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DETRITUS FROM VARISCAN LOWER CRUST IN ROTLIEGEND SANDSTONES OF THE INTRA-SUDETIC BASIN, SW POLAND, REVEALED BY DETRITAL HIGH-PYROPE GARNET

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Abstract: It is well established that pebbles in the Sudetic Permian conglomerates were derived from the nearby Variscan massifs of upper-crustal composition. However, the provenance of the sand-size grains remains enigmatic. Electron microprobe analyses (EMPAs) of detrital garnet from upper Rotliegend conglomerates and sandstones exposed at Golińsk, the Intra-Sudetic Basin, showed a distinct assemblage dominated by high-pyrope (high-grossular) almandine, typical of high-grade metamorphic rocks, such as high-pressure granulites. These results, coupled with a previously reported population of similar detrital garnet in the stratigraphically equivalent conglomerates and sandstones of the Karkonosze Piedmont Basin, suggest regional input of detrital lower-crustal material. This detritus was derived ultimately either from the Moldanubian Zone of the Bohemian Massif, or from high-grade rocks of the Orlica-Śnieżnik Massif that were exposed in the Carboniferous–Permian. Permian siliciclastic rocks might have covered a large part of the Sudetes. During the Mesozoic and Palaeogene, these rocks might have been recycled further, contributing high-pyrope garnet, as an accessory mineral, into siliciclastic rocks of the Sudetes and their foreland.

Key words: Permian, Sudetes, sandstone, provenance, detrital garnet, granulite.

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INTRODUCTION

By the end of the Variscan orogeny, in Carboniferous and Permian times, a series of small sedimentary basins formed within the Bohemian Massif. One of them, the Intra-Sudetic Basin on the north-eastern periphery of the Bohemian Massif (Fig. 1), was gradually filled with 10 km thick molasse. The Carboniferous–Middle Permian deposits of this molasse recorded the evolution of the surrounding areas from high mountains under humid tropical conditions to a pediment in a semi-arid climate (Dziedzic and Teisseyre, 1990). Coarse-grained siliciclastic rocks yield numerous lines of evidence that as early as the Early Carboniferous, shortly after metamorphism, the newly formed low- to medium-grade metamorphic rocks of the orogen were exposed and eroded (Teisseyre, 1968, 1971, 1975; Awdankiewicz *et al.*, 2003). In contrast, the later Late Permian to Early Cretaceous history of the Sudetes, which included their platform stage, has been far less recognized because of the poor sedimentary record and many hiatuses, which indicate that denudation prevailed over sedimentation. Recently, Aramowicz *et al.* (2006) and Mazur *et al.* (2010) suggested that the Sudetes, namely the Góry Sowie Massif, were not exposed during the Mesozoic but were buried under a thick sedimentary cover of predominantly Late Carboniferous–Permian age. This sedimentary cover had been almost completely eroded away by Oligocene time. If this assumption is true, the Upper Carboniferous–Permian siliciclastic rocks and not the crystalline rocks known from present-day exposures must have been the source for the Mesozoic sandstones deposited in the Sudetic sedimentary basins and on the foreland of the Sudetes. Although the composition of the hypothetical Upper Carboniferous–Permian cover is unknown, it presumably did not differ from the composition of the Upper Carboniferous–Permian rocks that are preserved in the nearby Intra-Sudetic Basin. Therefore, determination of the composition of the Upper Carboniferous–Permian siliciclastic rocks may help to identify some missing pieces in the Sudetic mosaic.

This contribution concerns conglomerates and sandstones from the upper part of the Rotliegend (lower/middle Permian) in the Intra-Sudetic Basin and discusses whether their provenance was local or more distant. The composition of pebbles in the Permian conglomerates and their local provenance have been long recognized (Berg, 1908; Petrascheck, 1936; Dziedzic, 1961; Dziedzic and Teisseyre,

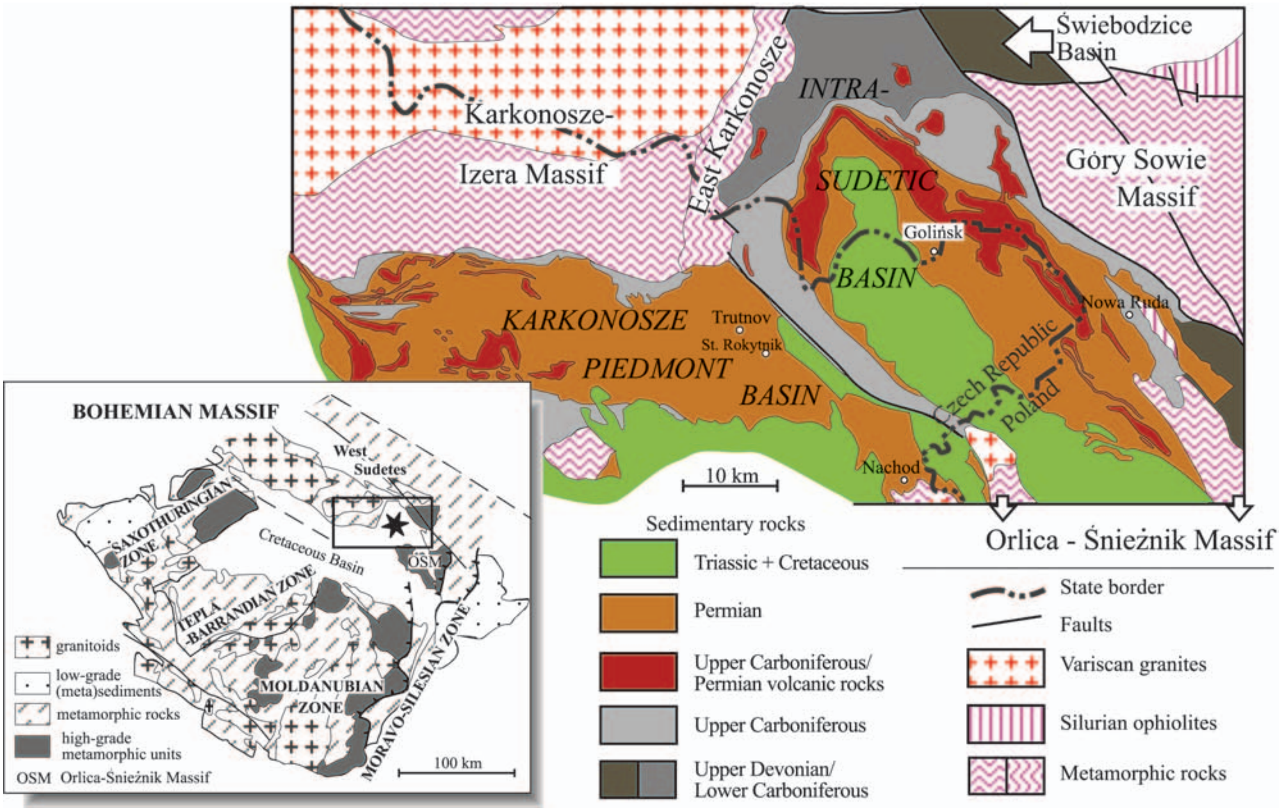


Fig. 1. Simplified geological map of the Intra-Sudetic Basin and adjacent areas. Cenozoic sediments omitted. Compiled from Sawicki (1995) and Prouza and Tásler (2001). Inset shows the entire Bohemian Massif (simplified from Dallmeyer *et al.*, 1995)

1990). However, the composition and provenance of sand-size grains remain enigmatic. A case study of conglomeratic sandstones exposed at Golińsk indicates that part of the finer-grained detritus was delivered from an unknown source of predominantly lower-crust lithology, most likely from the central-eastern part of the Bohemian Massif.

The provenance analysis was based largely on the interpretation of detrital garnet chemistry. Garnet is suitable for such considerations for a number of reasons. It shows extensive compositional variation, reflecting its host-rock chemistry and the pressure-temperature conditions of origin. It is a common mineral in metamorphic rocks and also occurs in peraluminous granites and pegmatites. Representing a wide spectrum of source rocks, garnet has been used in numerous provenance studies (cf. Mange and Morton, 2007). Although garnet is moderately resistant under conditions of weathering and diagenesis (Morton and Hallsworth, 1999), it may withstand mechanical and chemical breakdown over millions of years and under kilometers of overburden. Carboniferous siliciclastic rocks of the Intra-Sudetic Basin, buried to depths of over 5 km, still contain diverse assemblages of detrital garnets, which correspond well with the pebble composition in the same rocks (Felicka, 2000). In turn, the change in detrital garnet populations in the Lower Carboniferous conglomerates from southern Moravia recorded successive pulses in the Variscan orogeny (Hartley and Otava, 2001; Čopjaková *et al.*, 2005). Last but not least, garnet is the most abundant translucent heavy mineral in the rocks studied in this contribution.

