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GARNET PROVENANCE IN MIXED FIRST-CYCLE AND POLY-CYCLE HEAVY-MINERAL ASSEMBLAGES OF THE ROPIANKA AND MENILITE FORMATIONS (SKOLE NAPPE, POLISH FLYSCH CARPATHIANS): CONSTRAINTS FROM CHEMICAL COMPOSITION AND GRAIN MORPHOLOGY

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Abstract: Garnet in heavy-mineral assemblages, occurring in sandstones of the Campanian–Maastrichtian part of the Ropianka (Late Cretaceous–Palaeocene) and Menilite (Oligocene) formations of the Skole Nappe, is present as first-cycle and poly-cycle grains, derived from a proximal source, remote areas and/or from sedimentary rocks of the Skole Basin foreland. The garnets in the formations are compositionally similar, suggesting an origin from the same source rocks. Relatively large amounts of garnet, represented by euhedral or slightly rounded, weakly etched or unetched almandine and spessartine-almandine garnet, and minor pyrope-enriched almandine, were derived directly from a source close to the Skole Basin. These garnets are from sediments, metamorphosed at low- to medium-grade conditions (such as mica-schists, gneisses) and perhaps also granitic bodies. Rounded and variously etched garnets, especially high pyrope-almandine and pyrope-almandine-grossular varieties, but also partly almandine-dominated varieties, are suggested to have been derived from distant sources, such as sedimentary rocks of the Upper Silesian and Małopolska blocks. Rocks, forming uplifted parts of the crystalline basement of Brunovistulicum and/or crystalline domains of the Bohemian Massif, could have been protoliths for part of the almandine-dominated garnet population, whereas pyrope-grossular-almandine garnets may originate from the granulitic, eclogitic or metabasic rocks of the Bohemian Massif. The study shows that analyses of garnet composition, combined with observations on grain textural features and data on the lithology of clasts and pebbles, can permit the determination of sources for different garnet varieties in mixed-provenance populations.

Key words: detrital garnet, mixed-provenance, protolith location, flysch, Skole Nappe, Carpathians.

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INTRODUCTION

Sedimentary provenance has been the subject of considerable research on modern and ancient sedimentary deposits (e.g., Mange and Wright, 2007). Investigators dealing with modern sands have mostly a wide spectrum of mineral species available for analyses, which enables the matching of mineral assemblages and their existing source areas with a fair degree of certainty. However, the identification of mineral provenance can be especially difficult and sometimes impossible for assemblages, depleted in diagnostic mineral species, such as amphibole, pyroxene or olivine, which are often unstable during burial diagenesis (e.g., Morton and Hallsworth, 1999, 2007). Diagenetic processes are strongly influenced by chemical and P-T conditions in the buried strata (Sevastjanova *et al.*, 2012 and references therein). Additionally, the hydraulic behaviour of minerals, depending largely on grain habit and density (e.g., Komar and Wang, 1984; Morton and Hallsworth, 1999; Hughes *et al.*, 2000; Cascalho and Fradique, 2007), also influences mineral concentrations in sediments, making comparative studies and provenance interpretation based on mineral abundances difficult and uncertain. The possibility of multiple sources of heavy-mineral assemblages and recycling, additionally complicates such a study. In such cases, single-grain analyses (e.g., Mange and Morton, 2007; von Eynatten and Dunkl, 2012), especially of minerals reflecting protolith composition in their chemistry, bring invaluable information for provenance interpretations. Garnet is one such mineral, in which the P–T conditions experienced by the original source rock may be fingerprinted, making certain garnet varieties diagnostic for protolith determination (e.g., Deer *et al.*, 1992; Mange and Morton, 2007; Win *et al.*, 2007; Aubrecht *et al.*, 2009; Suggate and Hall, 2013).

Studies of the flysch deposits of the Skole Basin demonstrate the challenges in establishing the provenance of heavy minerals that may be depleted in diagnostic species, controlled by depositional processes, and with source rocks not available for direct comparison. Recent research (Salata and Uchman, 2012, 2013) has shown that heavy-mineral assemblages and so garnet populations of the Ropianka and Menilite formations have a mixed-provenance. Salata and Uchman (2013) have shown additionally, that a large part of the garnet in both formations represents first-cycle input. However, a higher proportion of garnet, derived directly from crystalline rocks, is more probable for the Ropianka Formation, whereas garnet in the Menilite Formation may have been derived from sedimentary rocks and palimpsest/recycled sediments (Salata and Uchman, 2013).

This study presents a compilation of data on garnet from the Ropianka Formation and a comparison with data on garnet chemical composition from the Menilite Formation (partly published in Salata, 2013a) and grain textural features. The work attempts to identify garnet protoliths, and the provenance of certain garnet varieties in sediments, deposited in the northern part of the Skole Basin.

GEOLOGICAL BACKGROUND AND SAMPLING

The Skole Nappe represents the marginal, north-eastern part of the Outer Carpathians in Poland. Main exposures of it occur from the border with Ukraine to the Brzesko area but they occur also in the area of Wadowice and Radziszów (e.g., Książkiewicz, 1977). It is also possible that southern prolongation of the Skole Nappe is represented by the Obidowa-Słopnice Unit (Żytko and Malata, 2001). The northern edge of the Skole Basin was the southern part of European Platform. At present, the southern part of the Skole Basin foreland is deeply buried beneath the overthrust of the Carpathian nappes. Thus the Carpathian basement is known only from a few deep boreholes (e.g., Buła and Habryn, 2011).

The area investigated is located in the north-western, marginal part of the Skole Nappe (Fig. 1), which includes sediments from Lower Cretaceous to Lower Miocene (Fig. 2). The Late Cretaceous–Eocene time interval is represented by the Ropianka Formation (Upper Cretaceous–Palaeocene; Kotlarczyk, 1978 and references therein), the Variegated Shale Formation (Palaeocene–lower Eocene) and the Eocene Hieroglyphic Formation (Rajchel, 1990). The Oligocene–Lower Miocene part is composed of the Menilite and Krosno formations (Kotlarczyk, 1966; Kotlarczyk and Leśniak, 1990).

Sediments of the Ropianka Formation and Kliva Sandstone in the study area of the Skole Nappe were supplied mainly from a north-western direction. However, the Kliva Sandstone was also supplied from the north and north-east, to the east of the study area (e.g., Książkiewicz, 1962; Kotlarczyk, 1966, 1976; Ślączka and Unrug, 1966; Kotlarczyk and Leśniak, 1990; Malata and Poprawa, 2006). The palaeotransport directions (e.g., Książkiewicz, 1962) suggest an uplifted area beyond the north-western margin of the basin, which so far has not been confirmed by direct investigations. A crystalline massif is suggested by the pebbles of metamorphic and igneous rocks, which are clasts in the flysch deposits. Pebbles of gneisses, mica-schists, granites and volcanic rocks were reported from the Ropianka Formation deposits of the study area (e.g., Wdowiarz, 1949; Bromowicz, 1974, 1986 and references therein) and Babica Clay (Fig. 2; Bukowy, 1957; Rajchel and Myszkowska, 1998 and references therein). Nowak (1963) also reported porphyritic andesites and dacites in the Ropianka Formation in the Przemyśl and Bircza areas. In contrast, according to literature data, the Menilite Formation contains pebbles of dominantly sedimentary rocks and phyllites (Wdowiarz, 1949; Kotlarczyk and Śliwowa, 1963; Kotlarczyk, 1966). Carboniferous coal pieces are typical for both the Ropianka Formation and Menilite Formation. However, recent preliminary investigations of pebbles, found in the Menilite Formation, confirm the presence of volcanic rocks there as well (Salata, Uchman, Dudek – unpublished data).

According to sedimentological data, the deposits of the Ropianka Formation represent the initial phase of erosion of the source massif, while the Menilite Formation strata accumulated during a late stage of erosion (Książkiewicz, 1962; Bromowicz, 1974, 1986). It is also probable that (e.g., Golonka *et al.*, 2006) before the northward thrusting and rotation of the Carpathian orogen, the area of the Skole basin studied here was probably also supplied with sediment, derived from the sedimentary cover of the Małopolska and the Upper Silesian blocks.

Sediments of the Ropianka Formation were deposited by turbidity currents or other density-flow currents (Kotlarczyk, 1978), while sediments of the Kliva and Boryslav sandstones types of the Menilite Formation accumulated by gravity flows, mainly in channel zones, though sediments of this type also may be found outside the main channel zones (Kotlarczyk and Leśniak, 1990). Sandstones of the Ropianka Formation in the study area are composed mainly of quartz, together with feldspars, lithic fragments and subordinate amounts of mica, glauconite and coalified plant detritus. The sandstones are mainly sublitharenites, with subordinate subarkoses types (Bromowicz, 1974, 1986 and references therein). The Kliva and Boryslav sandstones are mostly fine- to medium-grained and well- to moderately-sorted, although conglomeratic sandstones are also present. The sandstones are quartz-dominated. Feldspars and muscovite are less abundant and glauconite is often present, but not regularly distributed. The sandstones are mostly massive, rarely laminated and poorly cemented (Żgiet, 1963; Kotlarczyk, 1966, 1976; Ślączka and Unrug, 1966).

