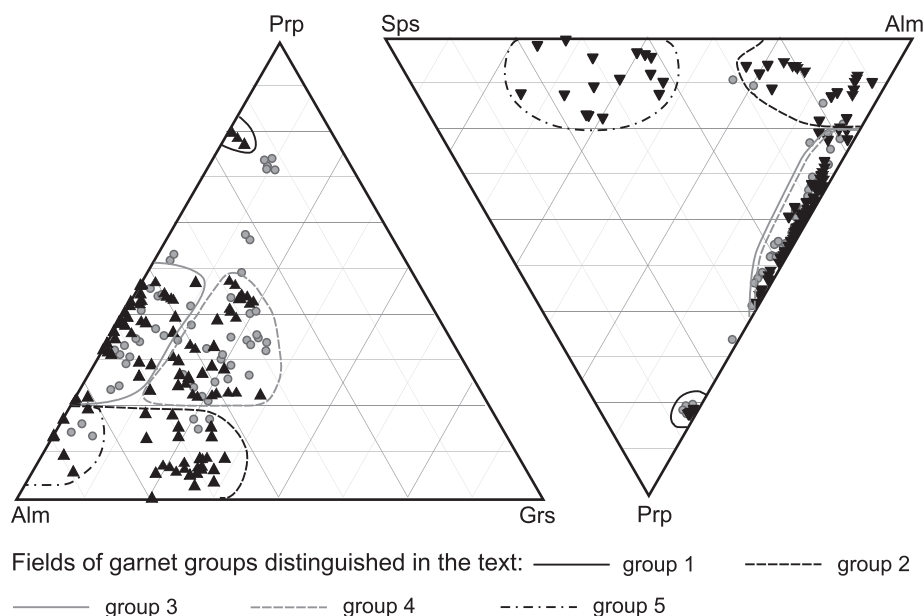


Fig. 6. Triangle projection of the end-members of the garnet population analysed (black triangles) in comparison to data obtained by Méres et al. (2012) for garnets from Middle Jurassic strata of the area adjacent to the Czatkowice Quarry (grey circles)

Alm – almandine, Grs – grossular, Prp – pyrope, Sps – spessartine

ceeding 0.50 apfu. The tourmalines studied display Si contents close to the stoichiometric value of 6.00 apfu and are rich in Al, which exceeds 6.00 apfu in almost all cases. The Mg/(Mg + Fe) ratio varies in a broad range from 0.08 to 0.85, however, most values exceed 0.40 (Fig. 8B and Table 3). The main divalent cations in the tourmaline structure are Fe²⁺ and Mg, thus most of them represent the schörl-dravite series (Fig. 8B), but those of dravitic composition prevail in the population analysed. Scarce tourmalines with X_{vac} values close to 0.50 display foititic composition (Fig. 8B and Table 3). The tourmalines contain also Ti in amounts below 0.30 apfu and minor contents of Mn and Cr comprising up to 0.07 and 0.02 apfu respectively (Table 3). Most tourmalines studied were chemically almost homogeneous. Some grains displayed visible change in colour tone in transmitted light but differences in composition (mainly Mg and Fe contents) of such zones were weak and did not influence affiliation to a tourmaline species. Only one grain displayed a distinct difference in composition between its marginal (schorlitic composition) and central (dravitic composition) parts (Table 3).

Tourmaline representing the composition described above are typical constituents of granitic as well as metamorphic rocks (e.g., Henry and Guidotti, 1985; Henry and Dutrow, 1996; Hinsberg et al., 2011a, b; Dutrow and Henry, 2011 and references therein). The Fe-rich tourmalines studied, representing the schorlitic series, may originate from Li-poor granitic rocks and their pegmatites, however, some projection points of such tourmalines locate close to the boundary with fields denoting metamorphic origin. The greater part of the tourmaline population shows compositions typical of Al-rich and Al-poor metapelites and metapsammites (Fig. 9; Henry and Guidotti, 1985). Additionally, they show Mg/(Mg + Fe) ratios exceeding 0.3 apfu (Table 3), consistent with metasedimentary derivation (Henry and Dutrow, 1996). The metamorphic tourmaline group is additionally featured by Mg/(Mg + Fe) and X_{vac} ratios in the range 0.50–0.85 and 0.20–0.40 respectively which suggests that they developed under medium-grade metamorphic conditions (Henry and Dutrow,

1996). Some tourmaline grains have compositions indicating their origin from Fe³⁺-rich quartz-tourmaline rocks, calc-silicates or metapelites (Fig. 9; Henry and Guidotti, 1985).