MATERIALS AND METHODS

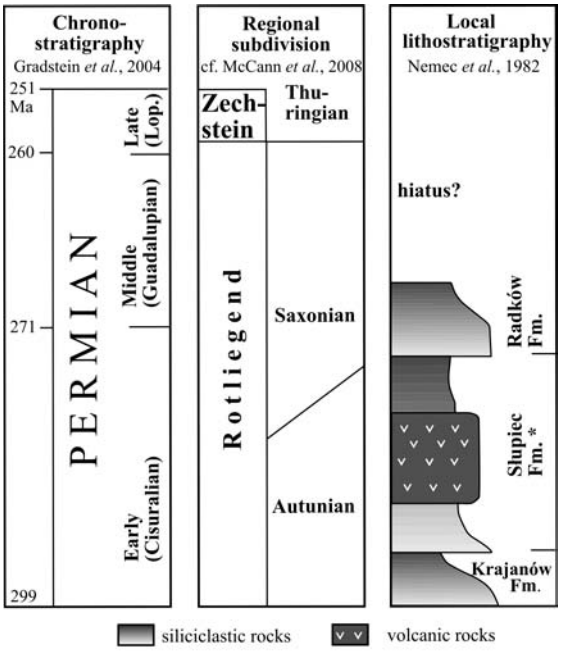
Three samples of conglomeratic sandstone (G1–G3) were taken from the disused quarry at Golińsk in the Intra-Sudetic Basin (Fig. 1). Upper Rotliegend conglomerates and sandstones of the Radków Formation are exposed in a 12 m high cliff at this locality (Aleksandrowski *et al.*, 1986; Fig. 2). The exposed sediments may be divided into three parts (Aleksandrowski *et al.*, 1986). The lowest part is represented by slump deposits, abundant in deformation and dewatering structures, the central part exhibits braided-river channel and bar deposits (Fig. 3A), and the upper conglomeratic part has been interpreted as alluvial fan deposits. Numerous indicators of soil-forming processes, such as green spots in the overall red sediments, root casts, and calcite cement of calcrete origin, can be observed in the exposure. The samples for this study were taken from the fluvial, central part. Sample G3, by comparison with two others, contained more sandy material.

Three thin sections were prepared from the rock samples. A point-counting procedure was used to estimate framework compositions. The number of points counted per thin section was 200–300; cement and matrix were omitted in the counting. The remaining sandstone samples were crushed and sieved to obtain the 3–4 phi (125–63 µm) fraction. This fraction was chosen in earlier research by the author (Biernacka and Józefiak, 2009; Biernacka 2012) to compare the results for different samples. Narrowing observations to one fraction is a recommended strategy to minimise the effects of the hydrodynamic sorting of grains caused by transport, and to make comparisons between different datasets feasible (Hubert, 1971; Mange and Maurer, 1992; Morton and Hallsworth, 1999). As well, the 63–125 µm fraction, by comparison with other grain-size fractions, usually shows the highest concentrations of heavy minerals (Morton, 1985; von Eynatten and Gaupp, 1999). This was demonstrated for the Permian Sudetic sandstones from the Nowa Ruda area, which were pre-examined for their detrital garnet content. Heavy minerals were separated in an aqueous sodium polytungstate solution (2.86 g/cm^3). The heavy fractions were treated with 10% HCl solution for 15 minutes to remove abundant dolomite crystals. The heavy minerals were embedded in araldite, polished and identified under a polarizing microscope; frequency data were obtained by ribbon counting of 300 non-opaque grains.

The garnet compositions of samples G1 and G3 were analysed by means of a Cameca SX-100 electron microprobe (15 kV accelerating voltage, 20 nA probe current, focused beam, 40 s counting time for each element) at Warsaw University. A ZAF matrix correction routine was used during data reduction. At first, a total of 228 garnet grains were examined in accordance with the procedure one EMPA spot per one grain. This procedure was used to assess the range of detrital garnet compositions, on the assumption that the data from statistical number of analyses in randomly cut garnet grains would reveal the entire compositional variation, including possible intra-grain variation. Although the garnets studied showed no visible zonation on back-scattered electron images, 20 randomly chosen garnet grains were tested for the presence of compositional zoning by collecting line analyses (10 spots per grain). Undoubtedly, the small garnet size hindered the observation of complete zonation profiles. It is well established that the larger the grains analysed, the greater the likelihood of observing growth zonation unaltered by high-temperature diffusional homogenisation (Caddick *et al.*, 2010). On the other hand, SEM observations revealed that the 63–125 µm garnet does not necessarily represent unabraded, fine crystals from the host-rock matrix, but rather fragmented larger grains and dissolution remnants. The morphology of the garnet grains was observed by means of a Hitachi 3700N scanning electron microscope at the Institute of Geology, Poznań University.

For comparison, two garnet populations (63–125 and 125–250 µm) from a stratigraphically equivalent sandstone from the Starý Rokytník quarry in the Karkonosze Piedmont Basin (Fig. 1) also were analysed. The larger grain fraction contained a lower amount of heavy minerals, including garnet. No compositional differences were observed between the two fractions.

SANDSTONE COMPOSITION AND GARNET CHEMISTRY



*Volcanic part of Słupiec Fm. recently dated as 300 ± 4 Ma (Awdankiewicz and Kryza, 2010).

Fig. 2. Lithostratigraphy of Permian in the Intra-Sudetic Basin

The conglomeratic sandstones are lithic arenites containing dispersed, angular ignimbrite pebbles, 5–20 mm in diameter (Fig. 3B). These ignimbrite pebbles constitute a grain-supported framework in the conglomerates and reach 20 cm (5 cm on average). The coarse- to medium-grained sandy ‘matrix’ is much more diverse and consists of monocrystalline quartz, at least partly of volcanic origin, rhyolite and trachybasalt rock fragments, polycrystalline quartz, metamorphic rock fragments, feldspars (K-feldspar predominates, compared to plagioclase), and rare fine-grained sandstones. The metamorphic rock fragments contain quartz, K-feldspar or plagioclase, muscovite or biotite, and show some foliation. However, the small sizes of grains make a more precise determination than ‘gneiss’ impossible (Fig. 3C, D). On average, judging by the percentages of polycrystalline quartz and metamorphic rock fragments, one quarter to one third of the sand grains ultimately originated from metamorphic rocks (Tab. 1). In contrast to the angular ignimbrite pebbles, a large proportion of the sand grains – particularly the metamorphic rock fragments – is subrounded to well rounded (Fig. 3C–E). The sandstones are rich in heavy minerals, individual species of which can be observed as separate grains in early diagenetic calcite/dolomite cement. Sample G1 differs from two others in showing a lack of haematite pigment (Fig. 3E).

Facetted garnet grains predominate in the translucent heavy mineral suites (Fig. 3F). The remaining, translucent heavy minerals are – in the order of decreasing frequency – zircon, tourmaline, rutile, staurolite, biotite, monazite, anatase, and apatite. Opaque minerals constitute 50% of the entire heavy mineral assemblage and consist of haematite, titanoferrous magnetite, and ilmenite.

The compositions of the detrital garnets (Tab. 2, Fig. 4) may be grouped into four populations. The first population (1) consists of high-pyrope high-grossular almandine with the most common composition $Alm_{40-60}Prp_{20-40}Grs_{8-35}Sps_{1}$. One pyrope grain ($Alm_{27}Prp_{52}Grs_{20}$) was found among the grains studied. These garnet grains are mostly homogenous

Table 1

Framework composition and heavy-mineral data for Rotliegend conglomeratic sandstones from Golińsk

	Qz_{mono} %	Qz_{poli} %	Kfs %	Pl %	VRF %	MRF %	SRF %	HM %	HM* wt%	Grt %	Zrn %	Tur %	Rt %	Ant %	St %	Mnz %	Bt %	Ap %
G1	16	18	6	2	43	13	2	tr.	0.4	35	36	12	13	-	2	1	1	tr.
G2	24	18	5	1	40	9	3	tr.	0.5	40	32	12	12	-	2	1	1	tr.
G3	28	21	10	1	30	7	2	1	1.5	56	17	11	7	2	3	1	3	tr.