The sandstones sampled are from the Wiar and Leszczyny Members (Kotlarczyk, 1978) of the Campanian–Maastrichtian part of the Ropianka Formation (Late Cretaceous–Palaeocene) and the Kliva and Boryslav sandstones members of the Menilite Formation (Oligocene; Fig. 2). The deposits were sampled south-east of Rzeszów (the Menilite Formation) and south-east of Łańcut (the Ropianka and Menilite formations; Fig. 1). The Boryslav and Kliva sandstones types of the Menilite Formation were sampled

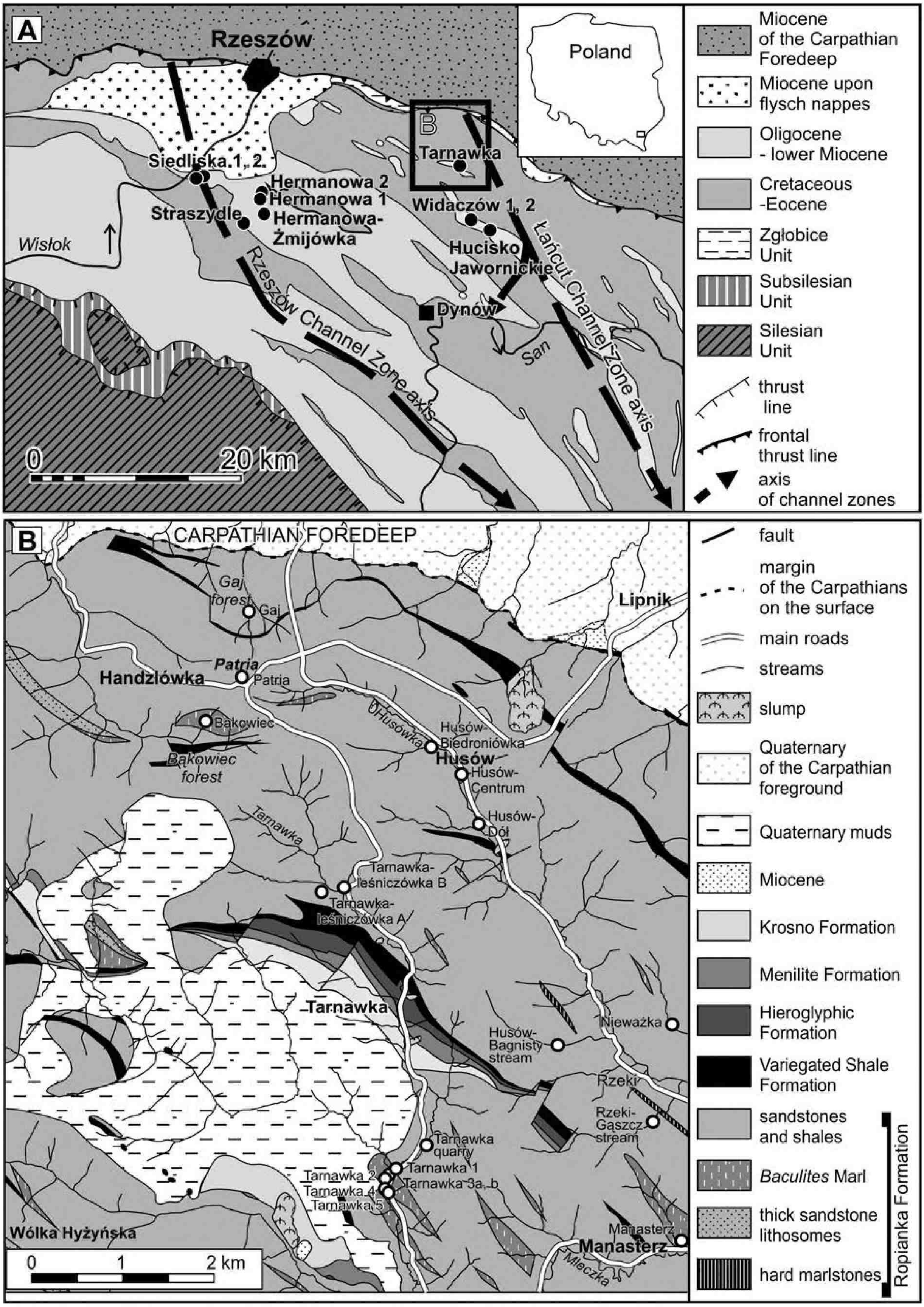

Fig. 1. Geological maps with locations of profiles sampled for heavy-mineral analyses. **A.** Sampled localities of the Boryslav and Kliva sandstones of the Menilite Formation. **B.** Sampled localities of the Ropianka Formation sandstones (Salata and Uchman, 2013 modified; part A based on Kotlarczyk and Leśniak, 1990; part B based on Wdowiarz, 1949, with modified description of lithostratigraphic units)

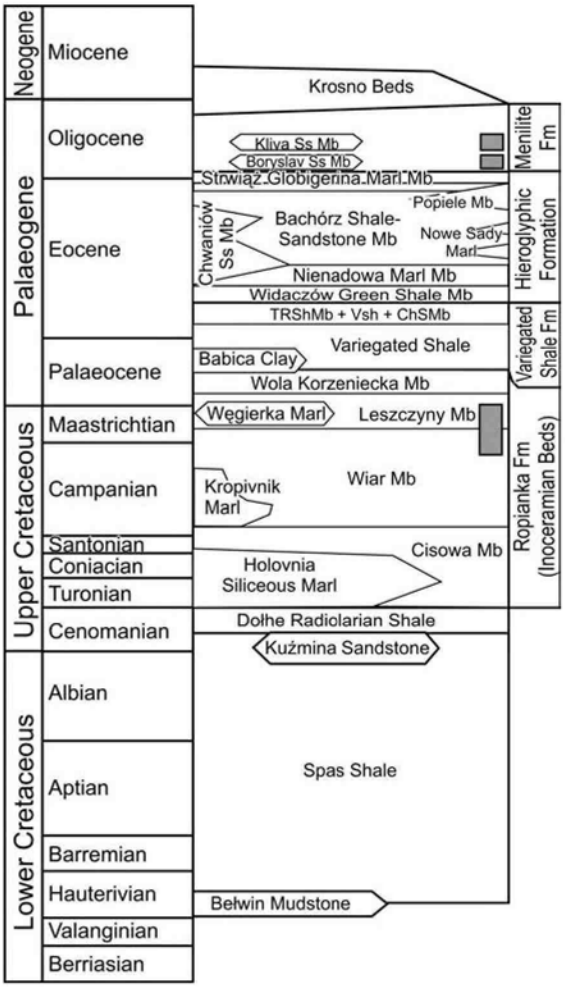

Fig. 2. Stratigraphic scheme of the Skole Nappe (based on Kotlarczyk, 1978; Gasiński and Uchman, 2009 and references therein) with indication of the studied time intervals of the Ropianka and Menilite formations (grey rectangles). Abbreviations: Fm – formation; Mb – member; Ss – sandstone; TRShMb – Trójca Red Shale Member; VSh – Variegated Shale; ChSMb – Chmielnik Striped Sandstone Member

following chiefly the Rzeszów and Łańcut channel zones (Kotlarczyk and Leśniak, 1990). For the detailed sampled profiles of the Ropianka and Menilite formations see Salata and Uchman (2012, 2013).

RESEARCH METHODS

As the sandstones sampled were very weakly consolidated, they were only gently disintegrated and washed with water to remove the clay fraction. Then the samples were sieved, using a mechanical shaker. Heavy minerals were separated by gravitational settling from the fraction of 0.063–0.25 mm, which best represented the heavy mineral spectrum, using sodium polytungstate of density 2.9 g/cm^3. Morphology, microtextures and solid inclusions of the garnet grains were studied in 100 grains (for each formation sampled), hand-picked under a stereomicroscope, using a HITACHI S-4700 Field Emission Scanning Electron Microscope in the Laboratory of Field Emission Scanning Electron Microscopy and Microanalysis, at the Institute of Geological Sciences, Jagiellonian University. The chemical composition of the garnets was studied in polished and carbon-coated grain mounts, using a Cameca SX-100 electron microprobe (EMP), operated in a wavelength-dispersion (WDS) mode, at the Joint-Institute Analytical Complex for Minerals and Synthetic Substances of Warsaw University. The WDS analytical conditions comprised a 15 kV accelerating voltage, a 20 nA beam current and a focused beam. The following, synthetic and natural mineral standards were used for calibration: Si and Mg (diopside), Al (orthoclase), Cr (Cr_2O_3), Ti (rutile), Fe (Fe_2O_3), Mn (rhodonite), and Ca (wollastonite). Single-spot analyses were performed on 120 grains of the Ropianka Formation and 140 grains from the Menilite Formation. Additionally, 27 grains from the Ropianka Formation and 21 grains from the Menilite Formation were analysed in traverses to check the compositional variability across the grains. The garnet formulas were calculated on the basis of 24 oxygen atoms. The Fe^{3+} content was not measured, but the Fe^{2+}/Fe^{3+} ratio was calculated by standard charge balance, assuming full-site occupancy. The molecular garnet end-members were computed, using the Excel spread-sheet developed by Locock (2008). To obtain comparable data and construct suitable fields on provenance diagrams, the same procedure was employed for garnet composition from the literature, if the Fe content was given only as FeO_{tot}.

RESULTS AND DISCUSSION

Garnet content and habit

Garnet is a significant component of heavy-mineral assemblages in both of the formations studied, but the content is lower and garnet is more uniformly distributed in the Menilite Formation (MF) than in the Ropianka Formation (RF) (Fig. 3). Garnet comprises 2–47% (mean value = mv = 21%) and 0–25% (mv = 11%) in the Ropianka and Menilite formations respectively (Fig. 3). Except garnet, the main constituents of the heavy mineral assemblages in both formations are zircon (mv: RF – 27%; MF – 18%), tourmaline (mv: RF – 19%; MF – 20%), rutile (mv: RF – 17%; MF – 20%), less abundant staurolite (mv: RF – 9%; MF – 16%) and kyanite (mv: RF – 4%; MF – 14%). Apatite is common in the Ropianka Formation, while it is almost absent in the Menilite Formation. Conversely, the latter contains small amounts of andalusite, which is not present in the Ropianka Formation. Epidote, monazite, Cr-spinel and brookite occur occasionally as single grains in individual samples (Salata and Uchman, 2012, 2013). One dark green amphibole grain was found in the Ropianka Formation (Salata and Uchman, 2013).