THE QUESTION OF PROVENANCE

ROUNDED HEAVY MINERAL SUITE

The mineral composition of the heavy mineral assemblages studied show considerable similarities to the heavy mineral fraction of one sample from the same generation, though no longer accessible, of Jurassic pre-Calloviaian palaeokarst in the Czatkowice Quarry (Paszkowski and Wieczorek, 1982). The similarities concern the dominant mineral varieties as well as their frequencies. In the samples described above and the one previously studied (Paszkowski and Wieczorek, 1982) zircon is clearly dominant, exceeding 50%, while the relative proportions of tourmaline, garnet and rutile are similar (Fig. 3A and Table 1). Some differences are shown by subordinate minerals, i.e., staurolite, epidote and kyanite. The staurolite content in the sample earlier studied is lower, comprising 0.5%, epidote reaches 2%, while kyanite is absent (Fig. 3A and Table 1). However, these differences are minor and may reflect sorting processes.

The large number of rounded grains in the heavy mineral assemblages studied as well as the elevated values of the ZTR index suggest that the minerals derive from sedimentary or metasedimentary source rocks. However, long transport from a distant source or repeated abrasion in aeolian or marine environments, which were typical of the Early Triassic and Early Calloviaian in the area studied, may also have caused the rounding of the minerals.

These data are similar to those obtained for heavy mineral assemblages occurring in Middle Jurassic clastic deposits of the area surrounding the Czatkowice Quarry (Przybyłowicz,

Table 2

Representative analyses of the garnet population studied

No.	1	2	4	8	21	25	26	30	35	38	46	51	56	59	125c*	125*	154c	154f	
SiO ₂	41.77	40.03	39.20	39.23	38.30	38.78	38.43	38.68	37.77	37.76	37.69	37.70	36.27	36.57	37.31	37.39	38.95	38.59	
TiO ₂	0.21	0.04	0.11	0.08	0.05	0.27	0.25	0.23	0.06	0.23	0.16	0.13	0.73	0.28	b.d.l.	0.04	0.14	0.07	
Al ₂ O ₃	21.36	22.45	22.12	22.05	21.36	21.33	21.52	21.53	20.96	21.21	20.67	20.97	19.87	20.22	20.21	20.08	21.15	21.13	
Cr ₂ O ₃	2.52	0.05	0.02	0.02	0.04	0.08	0.02	b.d.l.	b.d.l.	0.06	0.01	0.02	b.d.l.	b.d.l.	b.d.l.	0.03	0.05	0.03	
Fe ₂ O ₃ **	0.77	0.44	0.24	0.38	0.61	0.82	0.47	0.63	0.60	0.34	0.91	0.66	0.86	0.93	1.33	1.44	1.08	1.21	
FeO	7.90	19.73	25.36	23.45	27.84	20.72	24.81	19.17	26.75	27.52	25.09	26.19	20.07	10.74	23.18	23.62	25.84	26.08	
MgO	19.67	12.63	11.80	10.50	7.44	7.00	6.74	5.86	3.79	3.42	2.10	1.53	0.75	0.32	1.58	1.53	10.68	10.63	
CaO	5.26	4.45	0.58	3.97	3.72	9.72	7.52	13.27	8.50	8.65	10.71	12.48	2.26	5.39	10.10	8.80	0.75	0.80	
MnO	0.36	0.49	0.53	0.35	0.51	1.30	0.57	0.38	0.84	1.50	2.58	0.72	20.37	26.36	5.40	6.54	0.42	0.56	
Total	99.81	100.31	99.94	100.04	99.85	100.03	100.32	99.76	99.27	100.70	99.93	100.40	101.18	100.80	99.10	99.48	99.06	99.10	
Formula based on 12 oxygen atoms																			
Si	2.995	2.986	2.981	2.983	2.986	2.983	2.973	2.978	2.998	2.972	2.995	2.984	2.955	2.967	3.005	3.011	3.006	2.986	
Al	1.805	1.974	1.983	1.976	1.962	1.934	1.962	1.954	1.961	1.968	1.936	1.956	1.908	1.933	0.000	0.003	0.008	0.004	
Ti	0.012	0.002	0.006	0.005	0.003	0.016	0.015	0.014	0.004	0.014	0.010	0.008	0.045	0.017	1.919	1.906	1.924	1.927	
Cr	0.143	0.003	0.002	0.002	0.002	0.005	0.001	0.000	0.000	0.004	0.001	0.001	0.000	0.000	0.000	0.002	0.003	0.002	
Fe ^{3+*}	0.042	0.025	0.014	0.022	0.036	0.048	0.028	0.037	0.036	0.020	0.055	0.040	0.053	0.057	0.081	0.087	0.063	0.071	
Fe ²⁺	0.474	1.231	1.613	1.491	1.815	1.333	1.605	1.234	1.775	1.812	1.668	1.734	1.368	0.729	1.562	1.591	1.668	1.688	
Mg	2.102	1.404	1.337	1.190	0.864	0.804	0.777	0.673	0.448	0.402	0.249	0.181	0.091	0.039	0.189	0.184	1.229	1.226	
Ca	0.404	0.356	0.047	0.324	0.311	0.802	0.623	1.095	0.723	0.730	0.912	1.058	0.198	0.468	0.872	0.760	0.063	0.067	
Mn	0.022	0.031	0.034	0.022	0.034	0.085	0.038	0.025	0.057	0.100	0.174	0.049	1.406	1.811	0.368	0.446	0.027	0.037	
Total	7.997	8.011	8.015	8.013	8.011	8.008	8.018	8.008	8.000	8.020	7.998	8.008	8.021	8.020	7.995	7.989	7.991	8.005	
Garnet end-members [mol%]																			
Prp	70.0	46.5	44.1	39.3	28.6	26.6	25.5	22.2	14.9	13.2	8.3	6.0	3.0	1.3	6.3	6.2	40.7	40.1	
Alm	15.8	40.7	53.2	49.3	60.0	44.1	52.8	40.8	59.1	59.5	55.5	57.4	44.7	23.9	52.2	53.4	55.2	55.2	
Sps	0.7	1.0	1.1	0.7	1.1	2.8	1.2	0.8	1.9	3.3	5.8	1.6	45.9	59.4	12.3	15.0	0.9	1.2	
And	2.1	1.2	0.7	1.1	1.8	2.4	1.4	1.8	1.8	1.0	2.7	2.0	2.7	2.9	4.1	4.4	3.1	3.5	
Uv	7.1	0.2	0.1	0.1	0.1	0.3	0.1	0.0	0.0	0.2	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.1	
Grs	4.2	10.4	0.8	9.5	8.4	23.9	19.0	34.3	22.3	22.8	27.6	33.0	3.8	12.5	25.1	21.0	0.0	0.0	