Ant – anatase; Ap – apatite; Bt – biotite; Grt – garnet; HM – heavy minerals; Kfs – K-feldspar; Mnz – monazite; MRF – metamorphic rock fragments; Pl – plagioclase; Qz_{mono} – monocrystalline quartz; Qz_{poli} – polycrystalline quartz; Rt – rutile; SRF – sandstone fragments; St – staurolite; tr. – traces (<0.5%); Tur – tourmaline; VRF – volcanic rock fragments; Zrn – zircon; * in 63–125 µm fraction containing separate grains and fine fragments of crushed pebbles

Table 2

Selected garnet analyses

Grain	G1_19	G1_47	G1_62	G1_64	G1_75	G1_95	G1_68	G1_103	G3_1	G3_3	G3_8	G3_69
SiO_2	38.83	39.47	39.31	38.45	36.96	38.34	37.21	39.27	37.29	36.81	38.28	38.53
TiO_2	0.07	0.09	0.07	0.26	0.24	0.06	0.13	0.09	0.13	0.18	0.07	0.22
Al_2O_3	22.34	22.73	22.51	21.66	21.02	22.04	21.05	22.46	21.23	20.89	22.21	22.11
Cr_2O_3	0.01	0.03	0.05	0.01	0.02	0.05	b.d.l.	0.08	b.d.l.	0.02	0.05	b.d.l.
MgO	9.24	9.67	11.82	5.31	0.70	8.84	0.65	10.69	3.18	0.68	8.52	6.93
CaO	4.85	8.11	1.17	8.97	8.18	0.70	8.88	2.38	4.61	6.83	0.88	8.21
MnO	0.39	0.42	0.24	0.54	9.29	0.40	11.86	0.38	9.42	9.48	0.88	0.46
FeO^{tot}	23.68	19.93	24.40	25.63	24.05	29.48	20.69	24.90	23.85	25.19	29.05	23.34
Total	99.41	100.45	99.57	100.59	100.44	99.92	100.34	100.25	100.26	99.87	100.50	99.98
Si	2.978	2.966	2.983	2.969	2.965	2.969	2.979	2.978	2.993	2.999	2.978	2.997
Ti	0.004	0.005	0.004	0.015	0.014	0.003	0.008	0.005	0.008	0.002	0.010	0.000
Al	2.019	2.013	2.013	1.971	1.988	2.011	1.986	2.007	1.948	1.959	1.922	1.882
Cr	0.001	0.002	0.003	0.000	0.001	0.003	0.000	0.005	0.000	0.002	0.000	0.000
Fe^{3+}	0.016	0.043	0.010	0.060	0.052	0.041	0.041	0.022	0.048	0.037	0.102	0.125
Mg	1.056	1.083	1.337	0.611	0.083	1.021	0.077	1.209	0.724	1.328	0.078	0.651
Ca	0.398	0.653	0.095	0.742	0.703	0.058	0.761	0.193	0.825	0.077	0.414	0.165
Mn	0.025	0.027	0.016	0.035	0.631	0.026	0.804	0.024	0.035	0.026	0.764	0.985
Fe^{2+}	1.502	1.209	1.539	1.595	1.562	1.867	1.343	1.557	1.417	1.570	1.732	1.196
Total	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
Prp	35.4	36.4	44.8	20.5	2.8	34.3	2.6	40.5	24.1	44.3	2.6	21.7
Sps	0.8	0.9	0.5	1.2	21.2	0.9	26.9	0.8	1.2	0.9	25.6	32.9
Alm	50.4	40.7	51.5	53.5	52.4	62.8	45.0	52.2	47.2	52.3	58.0	39.9
Uv	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Adr	0.1	0.5	0.0	0.7	0.6	0.0	0.5	0.1	0.7	0.0	0.7	0.3
Grs	13.2	21.5	3.2	24.1	23.0	1.9	25.0	6.4	26.8	2.5	13.1	5.2

The garnet formulae were calculated on the basis of 12 oxygens and 8 cations; the Fe3+ concentrations were estimated using the algorithm of Droop (1987); b.d.l. – below detection limit

in composition (Fig. 5B, C), although some show a slight decrease in grossular and an increase in pyrope and almandine components from the cores towards the rims (Fig. 5D). The second population (2) encompasses high-pyrope low-grossular almandine, with a typical composition that may be summarized as $Alm_{50-65}Prp_{30-45}Grs_{1-5}Sps_1$. All garnets analyzed from this group lacked any significant major-element zonation (Figs. 5A, 6). The third population (3) includes high-spessartine high-grossular almandine (and minor spessartine) of the typical composition $Alm_{40-60}Prp_{1-5}Grs_{10-25}Sps_{15-45}$. A few garnet grains that show lower spessartine (10–15 mol%), but high-grossular (15–30 mol%) contents, were also included in this group. Line scans collected across three garnet grains exhibited flat compositio-

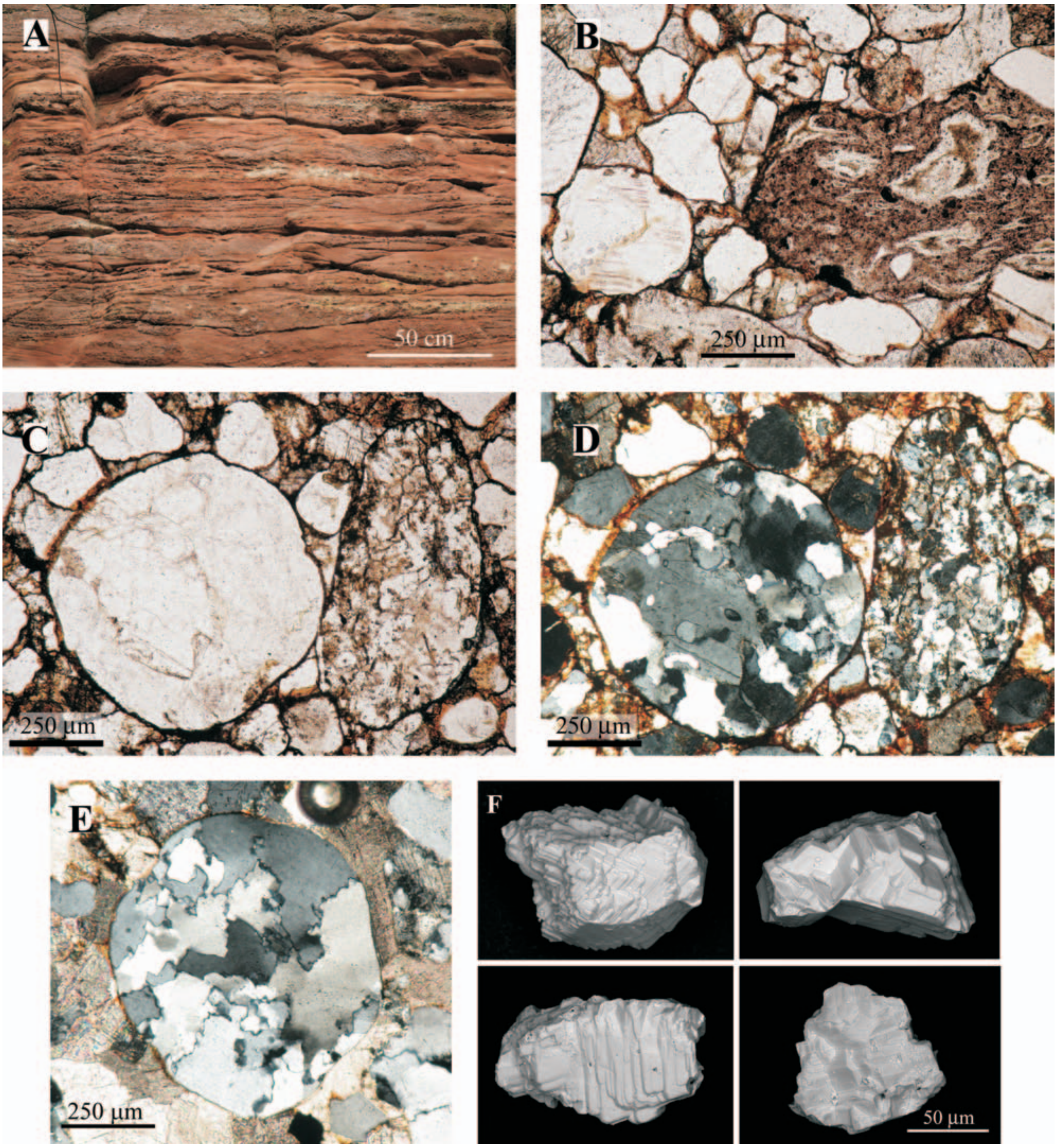


Fig. 3. Rotliegend conglomeratic sandstones, Radków Formation, Golińsk, Intra-Sudetic Basin. **A.** Fragment of exposure showing mid-channel bar deposits of braided river. **B.** Photomicrograph of ignimbrite clast in sandy matrix. Plane-polarized light. **C**, **D.** Well rounded sand-size fragments of metamorphic rocks composed of K-feldspar and quartz; C – plane-polarized light; D – crossed polars. **E.** Well rounded polycrystalline quartz grain set in calcite cement. Plane-polarized light. **F.** Secondary electron SEM micrographs of garnet grains

nal profiles (Fig. 5E). A characteristic feature of the garnets of the third population is greater abundance of mineral inclusions, primarily quartz, by comparison with the other garnets. The fourth group (4) consists of various garnet compositions, none of which predominates: almandine-rich ($Alm_{>75}$), high-spessartine almandine with elevated pyrope content ($Alm_{40-60}Prp_{10-15}Grs_{2-5}Sps_{20-45}$), almandine-spessartine solid solution, high-grossular almandine, and a few grains with the composition $Alm_{61-74}Prp_{8-18}Grs_{3-8}Sps_{10-20}$, typical of the Sowie Góry gneisses.