The zircon–tourmaline–rutile index value (ZTR; Hubert, 1962) varies widely from 27 to 95% (mv = 63%) and 29–55% (mv = 43%) in the Ropianka and Menilite formations, respectively. The higher value of the ZTR index in the Ropianka Formation results mainly from higher zircon abundances, compared to the Menilite Formation (Salata and Uchman, 2013).

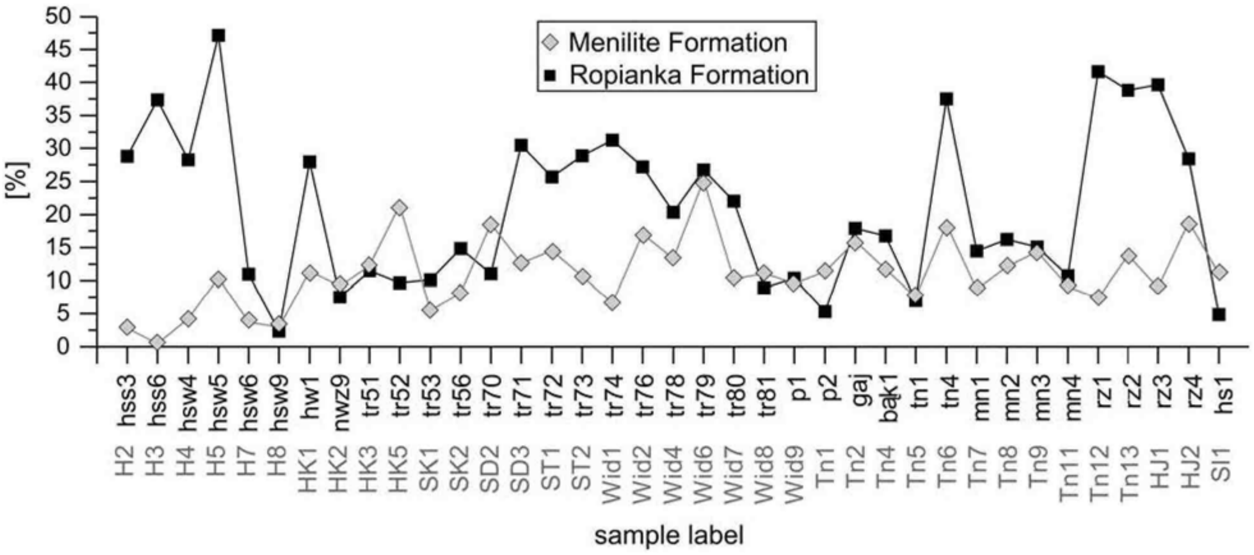

Fig. 3. Abundance of garnet in heavy-mineral assemblages of the Ropianka and Menilite formations (based on Salata and Uchman, 2012, 2013)

There is a strong negative correlation between the ZTR value and garnet content (Pearson's correlation coefficient – r = –0.90) for the Ropianka Formation. The garnet content increases as the ZTR value decreases. The correlation of ZTR and garnet content in the Menilite Formation is also negative, but the correlation is weak (r = –0.37; Salata and Uchman, 2013).

Garnet in both formations is present, mostly as irregular, broken grains, but unbroken, variably rounded and euhedral grains may also be found. Both garnet fragments and whole grains are variably corroded. The etching varies from very weak to advanced, and is reflected mostly as etch-pits, surface mamillae and small- and large-scale facets on garnet surfaces. Some of the corrosion marks are visible on smoothed grain surfaces (Fig. 4). Garnet grains are predominantly colourless or pale pink in transmitted light. Less commonly, they are salmon-pink and a few grains are dark pink. Rare green garnet grains are also present (Salata and Uchman, 2012, 2013).

Garnet composition

In both formations studied, the garnet populations are very similar, not only in colour and habit, but also in terms of their chemical composition. They also display similar compositional variability, in terms of the molecular proportions of the pyralspite garnet end-members: pyrope (Prp), almandine (Alm) and spessartine (Sps). Grossular (Grs) is the most significant representative of the ugrandite series, while contents of the remaining molecules are low (Fig. 5; Tables 1 and 2). On the basis of the four garnet end-members mentioned, several compositional varieties of garnet may be distinguished:

– grossular-dominated (Grs 82–94 mol%) garnets are uncommon and only single grains were found in each formation;

– spessartine-dominated (Sps = 64 mol%): only two grains of this composition were found in the Menilite Formation;

– pyrope-almandine-grossular (Prp 25–35 mol%, Alm 39–56 mol%, Grs 21–33 mol%) ranges from 1.5% to 5% of garnet populations in the Ropianka and Menilite formations respectively;

– grossular-almandine (Grs 20–36 mol%, Alm 52–72 mol%, while Prp + Sps < 15 mol%); such garnet comprises 3.5% and 9% of the garnet populations in the Ropianka and Menilite formations respectively;

– pyrope-almandine (Prp 20–45 mol%, Alm 44–75 mol%, with Sps + Grs + Adr < 15 mol%) constituting 16% of the garnet population in the Ropianka Formation and 33% in the Menilite Formation;

– spessartine-almandine (Sps 22–53 mol%, Alm 32–67 mol%, with Prp + Grs + Adr < 20 mol%); comprising 26% of the garnet population in the Ropianka Formation and 8% in the Menilite Formation;

– almandine (Alm > 60mol%; Prp + Sps < 20mol%, Grs + Adr < 15 mol%); this garnet variety is the most abundant and typical for both formations. It constitutes 53% and 44% of the garnet population of the Ropianka and Menilite formations respectively.

Although the garnet compositions are very similar in both formations, there is a noticeable difference in abundance of some garnet types. The contribution of garnet, rich in pyrope and grossular, is lower in the older sediments of the Ropianka Formation, which contain higher numbers of almandine and spessartine-almandine garnets, compared to the younger Menilite Formation deposits. The difference in abundance of garnet varieties may reflect a change in source area lithology, related to progressive erosion. However, this feature may be an effect of burial diagenesis, leading to depletion in the less stable garnet varieties in the older sediments, which causes a relative enrichment in almandine-rich garnet.

There is also significant etching and rounding. Rounding and the effects of dissolution processes advanced to different degrees were observed on grains of all of the garnet compositional types mentioned above, regardless of their

Table 1

Selected single-spot analyses of garnets from the Ropianka and Menilite formations of the Skole Nappe. Oxides in [wt%], molecular garnet end-members in [mol%]

Menilite Formation	**12**	**28**	**148**	**22**	**18**	**8**	**32**	**43**	**16a**	**10**	**1**	**16b**	**31**	**25**	**5**
SiO_2	40.53	37.95	38.11	36.72	38.41	39.21	37.03	36.71	37.50	38.72	38.00	36.23	37.41	37.09	37.61
TiO_2	b.d.l.	0.09	b.d.l.	0.02	0.06	0.13	0.22	b.d.l.	0.16	0.33	b.d.l.	0.04	0.15	0.13	0.05
Al_2O_3	21.64	21.84	20.31	21.04	22.35	22.61	20.62	19.27	21.67	19.90	21.79	20.71	21.34	20.54	21.37
Cr_2O_3	b.d.l.	0.05	b.d.l.	b.d.l.	0.05	b.d.l.	0.03	b.d.l.	0.03	b.d.l.	0.02	0.02	0.01	b.d.l.	0.06
Fe_2O_3calc	0.00	0.00	0.54	0.34	0.06	0.42	2.94	2.04	0.00	3.52	0.79	1.71	1.61	1.53	0.63
MgO	11.59	4.52	1.25	1.83	8.34	7.58	2.15	0.25	3.79	0.03	4.88	1.39	2.17	0.93	4.76
FeOre-calc	21.09	28.45	23.46	37.98	29.28	19.14	4.03	24.94	35.36	3.33	29.94	33.63	26.97	33.44	31.08
MnO	0.02	1.10	3.17	0.12	0.48	0.47	29.32	9.91	0.05	0.34	1.27	6.70	3.41	1.98	0.55
CaO	5.02	5.62	13.01	2.00	1.06	10.83	5.39	6.61	2.06	33.46	4.30	0.36	8.25	5.76	3.83
Total	99.89	99.61	99.80	100.01	100.08	100.36	101.53	99.55	100.61	99.59	100.91	100.62	101.16	101.31	99.86
Schorlomite-Al.	-	0.1	-	0.1	0.2	0.4	0.7	-	0.5	1.0	-	0.1	0.4	0.4	0.2
Majorite	3.3	-	3.2	-	-	-	-	0.7	-	-	-	-	-	-	-
Uvarovite	-	0.2	-	-	0.2	-	0.1	-	0.1	-	0.1	0.1	-	-	0.2
Spessartine	-	2.5	7.1	0.3	1.0	1.0	66.8	22.9	0.1	0.7	2.8	15.7	7.7	4.5	1.2
Pyrope	39.3	18.0	0.7	7.4	32.3	28.8	8.6	0.1	15.1	0.1	19.2	5.7	8.6	3.7	18.8
Almandine	44.6	63.5	52.0	86.5	63.7	40.7	9.1	57.0	78.9	7.1	65.9	77.1	60.1	75.2	69.0
Grossular	12.8	15.8	35.3	5.8	2.6	29.1	10.2	13.0	5.3	81.1	12.1	-	21.6	13.0	10.2
Andradite	-	-	1.6	-	-	-	4.5	6.3	-	9.9	-	1.3	1.4	3.2	0.4
Ropianka Formation	**11**	**28**	**11**	**39**	**50**	**10a**	**179**	**177**	**12**	**28**	**10b**	**12**	**27**	**22**	**52**
SiO_2	39.21	36.77	36.59	36.98	37.14	36.67	37.24	37.49	39.12	36.77	36.74	39.12	37.50	36.66	38.78
TiO_2	0.42	0.03	0.20	0.03	0.06	0.38	0.06	0.04	0.38	0.03	0.13	0.38	0.18	0.01	0.08
Al_2O_3	22.13	19.31	20.44	19.89	19.82	20.57	19.67	19.94	21.93	19.31	20.37	21.93	20.96	20.50	21.16
Cr_2O_3	0.13	0.01	0.06	0.01	0.03	0.03	0.04	0.06	0.11	0.01	b.d.l.	0.11	0.02	0.04	0.04
Fe_2O_3calc	0.41	2.43	2.02	0.94	1.57	1.07	1.17	0.67	0.00	2.43	1.03	0.00	1.08	0.69	0.21
MgO	11.96	0.58	4.01	1.19	2.22	0.92	1.71	2.18	11.71	0.58	1.89	11.71	3.43	2.61	7.72
FeOre-calc	24.02	26.43	31.30	40.25	14.26	24.72	14.99	30.26	23.97	26.43	22.29	23.97	24.28	29.10	29.97
MnO	0.38	8.23	0.64	0.91	22.89	7.60	22.84	8.28	0.31	8.23	13.75	0.31	0.95	8.85	0.61
CaO	1.20	6.40	3.77	0.74	2.39	7.90	2.67	1.82	1.39	6.40	3.49	1.39	10.65	0.89	1.65
Total	99.86	100.20	99.02	100.94	100.37	99.87	100.39	100.73	98.92	100.20	99.67	98.92	99.03	99.34	100.22
Schorlomite-Al.	1.2	0.1	0.6	-	-	1.2	-	-	0.4	0.1	0.4	0.4	0.5	-	-
Morimotoite	-	-	-	0.2	0.3	-	0.4	0.2	0.3	-	-	0.3	-	-	0.5
Majorite	-	-	-	1.4	0.3	-	1.9	2.7	-	-	-	-	-	-	1.8
Uvarovite	0.4	-	0.2	-	0.1	0.1	0.1	0.2	0.3	-	-	0.3	0.1	0.1	0.1
Spessartine	0.8	18.9	1.5	2.1	52.3	17.4	52.3	18.9	0.7	18.9	31.6	0.7	2.1	20.4	1.3
Pyrope	45.1	2.3	16.3	2.9	8.4	3.7	4.3	5.2	44.8	2.3	7.6	44.8	13.6	10.6	27.5
Almandine	50.8	60.1	71.3	90.5	32.0	55.9	33.7	68.0	51.3	60.1	50.6	51.3	54.0	66.4	64.9
Grossular	0.8	11.2	7.0	-	1.7	19.5	3.7	2.8	2.2	11.2	7.2	2.2	27.6	1.0	3.4
Andradite	0.8	7.3	3.2	2.9	4.8	2.2	3.6	2.1	-	7.3	2.6	-	2.1	1.5	0.6