Alm – almandine, And – andradite, Grs – grossular, Prp – pyrope, Sps – spessartine, Uv – uvarovite; *c – core; r – rim; ** – calculated assuming garnet stoichiometry; b.d.l. – below detection limit; oxides in [wt.%]

1958; Kryzowska, 1960, 1962; Méres et al., 2012). The heavy mineral assemblages display the same mineral composition, and there are close resemblances also in the colour varieties of tourmaline, garnet, zircon and rutile and their habit (cf. Przybyłowicz, 1958; Kryzowska, 1960, 1962). Nevertheless, there are noticeable differences in mineral frequencies. The Middle Jurassic deposits are variously dominated by zircon or garnet, while the frequencies of other constituents fluctuate in the range from several to over ten percent, though in the zircon-dominated assemblages the zircon content usually does not exceed 40% (Przybyłowicz, 1958; Kryzowska, 1960, 1962; Méres et al., 2012).

The heavy mineral fractions from the Czatkowice palaeokarst described here are clearly zircon-dominated. This may be either an effect of erosion of rocks where zircon dominates in the heavy fraction, relative enrichment in zircon due to disintegration and dissolution of less resistant minerals, a result of specific sorting processes during sedimentation in the karst, or a combination of all these.

The “productive” Carboniferous and Lower Triassic clastic deposits have long been considered as the source rocks for detritus of the Middle Jurassic sandstones and sandy limestones. This opinion was based on the rounded habit of minerals and on a comparison of garnet and other mineral frequencies (Przyby-

łowicz, 1958; Kryowska, 1960, 1962 and references therein). The dominant rounded heavy minerals from the Czatkowice palaeokarst display textural features indicating their recycling and derivation from sedimentary source rocks. Microtextures visible on the rounded grains, having smoothed surfaces, suggest that their dissolution took place prior to final deposition in the palaeokarst infill. As for the Middle Jurassic clastic rocks,

the minerals studied show close similarities to heavy mineral assemblages occurring in the Carboniferous, Permian and also Triassic clastic rocks occurring in the Kraków area (e.g., Łydka, 1955, 1956; Siedlecka and Kryowska, 1962). Therefore, these rocks may be the source rocks. An additional source of clastic material could be sediments of the northeastern surroundings of the area studied, uplifted due to Mesozoic reactivation along the Kraków–Lubliniec Fault Zone (e.g., Żaba, 1999).