The detrital garnet assemblages are dominated by groups (1) and (2), which together make up more than 60% (Fig. 7).

DISCUSSION

Without doubt, the angular, coarse, volcaniclastic material was delivered from the volcanic rocks nearby (cf. Fig. 1; Dziedzic, 1961; Aleksandrowski *et al.*, 1986). A tectonic pulse at the end of Rotliegend deposition caused the rejuve-

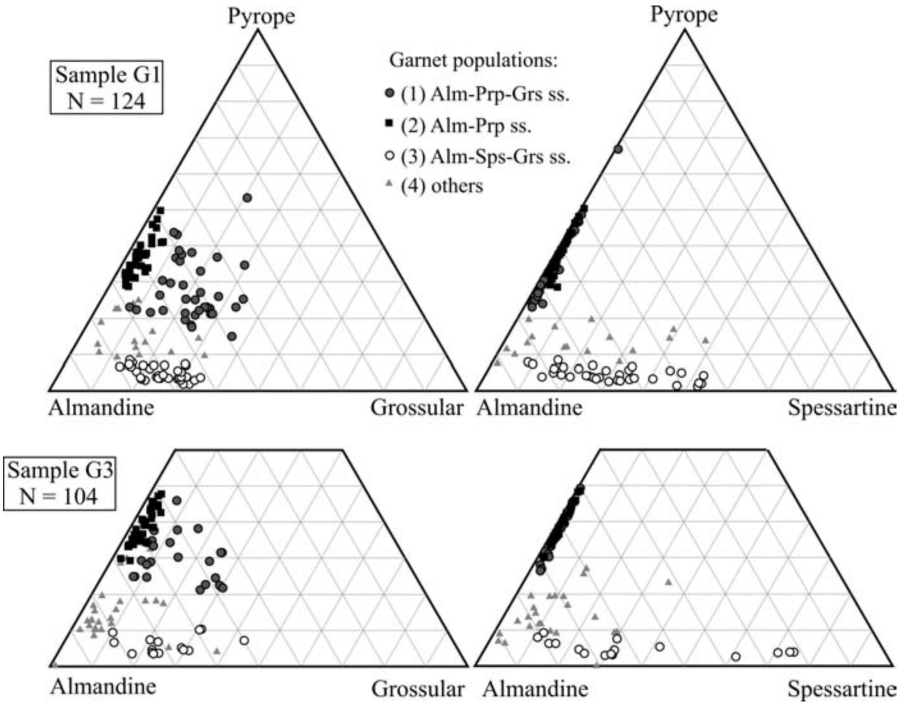


Fig. 4. Triangular diagrams showing proportions of almandine-pyrope-grossular and almandine-pyrope-spessartine components in detrital garnets from Rotliegend sandstones, Golińsk, Intra-Sudetic Basin

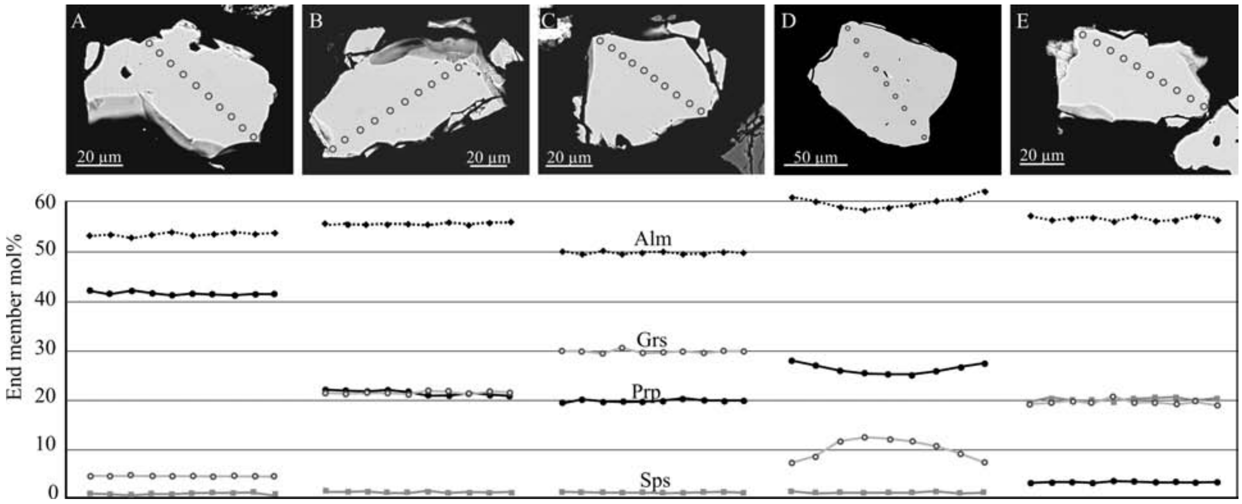


Fig. 5. Back-scattered electron images and zonation profiles of five detrital garnet grains from Rotliegend sandstones

nation of relief and resulted in coarse-grained sedimentation in the Intra-Sudetic Basin (Dziedzic, 1961; Nemec *et al.*, 1982; Wojewoda and Mastalerz, 1989). Coarse-grained deposits have been interpreted mainly as alluvial fan deposits (Dziedzic, 1961; Wojewoda and Mastalerz, 1989). The Golińsk succession also documents a braided river environment (Aleksandrowski *et al.*, 1986). This river carried volcanic pebbles, as well as finer siliciclastic material that originated from metamorphic rocks (cf. Fig. 3C–E). The latter material could have come from the eastern part of the Karkonosze-Izera Massif or the Orlica-Śnieżnik Massif, which also delivered coarse-grained rock fragments into the nearby sedimentary basins (Dziedzic, 1961; Aleksandrowski *et al.*, 1986; Prouza and Tásler, 2001). The derivation from older sedimentary rocks also cannot be excluded. However, the small size of the lithic grains and the limited diversity of altered heavy mineral assemblages hinder a direct interpretation. The study of detrital garnet sheds new light on the provenance of the fine-grained detritus.

Provenance of detrital garnet

The detrital garnet of group (1) – a solid solution of almandine, pyrope, grossular with minor andradite and spessartine – shows the characteristic composition of garnets in high-pressure (HP) metamorphic rocks, such as eclogites and HP granulites (e.g., O'Brien and Vrána, 1995; Bröcker and Klemd, 1996; Kryza *et al.*, 1996; Vrána *et al.*, 2005; O'Brien, 2006; Kotková, 2007). The lack of compositional zoning in the small garnet grains and the slight decrease of Ca component towards the rims are in accord with numerous observations in high-grade rocks, in which garnet zoning patterns are usually attributed to diffusional homogenisation and decompression (O'Brien, 1999, 2006; Anczkiewicz *et al.*, 2007; Kotková, 2007). Eclogites and HP granulites formed in the deep roots of the Variscan orogen in Europe, underwent rapid exhumation, and are presently exposed at many places along the Variscan belt, including the Bohemian Massif (O'Brien and Carswell, 1993). Because they recorded extreme metamorphic conditions, they have been intensively examined and their occurrences are widely known. The Góry Sowie, Śnieżnik, Kutná Hora complexes and a few occurrences within the Moldanubian Zone (western Moravia, Southern Bohemia, Lower Austria) represent the geographically closest localities to the Golińsk site. Although eclogites and HP granulites occur in various tectono-stratigraphic units that experienced diversity of geological evolution, the major-element composition of garnet is almost identical. This, and the lack of information on the bulk chemistry of the parent rocks of the detrital garnets, as well as the absence of many rock-forming minerals in the heavy-mineral suites (clinopyroxene, orthopyroxene, amphibole, spinel, kyanite, zoisite), make anything other than a qualitative interpretation of PT conditions impossible.