chemical composition. However, the euhedral garnets, which are weakly etched or not etched, are predominantly almandine or spessartine-almandine varieties. Additionally, fragments of almandine or spessartine-almandine varieties commonly have unetched fracture planes, in contrast to other garnet types. Only one slightly rounded grain of pyrope-almandine (Prp < 30mol%) was found (Fig. 4).

The garnets analysed predominantly did not display chemical change across the grains. Only one grain of grossular garnet showed slight changes (rim-to rim change

Table 2

Selected rim-to-rim analyses of garnets from the Ropianka and Menilite formations of the Skole Nappe. Oxides in [wt%], molecular garnet end-members in [mol%]

Menilite Formation	**grt13-2**			**grt2-4**			**grt4-2**			**grt9-4**		
	rim	core	rim	rim	core	rim	rim	core	rim	rim	core	rim
SiO_2	39.42	39.44	39.42	36.95	36.77	36.88	37.26	36.86	37.08	36.39	36.35	36.33
TiO_2	0.03	0.04	0.01	b.d.l.	0.03	b.d.l.	0.08	0.15	0.05	0.02	0.20	b.d.l.
Al_2O_3	21.62	21.54	21.51	20.15	20.17	20.18	20.05	19.78	2b.d.l.	19.58	19.52	19.83
Cr_2O_3	0.05	0.08	0.07	0.01	0.01	0.02	0.02	0.05	b.d.l.	b.d.l.	b.d.l.	b.d.l.
Fe_2O_3calc	1.01	1.10	1.04	1.81	1.43	1.27	1.32	1.95	1.18	1.69	1.64	1.84
MgO	11.48	11.43	11.54	2.44	2.47	2.41	2.11	2.24	2.06	1.05	1.09	0.96
FeOre-calc	24.66	24.43	24.59	27.17	27.34	27.28	26.43	25.68	26.23	31.67	31.68	31.64
MnO	0.34	0.46	0.35	11.38	10.96	11.19	11.63	11.69	11.77	8.89	8.92	8.96
CaO	1.34	1.51	1.28	0.88	0.90	0.92	2.07	2.11	2.00	0.77	0.77	0.79
Total	99.93	100.01	99.81	100.78	100.07	100.14	100.97	100.52	100.37	100.06	100.15	100.35
Schorlomite-Al.	0.1	0.1	-	-	0.1	-	-	0.5	-	0.1	0.5	-
Morimotoite	0.1	0.1	0.1	-	-	-	0.5	-	0.3	-	0.3	-
Majorite	-	-	0.2	-	-	-	0.3	-	0.5	-	-	-
Uvarovite	0.1	0.2	0.2	-	-	0.1	0.1	0.2	-	-	-	-
Spessartine	0.7	1.0	0.7	26.1	25.2	25.7	26.5	26.8	26.9	20.7	20.7	20.9
Pyrope	43.4	43.2	43.4	9.9	1-	9.8	8.1	9.0	7.6	4.3	4.4	3.9
Almandine	52.3	51.7	52.2	59.7	61.1	61.0	59.2	58.1	59.2	69.9	69.0	70.8
Grossular	0.5	0.5	0.2	-	-	-	1.4	-	1.9	-	-	-
Andradite	2.9	3.2	3.0	4.3	3.5	3.5	4.0	5.5	3.6	5.0	5.1	4.3
Ropianka Formation	**grt5-4**			**grt10-4**			**grt2-4**			**grt 5-1**		
	rim	core	rim	rim	core	rim	rim	core	rim	rim	core	rim
SiO_2	39.39	39.67	39.27	37.27	37.22	37.41	39.86	39.85	39.64	37.40	37.26	37.37
TiO_2	0.06	0.02	0.03	b.d.l.	0.10	0.04	0.38	0.43	0.41	b.d.l.	0.01	b.d.l.
Al_2O_3	21.58	21.43	21.51	19.84	19.85	20.01	20.51	19.93	19.79	20.38	20.06	20.41
Cr_2O_3	0.06	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	0.01	b.d.l.	0.01	b.d.l.	b.d.l.
Fe_2O_3calc	0.00	0.26	0.91	1.37	1.39	0.91	1.91	2.58	3.16	1.04	0.60	1.14
MgO	10.32	10.55	10.50	1.99	2.36	1.89	0.07	0.15	0.14	2.34	2.35	2.16
FeOre-calc	27.28	27.23	26.80	15.43	15.78	15.62	0.41	0.91	0.78	32.29	32.28	32.41
MnO	0.34	0.29	0.37	21.00	21.06	21.27	0.06	0.11	0.14	6.15	6.12	6.24
CaO	0.76	0.87	0.85	3.37	2.55	3.30	37.01	36.49	36.37	1.59	1.49	1.64
Total	99.78	100.31	100.24	100.27	100.31	100.46	100.21	100.46	100.43	101.19	100.17	101.38
Schorlomite-Al.	-	-	-	-	-	-	-	-	-	-	-	-
Morimotoite	0.4	0.1	0.2	-	0.6	0.3	2.2	2.5	2.3	-	0.1	-
Majorite	1.2	2.8	0.3	1.3	0.7	1.8	-	0.1	0.3	0.4	2.2	-
Uvarovite	0.2	-	-	-	-	-	-	-	-	-	-	-
Spessartine	0.7	0.6	0.8	47.9	48.0	48.5	0.1	0.2	0.3	13.9	14.0	14.2
Pyrope	37.8	36.4	39.5	6.3	8.6	5.2	0.3	-	0.1	8.8	6.5	8.6
Almandine	58.7	57.9	56.6	34.8	35.4	35.1	-	1.1	0.9	72.3	73.0	72.5
Grossular	0.9	1.5	-	5.6	2.5	6.5	91.9	88.6	87.1	1.4	2.4	1.3
Andradite	-	0.8	2.6	4.2	4.2	2.8	5.5	7.4	9.0	3.2	1.8	3.5

<5mol%) in grossular and andradite content (Tab. 2). Almandine or spessartine-enriched almandine garnets typically contain inclusions of quartz, rutile and Fe-Ti oxides, less frequent xenotime and occasionally feldspar (Fig. 6). Grossular- and pyrope-enriched garnets contain apatite inclusions.