The chemical composition of the garnet population studied is to a large extent comparable to that acquired for garnet from Middle Jurassic strata of the region adjacent to the Czatkowice Quarry (Fig. 6; e.g., Aubrecht et al., 2009a; Méres et al., 2012). The similarity especially concerns the garnet population rich in pyrope, though in the garnet population occurring in the Czatkowice palaeokarst more spessartine-rich euhedral garnet varieties were found (Fig. 6; the question of the euhedral garnet is discussed below). This suggests that the sediments preserved in the karst and that of the Middle Jurassic clastics were mostly supplied from the same rocks.

The original source area for the rounded group of heavy minerals studied may be inferred from tourmaline and particularly garnet chemical composition. The diversity of chemical composition of those minerals indicate that they formed in a lithologically

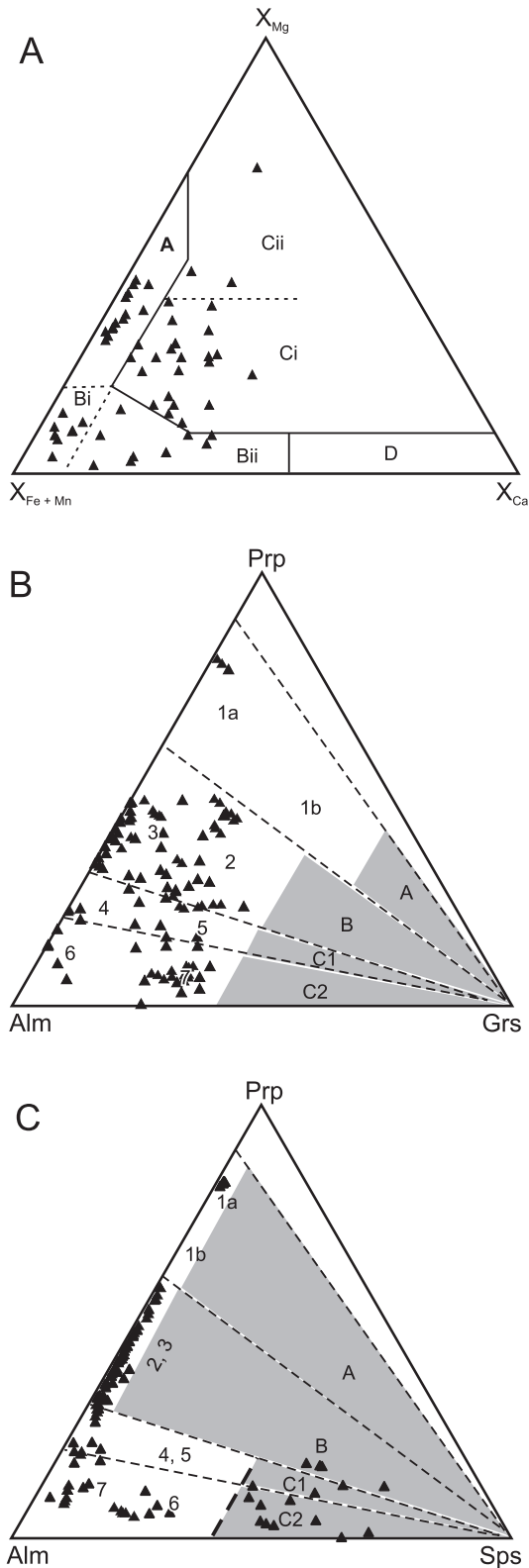


Fig. 7A – composition of garnets from the Jurassic pre-Calloviaian palaeokarst infill from the Czatkowice Quarry on a the ternary plot of natural sedimentary garnet concentrations (Mange and Morton, 2007): A – garnets mainly from high-grade granulite-facies metasedimentary rocks or charnockites, and also from intermediate-acidic igneous rocks sourced from deep in the crust; Bii and Bii – garnets derived from amphibolite-facies metasedimentary rocks where the Bi field is characteristic of garnet from intermediate-acidic igneous rocks; Ci and Cii – fields of garnets mainly from high-grade metabasic rocks where Cii imply sourcing from ultramafic rocks such as pyroxenites and peridotites; D – garnets generally derived from metasomatic rocks, very low-grade metabasic rocks or ultra-high temperature metamorphosed calc-silicate granulites. X_{Fe} , X_{Mg} , X_{Ca} , X_{Mn} – denote the ionic contents of