The group (2) garnet differs from group (1) by having a lower grossular component, which suggests a lower pressure of crystallization (Spear, 1993). High-pyrope almandine, with minor spessartine, grossular and andradite, is characteristic of medium-pressure granulites. The observed lack of garnet zoning is consistent with the high temperatures of the granulite facies, which promote homogenous growth and advance diffusional homogenisation (O'Brien, 1999; Caddick *et al.*, 2010). Intriguingly, medium- and low-pressure granulites are rare at the present-day erosion level of the Bohemian Massif (Janoušek *et al.*, 2006), and where they occur, their garnets show a slightly different composition to the detrital garnet. This garnet type is typical of ancient granulites (Fig. 8E; Čopjaková *et al.*, 2005; Kotková *et al.*, 2007). The group (2) garnet, in comparison with group (1), does not indicate unambiguously a new lithology. These grains could have originated from the same rocks as group (1). However, in contrast to the group (1) garnets, they show a more advanced high-temperature/medium- pressure overprint, attained at medium crustal depth. The occurrence of the garnet characterised by decreasing Ca content from its core to rim (Fig. 5D), and a gradual decrease of the grossular component from the group (1) to group (2) garnet (Fig. 4), support arguments for such an interpretation.

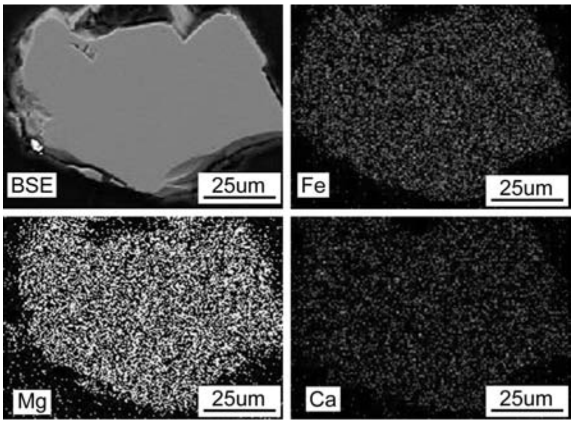


Fig. 6. Back-scattered electron image and three X-ray maps of granulitic garnet from Rotliegend sandstone

The composition of the group (3) garnet, an almandine-spessartine-grossular solid solution, is also distinct and quite rare (cf. Deer *et al.*, 1997). Garnets of this type were described from medium/high-pressure amphibolites and gneisses of the East Karkonosze complex (Kryza and Mazur, 1995), an area not distant from Golińsk, *c.* 25 km to the west (Fig. 1). The striking similarity between the range of compositions of the group (3) garnet and the compositional variation of garnet from the rocks of the East Karkonosze complex (Figs. 4 and 8C), the significant frequency of this garnet type (Fig. 7), and a record of Permian conglomerates, in which the pebbles were derived from the East Karkonosze complex (Dziedzic, 1961), all indicate that part of detritus was supplied from this proximal source directly, or was recycled from older sediments.

The garnet types in group (4) are not frequent and could have originated in a variety of medium- to low-pressure metamorphic rocks. If we compare the compositional data of this group with the composition of garnets from the dominant lithologies of the surrounding massifs (Fig. 8A–C),

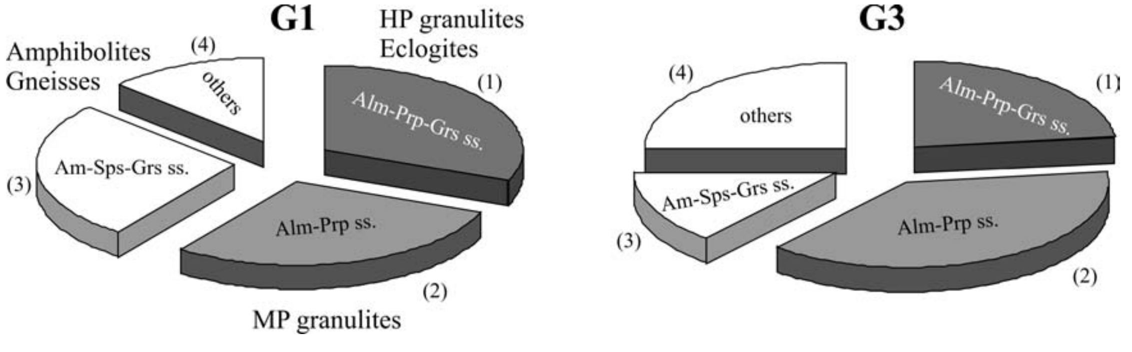


Fig. 7. Pie diagrams showing frequencies and inferred provenance of detrital garnet assemblages from Rotliegend sandstones, Golińsk, Intra-Sudetic Basin

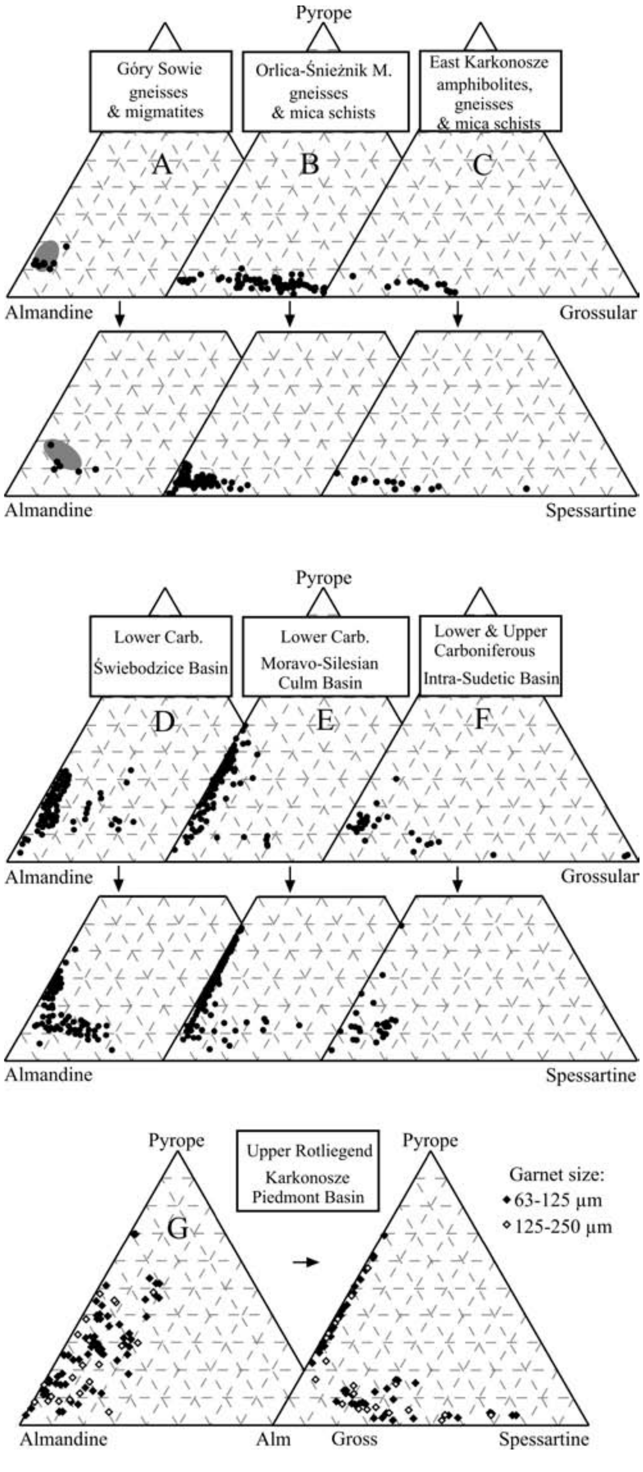


Fig. 8. Compositional data for garnet in dominant lithologies of massifs surrounding the Intra-Sudetic Basin (A–C) and in selected siliciclastic rocks of the Bohemian Massif (D–G) shown in almandine-pyrope-grossular and almandine-pyrope-spessartine triangular diagrams. Data from: A – Felicka (2000), Budzyń *et al.* (2004); B – Grześkowiak (2004), Szczepański (2010); C – Kryza and Mazur (1995); D – Otava and Sulovsky (1998); E – Čopjaková *et al.* (2005); F – Felicka (2000); G – author's data for sandstone from Starý Rokytník quarry

then several grains characteristic of the Góry Sowie gneisses and migmatites, few almandine-grossular grains similar to garnets in gneisses and metapelites of the Orlica-Śnieżnik Massif, and few grains of typical granitic almandine-spessartine composition can be recognized. This set of garnets occurs mainly in the G3 sample. It also resembles detrital garnets from the Carboniferous siliciclastic rocks of the Intra-Sudetic Basin (Fig. 8F; Felicka, 2000). The possibility cannot be excluded that a part of the group (4) is genetically linked to the other populations and may represent their extreme compositional variation. The almandine-spessartine with elevated pyrope content, detected in both samples, has hitherto been unrecognised in the Sudetic crystalline rocks. This unusual garnet composition has been detected recently in manganese-rich metasediments of the Moldanubian Zone of southern Bohemia (Vrána, 2011). The garnet host rocks are volumetrically minor and have been described as lithostratigraphic markers (Vrána, 2011).