Protolith composition

A number of diagrams have been used to link garnet chemical composition to the lithology of their source rocks. Among them are single ternary plots (e.g., Mange and Morton, 2007; Méres *et al.*, 2012) and double-ternary diagrams

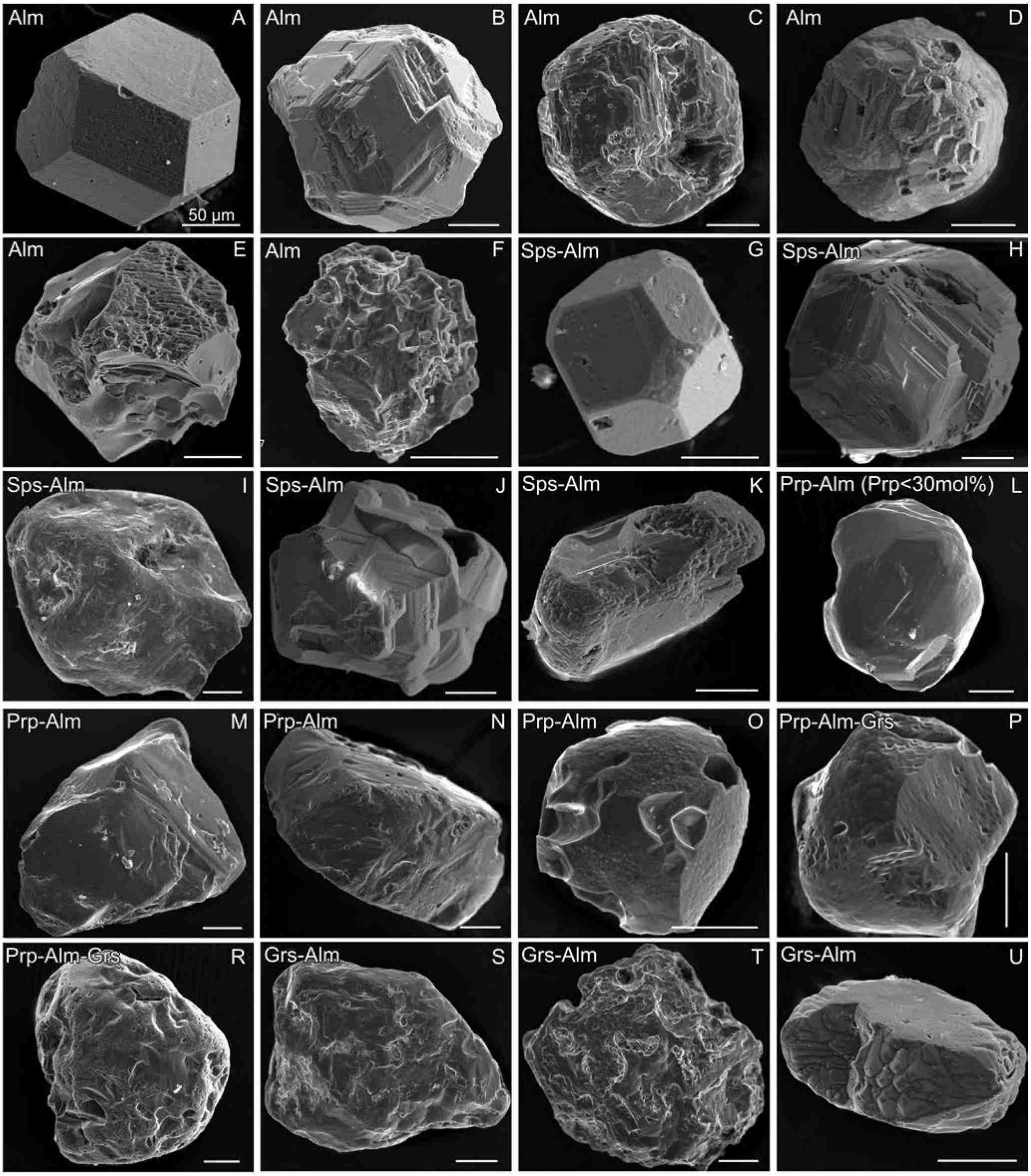

Fig. 4. SEM photographs showing various degree of rounding and corrosion features of certain garnet varieties occurring in the Ropianka and Menilite formations. *Almandine.* **A.** Euhedral, not-etched grain. **B.** Euhedral grain with large-scale facets. **C.** Subrounded grain with large-scale facets and etch-pits. **D.** Rounded grain with mamillae and etch-pits. **E.** Fragment with smooth fracture planes and a crystal face with incipient etching. **F.** Severely corroded grain; *spessartine-almandine.* **G.** Euhedral, not-etched grain. **H.** Grain with large-scale facets. **I.** Rounded grain with smooth surface and earlier etch-pits. **J.** Grain with large-scale facets. **K.** A fragment with small-scale imbricate wedge marks and etch-pits; *pyrope-almandine (Prp<30mol%).* **L.** Subrounded, unetched grain. **M.** A fragment with smooth, almost not-etched surface. **N.** A fragment with smooth fracture-planes and surfaces with mamillae and etch-pits. **O.** Rounded grain with surface mamillae and gaps possibly after inclusions; *pyrope-almandine-grossular.* **P.** Grain with rounded edges, numerous etch-pits and surface mamillae. **R.** Rounded grain with numerous etch-pits; *grossular-almandine.* **S.** A grain with rounded edges and smoothed, earlier corrosion features. **T.** Severely corroded grain. **U.** A fragment with large-scale imbricate wedge marks. Composition of garnet refers to garnet compositional types distinguished in the text. Abbreviations: Alm – almandine; Grs – grossular; Prp – pyrope; Sps – spessartine

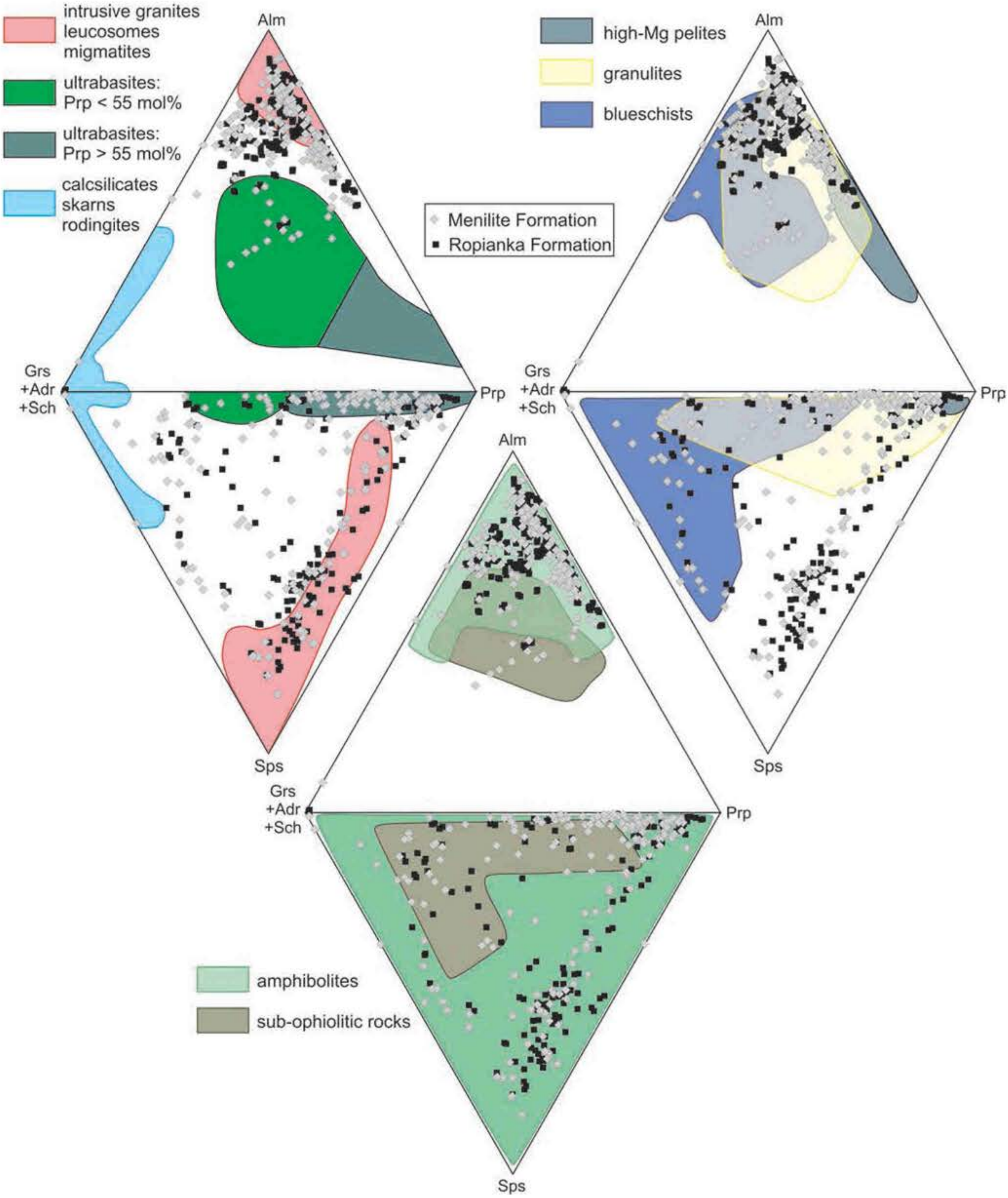

Fig. 5. Distribution of points, reflecting proportions of main end-members of the garnet analysed in the ternary plot, showing fields typical for garnet originating from various protoliths (ternary diagrams adapted from Suggate and Hall, 2013). Abbreviations: Adr – andradite; Sch – schorlomite; other abbreviations as in Fig. 4

(Suggate, 2011, *vide* Sevastjanova *et al.*, 2012) with different apices of triangles and protolith fields. Garnet composition also may be an indicator of metamorphic grade (see Win *et al.*, 2007; Andò *et al.*, 2013). However, there are some ubiquitous garnet varieties, such as almandine, common in various lithologies, for which clear protolith identification is often impossible. Recently published diagrams, constructed using 2500 garnet analyses (Suggate and Hall,