Fe, Mg, Ca and Mn normalized according to Droop and Harte (1995). B, C – composition of the detrital garnets from the palaeokarst infill studied from the Czatkowice Quarry on classification diagrams based on the compositions of garnets studied in their parent rocks (according to Aubrecht et al., 2009b; Méres et al., 2012): environmental fields: A – garnets from UHP/HP (ultra-high pressure/high pressure) conditions; B – garnets from eclogite and granulite facies conditions; C – garnets from amphibolite facies conditions, where C1 – transitional subgroup between granulite and high amphibolite facies conditions and C2 – subgroup of amphibolite facies conditions. Grey fields within environmental fields – immiscibility gap of garnet end-member compositions: A – from UHP/HP conditions, B – from eclogite and granulite facies conditions, C – from amphibolite facies conditions. Positions around numbers denote garnet derived from: 1a – UHP eclogites, garnet peridotites and kimberlites; 1b – UHP eclogites; 2 – HP eclogites and HP mafic granulites; 3 – HP felsic and intermediate granulites; 4 – gneisses metamorphosed under P–T transitional to granulite and amphibolite facies conditions; 5 – amphibolites metamorphosed under transitional P–T granulite to amphibolite facies conditions; 6 – gneisses metamorphosed under amphibolite facies conditions; 7 – amphibolites metamorphosed under amphibolite facies conditions. In the C2 subgroup garnets from other sources are integrated, e.g., garnet from igneous rocks (granitoids, syenites), garnet from HP/LT metamorphic rocks, garnet from contact-metamorphosed rocks; for other explanations see Figure 6

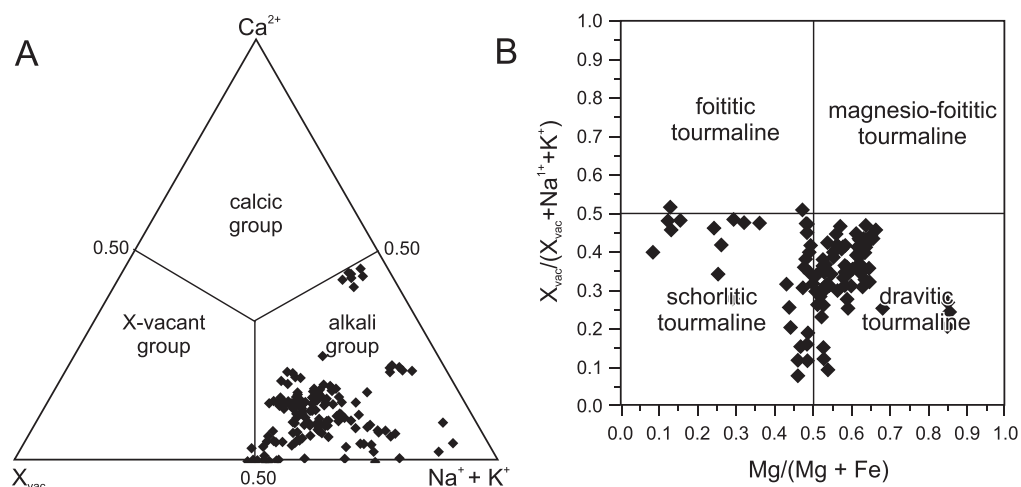


Fig. 8A – primary tourmaline groups, based on dominant occupancy of X-site; B – generalised tourmaline species

Classification diagrams after [Henry et al. \(2011\)](#)