Detritus from a lower crust

The detrital garnets from the Golińsk conglomerates and sandstones represent diverse and distinct populations. For the most part, they originated in high-grade metamorphic rocks. Judging by the sand-size fragments of metamorphic rocks, they could have come from HP felsic granulites, typical of the orogenic lower crust (cf. Schulmann *et al.*, 2008). The nearest known occurrences of HP granulites are the Góry Sowie and Śnieżnik complexes. However, at the present-day denudation level, the surrounding crystalline massifs contain only lens and inliers of HP metamorphic rocks (Żelaźniewicz, 1985; Kryza *et al.*, 1996). If the siliciclastic material did come from the Góry Sowie Massif or the Orlica-Śnieżnik Massif, it should have also been accompanied by other low-pyrope garnets, typical of the dominant lithologies there – gneisses, migmatites and metapelites (Fig. 8A, B). However, only the nearby East Karkonosze complex has yielded a significant contribution that is recognized in the detrital garnet record. Thus, either the erosion level of the orogen in the Permian was different than that obtained at present, and in the vicinity of the Intra-Sudetic Basin high-grade metamorphic rocks were extensively exposed, or the high-grade detrital material was delivered from a more distant source of predominantly lower-crust composition. None of these possibilities can be totally excluded. Recent thermochronological data from the eastern part of the Orlica-Śnieżnik Massif indicate that metamorphic rocks of the present denudation level were several km below the surface in the Permian–Triassic (Danišík *et al.*, 2012). Since the basement of the eastern part of the Bohemian Massif shows a complicated structure of mixed lower- and middle-crust boudins and blocks (Schulmann *et al.*, 2008), a wider occurrence of lower-crust rocks was likely. On the other hand, the high degree of roundness of sand-size particles indicates that a more distant source also was possible. The distance from the Góry Sowie and Orlica-Śnieżnik Massifs is short so the detritus should have been composed of unabraded grains, rather than well rounded rock fragments. Therefore, it is possible that a Permian river in the Intra-Sudetic Basin carried detritus from the 'interior' of the Bohemian Massif, where granulites formed larger bodies, i.e. from a distance of a hundred kilometres or more. Possibly, this detritus was of recycled rather than first-cycle origin.

The granulites were exhumed shortly after formation and already in Early Carboniferous times they were the source of detritus for the Moravo-Silesian Culm Basin (Hartley and Otava, 2001). Clasts of these granulites contain low-grossular pyrope-almandine garnet, which is also an abundant heavy mineral in the matrix of their host rocks, the Late Viséan Culm conglomerates (Fig. 8E; Čopjaková *et al.*, 2005). Kotková *et al.* (2007), on the basis of a detailed petrogenetic study of granulite pebbles in these conglomerates, suggest that they came from a higher part of the Moldanubian Zone than the one exposed at the present denudation level. Presumably, granulites from the Sudetic part of the Bohemian Massif were at the surface as early as in the Tournaisian. Conglomerates deposited north of the Góry Sowie Massif, in the Świebodzice Basin, contain detrital garnets typical of the Góry Sowie gneisses, with a minor admixture of granulitic garnet (Fig. 8D; Otava and Sulovsky, 1998).

The rapid exhumation of the deep roots of the orogen from a depth of *c.* 60–70 km, and the present-day relationship of lower- and upper-crustal rocks, have been the subject of long standing debate (e.g., O'Brien and Carswell, 1993). Recently, Schulmann *et al.* (2008) proposed a two-stage mechanism for the eastern part of the Bohemian Massif: vertical extrusion of the lower-crustal rocks to a mid-crustal depth, followed by thrusting in a subhorizontal channel. These processes eventually led to the rapid surface exposure of mixed lithologies. Since the Early Carboniferous, part of these rocks of unknown thickness has been eroded. The detrital high-pyrope garnet bears witness to ancient exposures of lower-crustal rocks.

First-cycle vs. multi-cycle origin

Several lines of evidence suggest that the detrital garnet may have been recycled from older sediments. The sand-size grains of metamorphic rock fragments and polycrystalline quartz are sub-rounded to well rounded (Fig. 3), which indicates long transport. Yet the distance of a hundred or more kilometres is not enough to produce well rounded sand-size grains in one cycle, because of the slow rate of rounding of such particles, particularly quartz grains (Pettijohn *et al.*, 1987). Many cycles of transport, each contributing a small part of abrasion, are much more probable. Similar rounded grains occur also in stratigraphically equivalent sandstones in the Czech part of the Intra-Sudetic Basin (Tásler, 1979) and in the nearby Karkonosze Piedmont Basin (the Trutnov Formation; Prouza and Tásler, 2001). These grains were interpreted as indirect evidence for the presence of aeolian dunes in the early/middle Permian. Indeed, transport in many cycles and additional aeolian abrasion could eventually produce the almost spherical sand-size grains. Rare rounded sandstone fragments are direct evidence of recycling. Middle Permian sedimentary rocks cover late- to post-orogenic molasse, several kilometers thick, and recycling must have operated in many places.

On the other hand, the occurrence of sedimentary rocks that are older than early/middle Permian (Saxonian) and contain a similar assemblage of detrital garnet is problematic in the case of the Intra-Sudetic Basin. A reconnaissance study by Felicka (2000) showed that Lower and Upper Carboniferous conglomerates and sandstones from the Intra-Sudetic Basin contain completely different garnet populations (Fig. 8F). The occurrence of detrital garnet in lower Permian alluvial siliciclastic rocks has not been recognized yet. This problem requires a more systematic approach, but it is possible that granulitic detritus reached the Intra-Sudetic Basin no earlier than the early/middle Permian. A possible source might have been some Carboniferous siliciclastic rocks in the Czech part of the Bohemian Massif, but relevant published data are lacking, except for the work of Čopjaková *et al.* (2005).

Regional dispersion of detrital high-pyrope garnet

The occurrence of this distinct garnet population is not local. Similar detrital garnets were recognised in fluvial conglomerates and sandstones of the Trutnov Formation, in the eastern part of the Karkonosze Piedmont Basin (the Trutnov–Náchod area; Fig. 1), which are stratigraphically equivalent to the deposits of the Radków Formation (Martínek *et al.*, 2008; Martínek and Štolfová, 2009). Although the number of reported garnet grains (Martínek and Štolfová, 2009) does not permit statistical evaluation, the only noticeable difference is the presence of Cr-pyrope, a typical mantle garnet. This garnet variety, however, is in accordance with the HP garnet population. The author's data from a sandstone from the Starý Rokytník quarry (the Trutnov Formation; Fig. 8G) show that *c.* 60% of the garnet population is composed of a high-pyrope variety (high-pyrope high-grossular almandine or high-pyrope almandine). A lower abundance of grains typical of the East Karkonosze complex and a slightly greater abundance of high-spessartine almandine, characteristic of Al-rich granites and pegmatites, were noticed by comparison with the Golińsk garnet populations. Regional palaeocurrent data from the eastern part of the Karkonosze Piedmont Basin suggest northward and northeastward sediment supply (Martínek and Štolfová, 2009). This and the similarity of the detrital garnet populations suggest a southern provenance for the high-pyrope garnet. The Intra-Sudetic Basin and the Karkonosze Piedmont Basin might have been connected in the early/middle Permian, as postulated by Prouza and Tásler (2001). It cannot be excluded, however, that fine-grained material got to both basins independently, from a common sedimentary predecessor covering large areas in the vicinity.

Some Triassic siliciclastic rocks that occur in the Karkonosze Piedmont Basin (Martínek and Štolfová, 2009) and in the NE foreland of the Bohemian Massif – the Fore- Sudetic Monocline (Muszyński *et al.*, 2007), also contain high-pyrope garnet of similar composition. Furthermore, Upper Cretaceous quartz-rich sandstones in the North-Sudetic and Intra-Sudetic Basins show high-pyrope garnet in their heavy-mineral spectra (Biernacka and Józefiak, 2009; unpublished data of the author). This garnet type occurs also in more distant areas, outside the Bohemian Massif (Aubrecht and

Méres, 2000; Aubrecht *et al.*, 2007). All these garnet assemblages might have been recycled from Permian siliciclastic rocks, and ultimately from a lower-crust unit of the Bohemian Massif. This solution seems simpler than derivation directly from nearby Sudetic crystalline rocks, as suggested by Biernacka and Józefiak (2009), because it explains the predominance of HP garnet among other garnet types. The extent of ancient exposures of lower-crustal rocks as well as the extent of Permian siliciclastic rocks in post-Permian times have not been recognized in detail (e.g., Mazur *et al.*, 2010). The record of the garnet population dominated by the high-pyrope variety in fluvial Permian sandstones from the Intra-Sudetic Basin may be a missing piece of evidence that Bohemian high-pressure rocks could be recycled into the Mesozoic sedimentary rocks deposited in remote areas at a time, when palaeogeography excluded direct delivery of them.