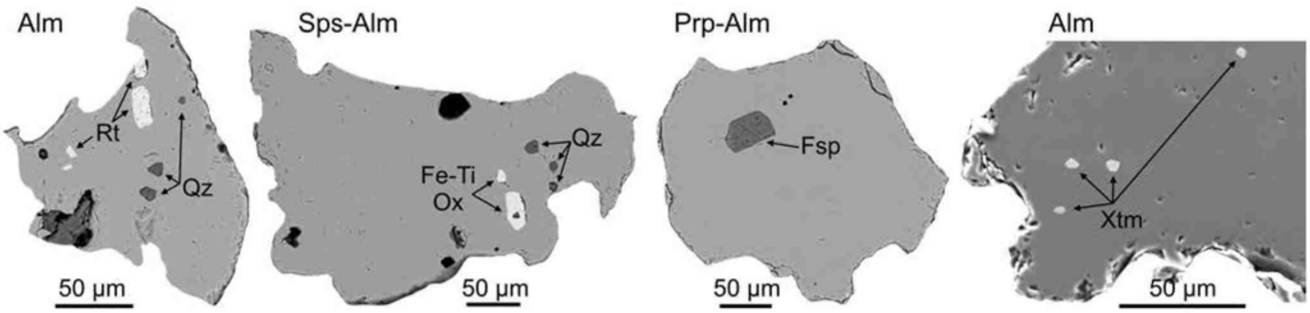

Fig. 6. Typical mineral inclusions present in garnet grains of particular compositions. Composition of garnet refers to garnet compositional types distinguished in the text. Abbreviations: Rt – rutile; Qz – quartz; Fe-Ti Ox – Fe-Ti oxides; Fsp – feldspar; Xtm – xenotime; other abbreviations as in Fig. 4. SEM images

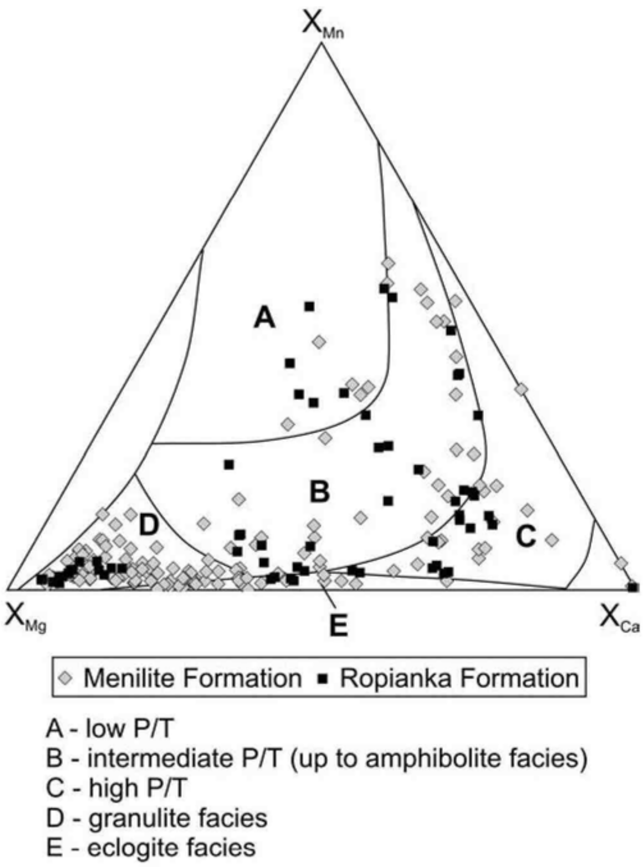

Fig. 7. Metamorphic grade of crystallisation of garnet studied. Points locating in the field of granites in Fig. 5 are excluded (diagram adapted from Win *et al.*, 2007)

2013) provide a new approach and offer good resolution in defining protolith types in garnet provenance studies.

Grossular garnet most likely originates from impure calcareous rocks, such as calc-silicates, skarns, and rodingites, formed during thermal or regional metamorphism (Fig. 5). The protoliths for the spessartine and spessartine-almandine varieties are commonly granites and granitic pegmatites (Fig. 5), though garnet of such a composition was also reported from skarn deposits (Deer *et al.*, 1992). Pyrope-almandine-grossular and pyrope-almandine garnets are typical of granulites, eclogites and ultrabasic rocks such as peridotites and sub-ophiolitic rocks (Fig. 5). Almandine garnet, commonly distinguished in the populations studied here, is widespread in various metamorphosed rocks and may originate from amphibolites (Fig. 5) or other rocks of low- to medium-grade metamorphic facies, such as metapelites, gneisses and mica-schists (Deer *et al.*, 1992). Unfortunately, some fields denoting granulites, blueschists, ultrabasites and sub-ophiolitic rocks overlap with each other and additionally with the field of amphibolites in the diagrams used for defining the protolith (Fig. 5). This makes the determination of source lithology uncertain without further evidence. Metapelitic and granitic origin displays also tourmaline, including euhedral grains, occurring in both formations studied (Salata, 2013a, 2014).

In the formations studied here, there are no data, e.g., an abundant chromian-spinel presence, suggesting derivation of the heavy-mineral assemblages from ophiolitic rocks or ultrabasites. Moreover, the distribution of points showing garnet composition indicates that they were formed over a wide range of metamorphic conditions, spanning from low P/T to eclogite facies (Fig. 7), confirming the lithological diversity of their source rocks. Garnet colour may also aid in determining garnet protolith. The dominance of colourless and pinkish garnet varieties suggests its provenance mainly from rocks of amphibolite- and granulite-facies (Andò *et al.*, 2013), as indicated by garnet compositions.

With regard to garnet colour, composition and the abundance of different garnet varieties, it may be concluded that most garnets were derived from rocks, formed under medium-grade metamorphic conditions, less frequently from granulite facies and granitic rocks, and a minority from high-grade metabasic rocks. Individual grains of grossular were derived from metamorphosed calc-silicate rocks or skarns, probably developed in the contact zone with an intrusive igneous body.

Provenance constraints and protolith massifs location

The heavy-mineral assemblages which contain the garnets studied, show features that indicate mixing of first-cycle and poly-cycle grains. These include different degrees of rounding and etching, which affect not only garnet (Fig. 4), staurolite and kyanite but also minerals resistant to abrasion and diagenesis such as zircon, tourmaline and rutile

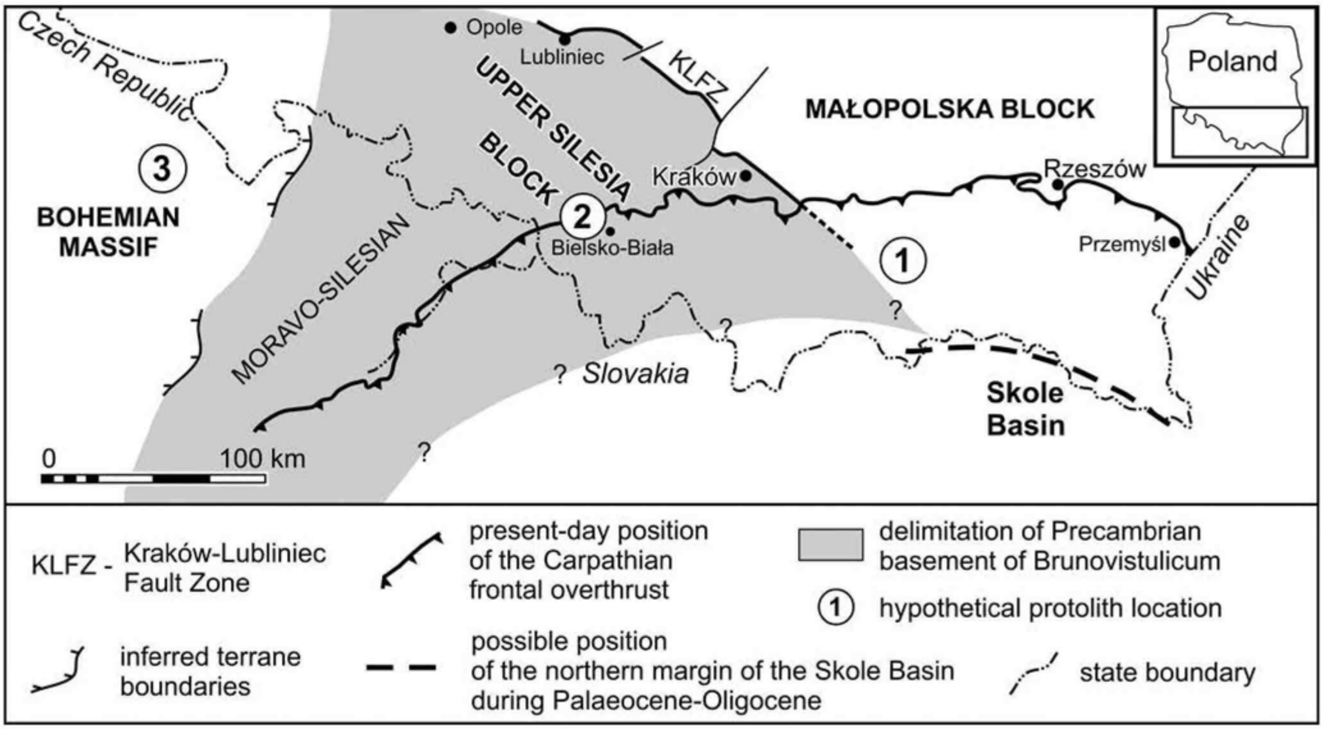

Fig. 8. Sketch-map, showing assumed location of protoliths for garnets from the Ropianka and Menilite formations (Salata, 2013a modified; based on Buła and Żaba, 2008 and Żelaźniewicz *et al.*, 2011): 1– proximal source located in the northern vicinity of the Skole Basin margin; 2 – crystalline basement of Brunovistulicum; 3 – Bohemian Massif domains

(Salata and Uchman, 2012, 2013). While etching is clearly the effect of burial diagenesis, rounding may be formed by mechanical abrasion or diagenetic dissolution, both of which could have influenced the garnet populations present in the deposits studied. Therefore, in the case of recycled grains, it is not clear, which process causing roundness was crucial, as rounding also may be inherited from previous sedimentary environment. Frequently, it is only possible to find proof of the final process. However, etching developed on rounded grain surfaces was eventually formed by diagenesis (Fig. 4D), whereas rounded grains with smoothed surfaces and without prominent etching (Fig. 4I) most probably formed finally by mechanical abrasion. Some of the corrosion etch-pits and facets visible on garnet grains may represent early stages of sedimentation or (in the case of recycled grains) may be inherited from previous sedimentary environment, since they are visible on smooth surfaces and are smooth themselves (Fig. 4I, R, S).