Table 3

Representative analyses of the tourmaline population studied

No.	51r ¹	51c ¹	121r	121c	156	3	9	8	13	2	6	5	19
SiO ₂	36.26	36.89	36.17	37.46	35.86	37.91	36.15	35.26	36.51	35.96	35.85	35.41	35.13
TiO ₂	1.05	1.34	0.80	0.75	0.32	0.74	0.62	0.14	0.45	1.26	2.48	0.49	1.15
B ₂ O ₃	10.69	10.62	10.45	10.81	10.52	10.98	10.60	10.44	10.87	10.38	10.48	10.47	10.53
Al ₂ O ₃	33.45	30.60	31.27	31.90	34.59	32.88	32.18	34.46	35.73	27.77	30.10	33.27	31.70
Cr ₂ O ₃	0.02	0.08	0.06	0.09	0.03	0.04	0.05	0.03	0.10	0.06	0.01	b.d.l.	0.04
MgO	5.97	6.60	4.64	9.23	1.10	9.28	5.65	0.72	5.46	7.19	4.74	2.46	5.70
CaO	0.50	0.23	0.04	0.48	0.03	0.36	0.42	0.05	0.54	1.20	0.05	0.33	1.41
MnO	0.10	b.d.l.	b.d.l.	0.04	0.43	b.d.l.	0.18	0.40	0.03	0.04	0.04	0.11	0.07
FeO	6.73	8.14	10.93	3.29	12.96	2.96	9.22	14.04	6.05	10.97	10.68	12.97	10.18
Na ₂ O	1.73	2.26	2.09	2.19	1.52	2.43	2.20	1.84	1.72	2.15	2.45	1.88	1.58
K ₂ O	0.05	b.d.l.	0.03	0.01	0.03	b.d.l.	0.05	0.01	b.d.l.	0.07	0.01	0.06	0.02
F	0.01	0.07	b.d.l.	0.10	0.06	0.06	0.04	0.13	0.09	0.12	0.01	0.08	0.16
O = F	0.01	0.03	0.00	0.04	0.03	0.03	0.02	0.05	0.04	0.05	0.00	0.03	0.07
Total	96.55	96.79	96.47	96.31	97.43	97.61	97.34	97.45	97.51	97.11	96.88	97.49	97.61
Numbers of ions in formula based on 31 anions													
Si	5.895	6.038	6.015	6.024	5.925	6.002	5.928	5.871	5.837	6.019	5.945	5.879	5.799
Ti	0.128	0.165	0.100	0.091	0.040	0.088	0.076	0.017	0.054	0.159	0.309	0.061	0.143
B	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000
Cr	0.002	0.010	0.008	0.012	0.004	0.005	0.006	0.004	0.012	0.008	0.001	0.000	0.005
Al	6.410	5.904	6.129	6.046	6.735	6.135	6.221	6.763	6.734	5.478	5.884	6.509	6.167
Mg	1.446	1.610	1.150	2.213	0.272	2.191	1.381	0.178	1.301	1.795	1.172	0.609	1.404
Mn	0.013	0.000	0.000	0.005	0.060	0.000	0.025	0.056	0.005	0.006	0.006	0.015	0.009
Ca	0.088	0.041	0.007	0.082	0.005	0.061	0.074	0.008	0.092	0.215	0.009	0.059	0.250
Fe ²⁺	0.914	1.115	1.520	0.443	1.791	0.391	1.265	1.955	0.809	1.535	1.481	1.800	1.405
Na	0.546	0.716	0.672	0.684	0.486	0.746	0.701	0.593	0.534	0.698	0.787	0.606	0.507
K	0.010	0.000	0.006	0.003	0.006	0.000	0.011	0.003	0.000	0.014	0.003	0.013	0.005
Total	18.453	18.599	18.609	18.604	18.325	18.618	18.689	18.448	18.379	18.926	18.597	18.552	18.694
F ⁻	0.007	0.037	0.000	0.050	0.032	0.031	0.019	0.066	0.045	0.062	0.004	0.043	0.085
OH ⁻	3.993	3.963	4.000	3.950	3.968	3.969	3.981	3.934	3.955	3.938	3.996	3.957	3.915
X _{vac} ³	0.36	0.24	0.31	0.23	0.50	0.19	0.21	0.40	0.37	0.07	0.20	0.32	0.24
X _{Mg} ⁴	0.61	0.59	0.43	0.83	0.13	0.85	0.52	0.08	0.62	0.54	0.44	0.25	0.50
Name ⁵	D	D	S	D	F	D	D	S	D	S	S	S	S

¹c – core; r – rim, ² – calculated according to stoichiometry, ³ – X_{vac} = X-site vacancy, ⁴ – X_{Mg} = Mg/(Mg + Fe), ⁵ Name: D – dravite, S – schörl, F – foitite; b.d.l. – below detection limit; oxides in [wt.%]; cations in [apfu]