SUMMARY AND CONCLUSIONS

It long has been recognized that pebbles in Permian conglomerates of the Intra-Sudetic Basin were derived from the nearby Variscan massifs, which were composed largely of upper-crustal rocks. In the case of the conglomerates and sandstones exposed at Golińsk, the coarse-grained material came from ignimbrite covers occurring in the vicinity. The sand-size particles in these conglomerates show a more diverse than solely volcaniclastic composition. A study of detrital garnet revealed that:

(1) part of the detritus ultimately came from high-grade metamorphic rocks typical of an orogenic lower crust, such as HP granulites;

(2) the compositions of the detrital garnets for the most part do not correspond to the compositions of garnets from the rocks of massifs surrounding the Intra-Sudetic Basin. Only a significant input from the East Karkonosze complex was recognized.

These results coupled with a previously reported population of similar detrital garnet in stratigraphically equivalent conglomerates and sandstones from the Karkonosze Piedmont Basin suggest a common source for the lower-crustal detritus, probably of recycled nature. This detritus could have been derived ultimately either from the Moldanubian Zone of the Bohemian Massif, or from a lower-crust complex of the Orlica-Śnieżnik Massif that were exposed in the Carboniferous–Permian.

Presumably, the Permian siliciclastic rocks covered a much wider area than the present-day occurrences, but they were eroded in the Mesozoic and Palaeogene. Detrital material from the Permian rocks contributed to the Mesozoic sandstones deposited in the Sudetes and their foreland region. Thus, from the Carboniferous onwards, siliciclastic material derived ultimately from the lower-crustal rocks of the Bohemian Massif could have been transported gradually towards the northern periphery and further outside the massif, by multiple-sediment recycling,

Investigation of the composition of Permian sandstones on a larger-scale should verify these conclusions.

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REFERENCES

Aleksandrowski, P., Śliwinski, W. & Wojewoda, J., 1986. Frontally and surficially fluidized slump to debris flow sheets in an alluvial sequence, Lower Permian, Intra-Sudetic Basin. In: Teisseyre, A. K. (ed.), *IAS 7th European Regional Meeting, Kraków-Poland, Excursion Guidebook*. Ossolineum, Wrocław, pp. 9–29.

Anczkiewicz, R., Szczepański, J., Mazur, S., Storey, C., Crowley, Q., Villa, I. M., Thirlwall, M. E. & Jeffries, T. E., 2007. Lu-Hf geochronology and trace element distribution in garnet: Implications for uplift and exhumation of ultra-high pressure granulites in the Sudetes, SW Poland. *Lithos*, 95: 363–380.

Aramowicz, A., Anczkiewicz, A. & Mazur, S., 2006. Fission-track dating of apatite from the Góry Sowie Massif, Polish Sudetes, NE Bohemian Massif: implications for post-Variscan denudation and uplift. *Neues Jahrbuch für Mineralogie Abhandlungen*, 182: 221–229.

Aubrecht, R. & Méres, S., 2000. Exotic detrital pyrope-almandine garnets in the Jurassic sediments of the Pieniny Klippen Belt and Tatric Zone: where did they come from? *Mineralia Slovaca*, 32: 17–28.

Aubrecht, R., Méres, S., Gradziński, M. & Sýkora, M., 2007. Provenance of detritic garnets in the Middle Jurassic clastic sediments of the Cracow region. *Mineralogia Polonica – Special Papers*, 31: 47–52.

Awdankiewicz, M. & Kryza, R., 2010. The Góry Suche Rhyolitic Tuffs (Intra-Sudetic Basin, SW Poland): preliminary SHRIMP zircon age. *Mineralogia – Special Papers*, 37: 70.

Awdankiewicz, M., Kurowski, L., Mastalerz, K. & Raczyński, P., 2003. The Intra-Sudetic Basin – a record of sedimentary and volcanic processes in a late- to post-orogenic tectonic setting. *GeoLines*, 16: 165–183.

Berg, G., 1908. Zur Geologie des Braunauer Landes. *Jahrbuch der Königlich Preußischen Geologischen Landesanstalt und Bergakademie*, 29: 23–38.

Biernacka, J., 2012. Provenance of Upper Cretaceous quartz-rich sandstones from the North Sudetic Synclinorium, SW Poland: constraints from detrital tourmaline. *Geological Quarterly*, 56: 315–332.

Biernacka, J. & Józefiak, M., 2009. The Eastern Sudetic Island in the Early-to-Middle Turonian: evidence from heavy minerals in the Jerzmanice sandstones, SW Poland. *Acta Geologica Polonica*, 59: 545–565.

Bröcker, M. & Klemd, R., 1996. Ultrahigh-pressure metamorphism in the Śnieżnik Mountains (Sudetes, Poland): P-T constraints and geological implications. *Journal of Geology*, 104: 417–433.

Budzyń, B., Manecki, M. & Schneider, D. A., 2004. Constraints on P-T conditions of high-grade metamorphism in the Góry Sowie Mts., West Sudetes. *Mineralogia Polonica*, 35: 39–52.

Caddick, M. J., Konopásek, J. & Thompson, A. B., 2010. Preservation of garnet growth zoning and the duration of prograde metamorphism. *Journal of Petrology*, 51: 2327–2347.

Čopjaková, R., Sulovský, P. & Paterson, B. A., 2005. Major and trace elements in pyrope-almandine garnets as sediment provenance indicators of the Lower Carboniferous Culm sediments, Drahany Uplands, Bohemian Massif. *Lithos*, 82: 51–70.

Dallmeyer, R. D., Franke, W. & Weber, K. (eds), 1995. *Pre-Permian Geology of Central and Eastern Europe*. Springer-Verleg, Berlin, 593 pp.

Danišík, M., Štěpančíková, P. & Evans, N. J., 2012. Constraining long-term denudation and faulting history in intraplate regions by multisystem thermochronology: An example of the Sudetic Marginal Fault (Bohemian Massif, central Europe). *Tectonics*, 31 (in press), TC2003, doi: 10.1029/2011TC00 3012.0

Deer, W. A., Howie, R. A. & Zussman, J., 1997. *Rock-Forming Minerals. Orthosilicates. Vol. 1A* (*2^{nd} Ed.*). The Geological Society, London, 919 pp.

Droop, G. T. R., 1987. A general equation of estimating Fe^{3+} concentrations in ferromagnesian silicates and oxides from microprobe analyses, using stoichiometric criteria. *Mineralogical Magazine*, 51: 431–435.

Dziedzic, K., 1961. Lower Permian of the Intra-Sudetic Basin. *Studia Geologica Polonica*, 6: 1–121. [In Polish, English summary].

Dziedzic, K. & Teisseyre, A. K., 1990. The Hercynian molasse and younger deposits in the Intra-Sudetic Depression, SW Poland. *Neues Jahrbuch für Geologie und Paläontologie Abhandlungen*, 179: 285–305.

Eynatten, H., von & Gaupp, R., 1999. Provenance of Cretaceous synorogenic sandstones in the Eastern Alps: constraints from framework petrography, heavy mineral analysis and mineral chemistry. *Sedimentary Geology*, 124: 81–111.

Felicka, E., 2000. Heavy minerals in the Carboniferous sediments of the Intra-Sudetic Basin as palaeogeographic indicators. *Geologia Sudetica*, 33: 49–65.

Gradstein, F. M., Ogg, J. G. & Smith, A. G. (eds), 2004. *A Geologic Time Scale 2004*. Cambridge University Press, Cambridge, 589 pp.

Grześkowiak, A., 2004. *Genesis of diversification of the Międzygórze Structure gneisses, Śnieżnik Metamorphic Unit*. Unpublished Ph.D. Thesis, University of Poznań, 233 ms. pp.

Hartley, A. J. & Otava, J., 2001. Sediment provenance and dispersal in a deep marine foreland basin: the Lower Carboniferous Culm Basin, Czech Republic. *Journal of the Geological Society, London*, 158: 137–150.