The mixed-provenance character of grains is supported by the lithologies of the pebbles occurring in the deposits studied; these include crystalline and sedimentary rocks (e.g., Kotlarczyk and Śliwowa, 1963; Bromowicz, 1974, 1986; Rajchel and Myszkowska, 1998).

The mixed character of the assemblages studied causes difficulties in locating protoliths for certain garnet types of the populations. The different degrees of roundness and variable amount of etching of the garnets suggest that some garnet grains in both formations were derived directly from crystalline source rocks, proximal or distant, and some were derived from the sedimentary cover of the Skole Basin foreland. The rounded and highly etched grains also may have been derived from metasediments. There is a large similarity of garnet populations in the Ropianka and Menilite formations. However, recent work by Salata and Uchman (2013) has shown that the Ropianka Formation contains larger amounts of first-cycle garnet, compared to the Menilite Formation, whereas garnets in the Menilite Formation, may have been recycled to a relatively larger extent, than those in the Ropianka Formation. Consideration of the polycycle provenance of some of the garnets studied raises the question of whether garnet can survive two cycles of sedimentation or long transportation. Garnet is generally regarded as a moderately stable mineral (e.g., Mange and Maurer, 1992; Morton and Hallsworth, 1999, 2007; Mange and Morton, 2007 and references therein). Minerals considered less stable, such as olivine, may survive abrasion during extremely long transport distances (see Morton and Hallsworth, 1999 and references therein) and therefore long-distance transportation seems unlikely to influence garnet preservation. Moreover, the study by Sevastjanova *et al.* (2012) showed that minerals, regarded as unstable, survived transport and some of them also survived recycling in a tropical climate. However, the survival of garnet, especially if it was deeply buried, may depend on its chemical composition. For example, grossular-rich varieties are considered to be less stable than almandine-rich garnet (Morton, 1984, 1987). Therefore, the less stable garnet varieties could have been dissolved during burial diagenesis, prior to sediment deposition in the Skole Basin, even if they had survived earlier transportation or recycling.

Euhedral crystals and slightly rounded grains, displaying few effects of diagenetic dissolution, obviously represent the first-cycle garnet population. Such grains may have been derived from an uplifted source area (point 1 in Fig. 8; e.g., the so-called Northern Marginal Cordillera in older literature), the existence of which at the northern margin of the Skole Basin is documented by palaeocurrent distribution patterns (e.g., Książkiewicz, 1962; Unrug, 1979). The almandine or spessartine-almandine composition of euhedral garnet indicates, that its source rocks could have been gneisses and mica-schists, formed under medium-grade metamorphic conditions, and also granitic rocks. The minerals occurring with garnet in the heavy-mineral assemblages studied are typical of metasediments, formed under medium-grade metamorphic conditions. The crystalline basement of the Małopolska Block, penetrated by boreholes beneath deposits forming the Skole Nappe, cannot be the protolith of such mineral assemblage, since it is composed of anchimetamorphic rocks (Buła and Habryn, 2011). The presence of medium-grade metamorphic and igneous rocks under the Carpathian overthrust so far has not been confirmed by direct observations, but it is evidenced by metamorphic and igneous rock clasts and pebbles.

The location of protoliths for the suite of rounded garnet grains studied is much more problematic and complex. The diversity of composition of the rounded and etched grains suggests either diverse lithologies in a single source area or derivation from different source areas. As discussed above, the rounded garnet compositions suggest derivation from granitic rocks and medium- to high-grade metamorphic rocks, such as gneisses, mica-schists, amphibolites, granulites and ultrabasites. However, there is no evidence from the exotic clasts and pebbles, found in the Ropianka and Menilite formations, for high-grade metamorphic rocks, such as granulites and eclogites, or ultramafic bodies, in the source massif at the northern margin of the Skole Basin. Therefore, garnets originating from such lithologies must have been eroded from another source, which could be distant and/or sedimentary. The areas, containing rocks with lithologies indicated by garnet composition, which may be considered as remote sources, are the crystalline basement of Brunovistulicum (point 2 in Fig. 8) and the Variscan internides of the Bohemian Massif (point 3 in Fig. 8). Mica-schists, gneisses and amphibolites, formed under greenschist to amphibolite facies conditions, containing garnet (e.g., Burtan, 1962; Heflik and Konior, 1972, 1974; Górska and Heflik, 1975), identified as almandine (Heflik and Konior, 1974; Górska and Heflik, 1975), are known from boreholes drilled into the Precambrian crystalline basement of Brunovistulicum in the area of Bielsko-Biała (see Moryc and Heflik, 1998; Buła and Żaba, 2008). The Precambrian crystalline rocks are elevated in the southern part of the Bielsko-Andrychów Massif (situated currently under the Carpathian overthrust), where they are overlain directly by Miocene strata (Buła *et al.*, 2004). They are also uplifted and covered by Middle Jurassic deposits, in the Rzeszotary Horst (Burtan, 1962; Pelczar and Wieser, 1962; Heflik and Konior, 1972, 1974; Konior, 1974; Buła *et al.*, 2004). The Bohemian Massif crystalline domains, in turn, are built of various metamorphic and granitic rocks, which are well recognised and widely studied in natural exposures (e.g., Mazur *et al.*, 2006 and references therein). The rocks contain garnet, which is similar in composition to the garnet analysed in this study. The almandine and spessartine-rich garnet varieties are similar in composition to garnet from various metapelites, gneisses and mica-schists, exposed in the Moravo-Silesian, Moldanubian and Lugian zones of the Bohemian Massif (Fig. 9). Pyrope- and grossular-rich almandine are compositionally similar to the garnet, occurring in metabasites and granulites of the Moldanubian Zone and Sudetes (Fig. 9).

Other crystalline massifs, with rocks indicated by the chemical composition of the garnets analysed, are not known in the upflow direction for palaeocurrents, recorded from the Ropianka and Menilite formations. Moreover, it has been documented, that the Variscan internides of the Bohemian Massif are the most probable sources of the clastic material in Upper Carboniferous deposits of the Upper Silesian Block (Paszkowski *et al.*, 1995; Kusiak *et al.*, 2006). The Bohemian Massif domains and the elevated parts of the basement of Brunovistulicum could also have been sources for the clastic infill of the Jurassic pre-Callovian palaeokarst in the Czatkowice quarry (Salata, 2013b) and the Middle Jurassic clastic rocks of the Kraków-Wieluń Upland, though the latter also may have been supplied from a hypothetical landmass, located south of the upland (Méres *et al.*, 2012). Upper Carboniferous and Middle Jurassic clastics, together with other deposits of the Upper Silesian and Małopolska blocks, subsequently could have been sources for a part of the garnet population, buried in the Skole Basin. Garnets occurring in the deposits of the Upper Silesian Block, especially those with elevated pyrope and grossular or spessartine molecules, are compositionally congruent with the garnets studied (Fig. 9). The erosion of