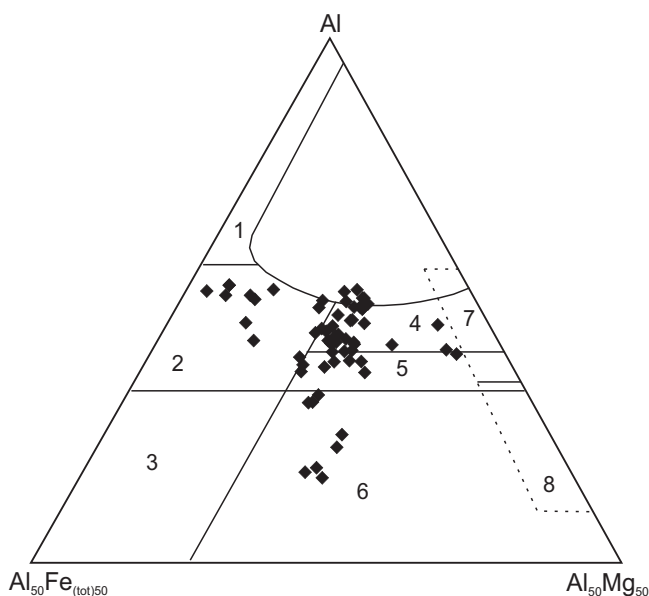


Fig. 9. Provenance of the tourmalines studied on the provenance diagram of Henry and Guidotti (1985)

1 – Li-rich granitoids, pegmatites and aplites; 2 – Li-poor granitoids, pegmatites and aplites; 3 – hydrothermally altered granitic rocks; 4 – Al-rich metapelites and metapsammities; 5 – Al-poor metapelites and metapsammities; 6 – Fe³⁺-rich quartz-tourmaline rocks, calcsilicates and metapelites; 7 – Ca-poor ultramafites; 8 – metacarbonates and metapyroxenites

diverse source area or several different source areas. The most probable source area built of igneous and various grade metamorphic rocks, as indicated by garnet and tourmaline composition, is located in the Moldanubian Zone of the Bohemian Massif (e.g., Dallmeyer et al., 1995; Novák et al., 2004; Mazur et al., 2006; Kotková, 2007; Buriánek and Novák, 2007; Żelaźniewicz et al., 2011; Biernacka, 2012a, b and references therein). Crystalline igneous and metamorphic massifs of this region have also repeatedly been shown to be the origin of detritus of the Carboniferous clastic rocks of the Upper Silesia Block (e.g., Paszkowski et al., 1995; Kusiak et al., 2006). Moreover, the composition of garnet and tourmaline is generally comparable with the compositions of detrital garnet and tourmaline derived from certain massifs of the Moldanubian Zone within the Bohemian Massif (Felička, 2000; Čopjaková et al., 2005; Kotková et al., 2007; Biernacka and Józefiak, 2009; Biernacka, 2012a, b; Kowal-Linka and Stawikowski, 2013).

Regarding the garnet group, one question is whether a two-stage provenance would affect the whole population. Garnet is regarded as moderately stable during transport and burial diagenesis (e.g., Morton, 1984; Morton and Hallsworth, 1999, 2007 and references therein). It can persist to depths of over 3500 m (Morton, 1984; Andò et al., 2012), however, the deeper under ground level, the more etched the garnet grains become and the primary garnet population is gradually depleted in less stable end-members. According to Morton (1987) the less stable garnet molecule is grossular, and in the system almandine–spessartine–grossular–pyrope its relative content decreases with increasing depth. Consequently, the garnet population becomes relatively enriched in pyrope, spessartine and almandine molecules. Taking this into consideration, if grossular garnet was present in the primary source rocks, it may be impoverished in the population studied, while other varieties survive.

EUHEDRAL HEAVY MINERAL SUITE

Only the euhedral minerals have most probably directly derived from a crystalline massif that was exposed and eroded simultaneously with erosion of Carboniferous–Triassic clastic strata delivering the rounded grain population. Elongated euhedral zircon is characteristic of rapidly cooled, porphyritic shallow igneous bodies, while euhedral short prismatic zircon crystals often form in deep igneous intrusions (e.g., Corfu et al., 2003). A source for the elongated zircons could be therefore Carboniferous–Permian volcanic rocks around Czatkowice (e.g., Harańczyk, 1989; Żaba, 1999; Nawrocki et al., 2008; Słaby et al., 2010 and references therein). This idea is supported by the presence of volcanic fragments in the Jurassic strata of the Krzeszowice region (Przybyłowicz, 1958).