Hubert, J. F., 1971. Analysis of heavy-mineral assemblages. In: Carver, E. (ed.), *Procedures in Sedimentary Petrology.* Wiley-Interscience; New York, London, pp. 453–478.

Janoušek, V., Gerdes, A., Vrána, S., Finger, F., Erban, V., Friedl, G. & Braithwaite, C.J.R., 2006. Low-pressure granulites of the Lišov Massif, Southern Bohemia: Viséan metamorphism of Late Devonian plutonic arc rocks. *Journal of Petrology*, 47: 705–744.

Kotková, J. 2007. High-pressure granulites of the Bohemian Massif: recent advances and open questions. *Journal of Geosciences*, 52: 45–71.

Kotková, J., Gerdes, A., Parrish, R.R. & Novák, M., 2007. Clasts of Variscan high-grade rocks within Upper Viséan conglomerates – constraints on exhumation history from petrology and U-Pb chronology. *Journal of Metamorphic Geology*, 25: 781–801.

Kryza, R. & Mazur, S., 1995. Contrasting metamorphic paths in the eastern margin of the Karkonosze-Izera Block, SW Poland. *Neues Jahrbuch für Mineralogie, Abhandlungen*, 169: 157–192.

Kryza, R., Pin, C. & Vielzeuf, D., 1996. High-pressure granulites from the Sudetes (south-west Poland): evidence of crustal subduction and collisional thickening in the Variscan Belt. *Journal of Metamorphic Geology*, 14: 531–546.

Mange, M. A. & Maurer, H. F. W., 1992. *Heavy Minerals in Colour*. Chapman and Hall, London, 147 pp.

Mange, M. A. & Morton, A. C., 2007. Geochemistry of heavy minerals. In: Mange, M. A. & Wright, D. T. (eds), *Heavy minerals in use. Developments in Sedimentology, 58.* Elsevier, Amsterdam, pp. 345–391.

Martínek, K. & Štolfová, K., 2009. Provenance study of Permian non-marine sandstones and conglomerates of the Karkonosze Piedmont Basin (Czech Republic): exotic marine limestone pebbles, heavy minerals and garnet composition. *Bulletin of Geosciences*, 84: 555–568.

Martínek, K., Wojewoda, J. & Burliga, S., 2008. Perm Karkonoskiego Basenu Piedmontowego i Basenu Nachodu. In: Wojewoda, J. (ed.), *Baseny śródgórskie. Kontekst regionalny środowisk i procesów sedymentacji*. Wind, Wrocław, pp. 85–110. [In Polish].

Mazur, S., Aleksandrowski, P., Turniak, K., Mastalerz, K., Górecka-Nowak, A., Kurowski, L., Krzywiec. P., Żelaźniewicz, A. & Fanning, M.C., 2010. Uplift and late orogenic deformation of the Central European Variscan belt as revealed by sediment provenance and structural record in the Carboniferous foreland basin of western Poland. *International Journal of Earth Sciences*, 99: 47–64.

McCann, T., Kiersnowski, H., Krainer, K., Vozárová A, Peryt, T., Oplustil, S., Stollhofen, H., Schneider, J., Wetzel, A., Boulvain, F., Dusar, M., Török Á., Haas J., Tait, J. & Körner, F., 2008. Permian. In: McCann, T. (ed.), *The Geology of Central Europe, Vol. 1: Precambrian and Paleozoic.* Geological Society, London, pp. 531–598.

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. & Hallsworth, C. R., 1999. Processes controlling the composition of heavy mineral assemblages in sandstones. *Sedimentary Geology*, 124: 3–29.

Muszyński, M., Gaweł, A. & Skowroński, A., 2007. Facetted garnets from the sandstones of the Buntsandstein on the Fore-Sudetic Monocline (Głogów area, SW Poland). *Geologia*, 33: 51–68. [In Polish, English summary].

Nemec, W., Porębski, S. J. & Teisseyre, A. K., 1982. Explanatory notes to the lithotectonic molasse profile of the Intra-Sudetic Basin, Polish part. *Veröffentlichungen des Zentralinstituts für Physik der Erde/ Akademie der Wissenschaften der DDR*, Potsdam, 66: 267–278.

O'Brien, P. J., 1999. Asymmetric zoning profiles in garnet from HP-HT granulite and imlications for volume and grain boundary diffusion. *Mineralogical Magazine*, 63: 227–238.

O'Brien, P. J., 2006. Type-locality granulites: high-pressure rocks formed at eclogite-facies conditions. *Mineralogy and Petrology*, 86: 161–175.

O'Brien, P. J. & Carswell, D. A., 1993. Tectonometamorphic evolution in the Bohemian Massif: evidence from high-pressure metamorphic rocks. *Geologische Rundschau*, 82: 531–555.

O'Brien, P. J. & Vrána, S., 1995. Eclogites with a short-lived granulite facies overprint in the Moldanubian Zone, Czech Republic: petrology, geochemistry and diffusion modeling of garnet zoning. *Geologische Rundschau*, 84: 473–488.

Otava, J. & Sulovsky, P., 1998. Detrital garnets and chromites from the Książ Formation, Świebodzice Depression: Implications for the Variscan evolution of Sudetes. *GeoLines*, 6: 49–50.

Petrascheck, W. E., 1936. Sedimentation, Vulkanismus und Kupfererzführung im mittel-sudetischen Rotliegenden. In: *Festschrift zum 60. Geburtstag von Hans Stille*. F. Enke Verlag, Stuttgard, pp. 63–84.

Pettijohn, F. J., Potter, P. E. & Siever, R., 1987. *Sand and Sandstone* (2nd ed.). Springer-Verlag, Berlin, 553 pp.

Prouza, V. & Tásler, R. 2001. Podkrkonošská pánev. In: Pešek, J. *et al.* (eds), *Geologie a ložiska svrchnopaleozoických limnických pánví České republiky*. Český geologický ústav, Praha, pp. 128–166. [In Czech].

Sawicki, L. (ed.), 1995. Geological map of Lower Silesia with adjacent Czech and German territories 1:100,000. Państwowy Instytut Geologiczny, Warszawa.

Schulmann, K., Lexa, O., Štípská, P., Racek, M., Tajčmanová, L., Konopásek, J., Edel, J.-B., Peschler, A. & Lehmann, J., 2008. Vertical extrusion and horizontal channel flow of orogenic lower crust: key exhumation mechanisms in large hot orogens? *Journal of Metamorphic Geology*, 26: 273–297.

Spear, F. S., 1993. *Metamorphic Phase Equilibria and Pressure-Temperature-Time Paths*. Monograph no 1, Mineralogical Society of America, Washington, 799 pp.

Szczepański, J., 2010. *Provenance and Tectonometamorphic Evolution of the Supracrustal Series from the Bystrzyckie Mts. Crystalline Massif*. Uniwersytet Wrocławski, Wrocław, 166 pp. [In Polish, English summary].

Tásler, R., 1979. The Trutnov Formation. In: Tásler, R. *et al.* (eds), *Geologie české části vnitrosudetské pánve*. Ústředni ústav geologický v Academii, Praha, pp. 107–114. [In Czech, English summary].

Teisseyre, A. K., 1968. The Lower Carboniferous in the Intrasudetic Basin: A study in sedimentary petrology and basin analysis. *Geologia Sudetica*, 4: 221–298. [In Polish, English summary].

Teisseyre, A. K., 1971. Sedimentology of the Kulm of Ciechanowice and palaeogeography of the lowest Kulm in the Intrasudetic Basin. *Geologia Sudetica*, 5: 237–280. [In Polish, English summary].

Teisseyre, A. K., 1975. Sedimentology and palaeogeography of the Kulm alluvial fans in the western Intrasudetic Basin (Central Sudetes, SW Poland). *Geologia Sudetica*, 9: 1–135. [In Polish, English summary].

Vrána, S., 2011. Manganese-rich garnet-quartz rock and gneisses in the Bohemian part of the Moldanubian Zone: lithostratigraphic markers. *Journal of Geosciences*, 56: 359–374.

Vrána, S., Štědrá, V. & Fišera, M., 2005. Petrology and geochemistry of the Běstvina granulite body metamorphosed at eclogite facies conditions, Bohemian Massif. *Journal of the Czech Geological Society*, 50: 95–106.

Wojewoda, J. & Mastalerz, K., 1989. Climate evolution and allo- and autocyclic sedimentation of Upper Carboniferous and Permian continental deposits in the Sudetes. *Przegląd Geologiczny*, 37: 173–180. [In Polish, English summary].

Żelaźniewicz, A., 1985. Granulitic inliers amidst a gneissic/migmatitic complex of the Owl Mts, Sudetes. *Acta Geologica Polonica*, 35: 157–171.