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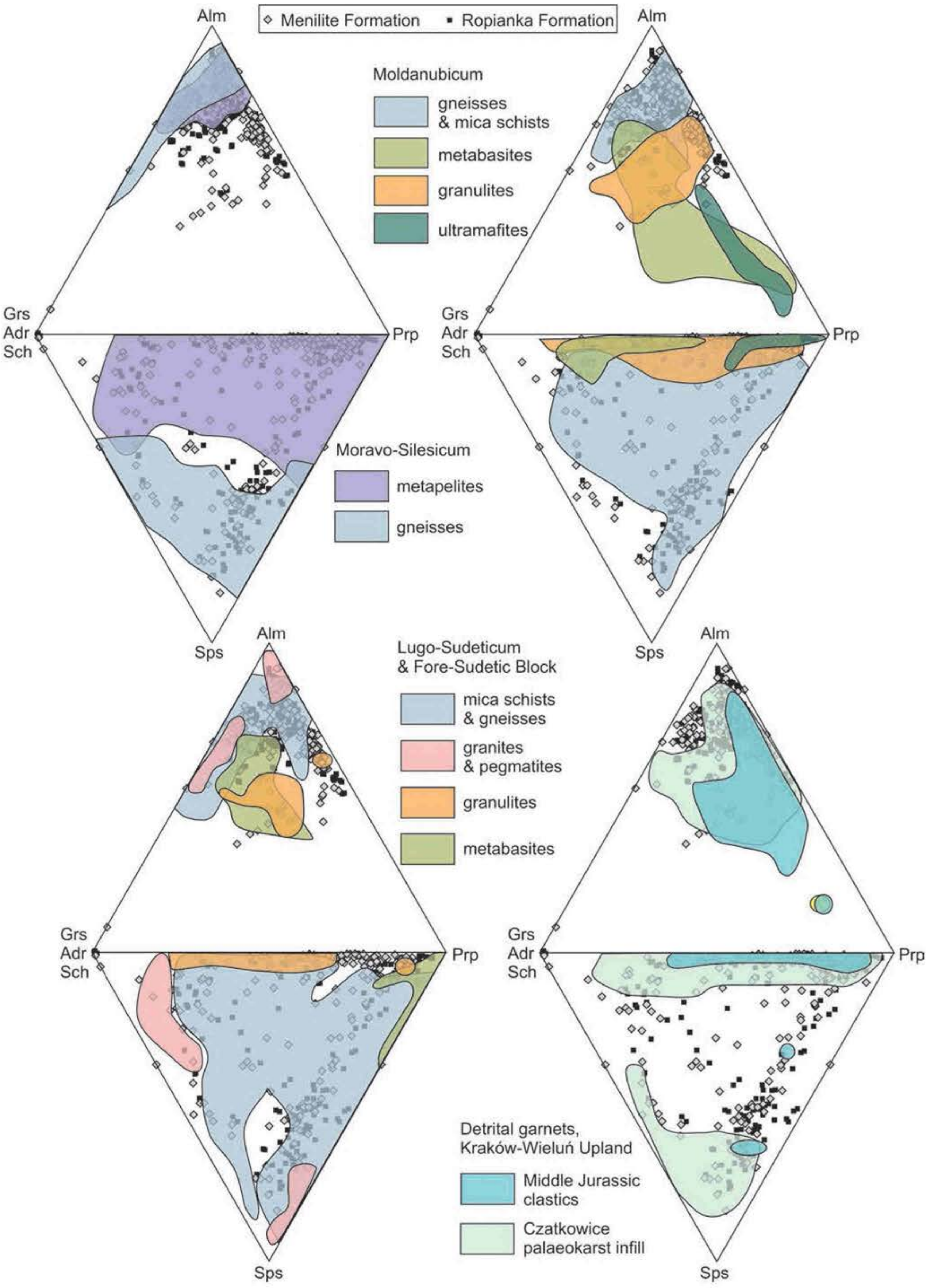
Fig. 9. Comparison of garnets from the Ropianka and Menilite formations to garnets occurring in metamorphic and igneous rocks of the Moldanubicum, Lugo-Sudeticum and Moravo-Silesicum and to detrital garnets from the Middle Jurassic clastics from the Kraków-Wieluń Upland and clastic infill of the Jurassic pre-Callovian palaeokarst in the Czatkowice quarry (compositional fields of garnets in the diagrams based on data from: (Janeczek and Sachanbiński, 1989; Oberc-Dziedzic, 1991; Makała, 1994; Dziedzic, 1996; Kryza *et al.*, 1996; Owen and Dostal, 1996; O'Brien *et al.*, 1997; Pieczka *et al.*, 1997; Bakun-Czubarow, 1998; Puziewicz and Rudolf, 1998; Puziewicz *et al.*, 1999; Bues and Zulauf, 2000; Kröner *et al.*, 2000; Kryza and Pin, 2002; Budzyń *et al.*, 2004; Čopjaková *et al.*, 2005; Medaris *et al.*, 2005, 2006; Vrána and Bártek, 2005; Vrána *et al.*, 2005; Racek *et al.*, 2006, 2008; Štipská *et al.*, 2006; Tajčmanová *et al.*, 2006; Janoušek *et al.*, 2007; Vrána, 2008; Faryad, 2009; Jastrzębski, 2009, 2012; Faryad *et al.*, 2010; Redlińska-Marczyńska, 2011; Méres *et al.*, 2012; Salata, 2013b)


◇ Menilite Formation ▪ Ropianka Formation
Alm
Grs
Adr
Sch
Prp
Sps
Moldanubicum
gneisses & mica schists
metabasites
granulites
ultramafites
Moravo-Silesicum
metapelites
gneisses
Lugo-Sudeticum & Fore-Sudetic Block
mica schists & gneisses
granites & pegmatites
granulites
metabasites
Detrital garnets, Kraków-Wieluń Upland
Middle Jurassic clastics
Czatkowice palaeokarst infill

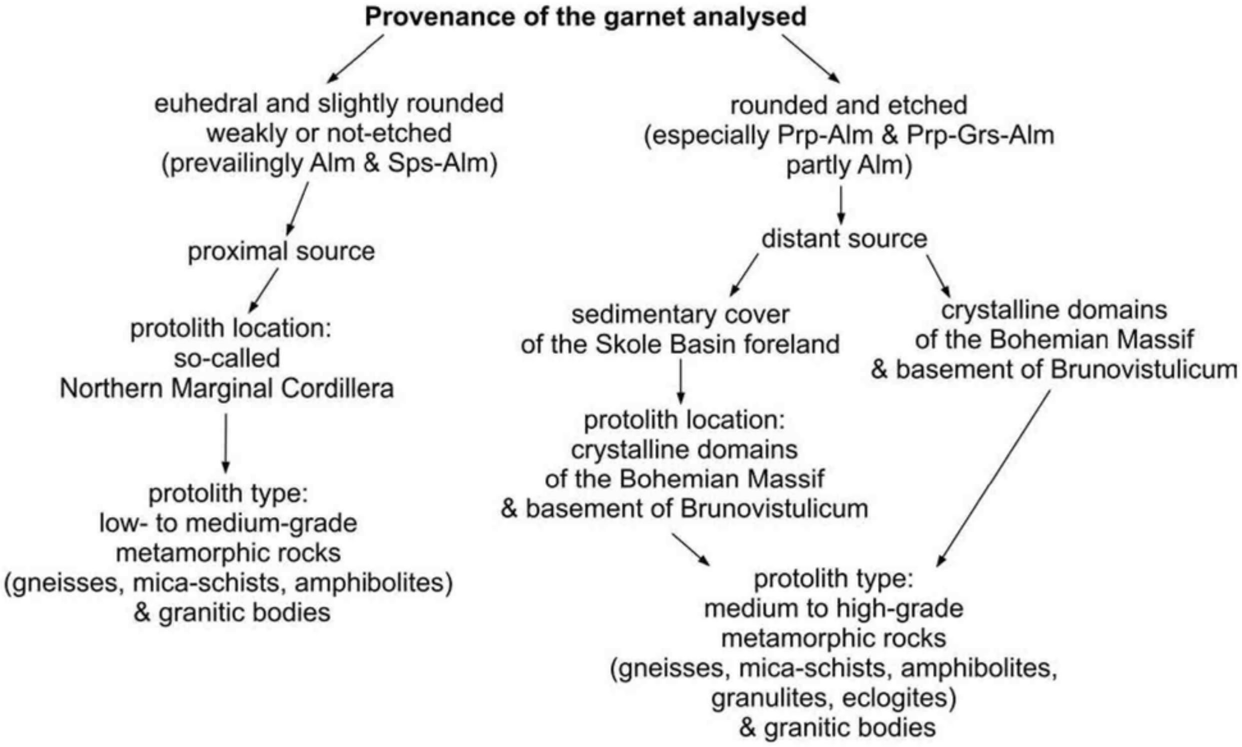


Fig. 10. Scheme summarizing provenance of garnet grains from the Ropianka and Menilite formations. Abbreviations as in Fig. 4

the sedimentary cover of the Skole Basin foreland is also evidenced by Carboniferous coal fragments and other Palaeozoic and Mesozoic rocks, present in the deposits sampled (Turnau, 1962, 1970; Kotlarczyk and Śliwowa, 1963; Kotlarczyk, 1979). The interpreted provenance of the garnet grains of the Ropianka and Menilite formations is schematically summarized in Fig. 10.

Considering all the data, a diverse provenance and mixed character of garnet grains seems reasonable. However, without further evidence, it is impossible to judge to what extent the rounded and etched garnet population was derived from a primary source, remote areas or a secondary source. The grains were influenced by the coastal environment of the Skole Basin, where some garnet features, such as primary diagenetic corrosion textures, could have been obliterated. Moreover, highly corroded grains could have been totally destroyed during transportation. The garnet population could have been also depleted in the less stable varieties. Nonetheless, there are some observations that argue for the primary provenance of a major part of the almandine and spessartine-almandine garnet with a minor admixture of almandine, slightly enriched in pyrope. These are: i) the large amount of garnet from both formations that may come from first-cycle delivery (Salata and Uchman, 2013); ii) the almandine, spessartine-almandine or pyrope-enriched almandine compositions of all of the euhedral, slightly rounded and weakly corroded garnet and uncorroded sharp-edged fragments, and iii) the lithologies of pebbles (gneisses, mica-schists, granites). It also seems possible that relatively smaller numbers of garnet grains, especially those originating from high-grade metamorphic rocks, have their protoliths located in remote areas, which may be the crystalline basement of the Brunovistulicum and Bohemian Massif domains.

CONCLUSIONS

Garnet populations, occurring in the Ropianka and Menilite formations, contain a mixture of grains, derived from a proximal source, remote areas and/or recycled grains, eroded from sedimentary rocks of the Skole Basin foreland.

Garnets in both of the formations studied are compositionally similar, suggesting a provenance from lithologically similar source rocks.

Much of the garnet represented by euhedral, slightly rounded, weakly etched or unetched almandine, spessartine-almandine and minor pyrope-enriched almandine varieties, originated from metamorphic rocks formed under low- to medium-grade metamorphic conditions (such as mica-schists, gneisses) and granitic bodies, located in a proximal position in relation to the Skole Basin.

Rounded and variably etched garnet, especially high pyrope-almandine and pyrope-almandine-grossular varieties, may have been derived directly from distant sources or the sedimentary cover of the Skole Basin foreland. Uplifted parts of the crystalline basement of Brunovistulicum or crystalline domains of the Bohemian Massif could have been sources for part of the almandine-dominated garnet population. Additionally, pyrope-almandine-grossular garnet may originate from the granulitic, eclogitic or metabasic rocks of the Bohemian Massif.

The study shows that single-grain chemical analyses of garnet, combined with observations of the textural features of grains and data on the lithology of clasts and pebbles, permit the determination of sources for garnet varieties in mixed-provenance garnet populations.

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