The euhedral garnet provenance is more problematic. The presence of euhedral spessartine-rich almandine among the compositionally variable rounded garnet population in the Czatkowice palaeokarst implies that an additional crystalline source massif was eroded during karst infill. The supply seems to have been shut off when the Middle Jurassic sediments were deposited, as suggested by lower frequency of spessartine-rich garnet in those clastic deposits (Fig. 6; Aubrecht et al., 2009a; Méres et al., 2012). Metamorphic rocks which could supply such garnet are known from the crystalline basement of Bruno-vistulicum, in which the area studied is situated (e.g., Buła and Żaba, 2005, 2008; Buła et al., 2008; Żelaźniewicz et al., 2009). The Bielsko-Andrychów Massif contains mica-schists and gneisses formed under middle to upper amphibolite facies conditions (e.g., Moryc and Heflik, 1998; Żelaźniewicz et al., 2009) but these rocks are overlain by strata dating back to the Devonian. However, in the southern part of the Bielsko-Andrychów Massif the Precambrian crystalline rocks are elevated (a situation that may continue under the Carpathians) and occur directly under Miocene strata (Buła et al., 2004). The other known area (much closer to the Czatkowice Quarry) built of metamorphic rocks covered directly by Middle Jurassic deposits (Burtan, 1962; Kryszowska, 1962) is the Rzeszotary horst, as determined in the boreholes Rzeszotary 1 and 2, Dobczyce 1 and 4 and Wiśniowa 6 (Burtan, 1962; Pelczar and Wieser, 1962; Heflik and Konior, 1972, 1974; Konior, 1974; see also Buła et al., 2004). Among metamorphic rocks building the horst mica-schists, gneisses and amphibolites formed under greenschist to amphibolite facies conditions, containing garnet as one of the accessory minerals, were described (Burtan, 1962; Heflik and Konior, 1972, 1974; Górska and Heflik, 1975). The garnet was recognized as almandine using optical methods only (Heflik and Konior, 1974; Górska and Heflik, 1975). However, as this identification was not accompanied by analytical data on the garnet, it cannot be excluded that this almandine could contain a significant amount of the spessartine molecule. Therefore, the Rzeszotary horst may be taken into account as a potential source area for the euhedral spessartine-almandine garnet occurring in the Czatkowice palaeokarst filling. The area is also close enough to the Czatkowice region for garnet to remain in a good preservation state during transport. Nevertheless, it cannot be excluded that other local igneous bodies with metamorphic envelopes delivering euhedral grains existed in the area south of the Kraków–Wieluń Upland, and are now located deep under the Carpathian overthrust. Alternatively, the euhedral grains may have been released from pebbles of igneous and metamorphic rocks of Carboniferous conglomerates (e.g., Paszkowski et al., 1995).

CONCLUSIONS

The high degree of rounding of heavy minerals found in the remnants of Jurassic pre-Calloviaan palaeokarst in the Czatkowice Quarry suggests their recycling and provenance from sedimentary or metasedimentary rocks. Mineral frequencies and mineral species in the assemblages point mainly at Carboniferous or Triassic clastic deposits of the area surrounding the Czatkowice Quarry as the direct sedimentary source rocks, though other sedimentary clastic rocks cannot be excluded as sources.

The chemical compositions of the rounded garnets indicates their initial origin from diverse rock types including acidic to intermediate igneous rocks, metasedimentary rocks of amphibolite facies conditions, high-grade metamorphic rocks as well as ultramafites and ultra-high pressure metabasites. Tourmaline composition suggests a primary provenance from Li-poor granitic rocks and metasedimentary rocks of low Ca and various Al contents. The Bohemian Massif crystalline complexes seem to be the most probable initial source areas for the rounded group of heavy mineral assemblages studied. However, other crystalline massifs exposed during infill of the palaeokarst studied cannot be ruled out.

Only the scarce euhedral grains may have been derived directly from igneous or metamorphic parent rocks. Carboniferous-Permian volcanic rocks intruded within the sedimentary

cover of the Upper Silesia Block, being a part of Brunovistulicum, appear to be parent rocks for euhedral zircon, while crystalline metamorphic rocks building the uplifted parts of basement of Brunovistulicum may be source rocks for the euhedral garnet population.

Summing up two simultaneously operating provenance models may be proposed to explain the heavy minerals occurring in the Czatkowice Jurassic pre-Calloviaan palaeokarst infills:

1) Bohemian Massif igneous and metamorphic bodies (initially) → Carboniferous-Triassic clastic deposits of the area surrounding the Czatkowice Quarry → Czatkowice palaeokarst infill or/and additional delivery from exposed sedimentary or metasedimentary rocks – for the rounded grains and

2) Permian volcanic rocks, the Rzeszotary horst and/or other local igneous and metamorphic bodies, for the euhedral zircon and garnet grains.

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