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Provenance of the detrital garnets and spinels from the Albian sediments of the Czorsztyn Unit (Pieniny Klippen Belt, Western Carpathians, Slovakia)

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Abstract: According to earlier concepts, the Czorsztyn Unit (Oravic Superunit, Pieniny Klippen Belt, Western Carpathians) sedimented on the isolated Czorsztyn Swell which existed in the Middle Jurassic–Late Cretaceous time in the realm of the Outer Western Carpathians. This paper brings new data providing an alternative interpretation of its Cretaceous evolution. They are based on heavy mineral analysis of the Upper Aptian/Lower Albian sediments of the Czorsztyn Unit. They rest upon a karstified surface after a Hauterivian-Aptian emersion and are represented by condensed, red marly organodetritic limestones with some terrigenous admixture (Chmielowa Formation). The heavy mineral spectrum is dominated by spinels, followed by garnet, with lesser amounts of zircon, rutile and tourmaline. The composition of the majority of the detrital garnets shows that they were derived from primary HP/UHP parental rocks which were recrystallized under granulite and amphibolite facies conditions. The garnets were most probably derived directly from the magmatic and metamorphic rocks of the Oravic basement, as the high-pyrope garnets are known to be abundant in Mesozoic sediments all over the Outer Western Carpathians. The presence of spinels is surprising. According to their chemistry, they were mostly derived from mid-oceanic ridge basalts (MORB) peridotites, supra-subduction zone peridotites (harzburgites) and transitional lherzolite/harzburgite types. Only a lesser amount of spinels was derived from volcanics of BABB composition (back-arc basin basalts). The presence of this ophiolitic detritus in the Czorsztyn Unit is difficult to explain. Ophiolitic detritus appeared in the Aptian/Albian time only in the units which were considered to be more distant, because they were situated at the boundary between the Central and the Outer Western Carpathians (Klape Unit, Tatric and Fatric domains). The hypothetical Exotic Ridge which represented an accretionary wedge in front of the overriding Western Carpathian internides was considered to be a source of the clastics. In previous paleogeographical reconstructions, the Czorsztyn Unit was situated north of the Pieniny Trough (considered to be one of the branches of the Penninic-Vahic Ocean). In the trough itself, the ophiolitic detritus appeared as late as in the Senonian and there was no way it could reach the Czorsztyn Swell which was considered to be an isolated elevation. The new results presented herein show that these reconstructions do not fit the obtained data and infer a possibility that the Czorsztyn sedimentary area was not isolated in the Cretaceous time and it was situated closer to the Central Carpathian units than previously thought. A new paleogeographical model of the evolution of the Pieniny Klippen Belt is presented in the paper: Oravic segment was derived from the Moldanubian Zone of the Bohemian Massif by the Middle Jurassic rifting which caused block tilting where most of the Oravic units were arranged north of the Czorsztyn Swell. The Oravic segment was situated in the lateral continuation of the Central and Inner Western Carpathians from which it was detached by later clockwise rotation. The Oravic segment was then laterally shifted in front of the Central Western Carpathians, together with remnants of the Meliatic suture zone which represented a source for the exotics to the Klape, Tatric, Fatric and Oravic units.

Key words: Cretaceous paleogeography, provenance, Pieniny Klippen Belt, heavy minerals.

Introduction

The Pieniny Klippen Belt (Fig. 1) is a narrow, tectonically complicated zone of the Western Carpathians, forming the boundary between their internides and externides. The zone represents a melange of various paleogeographic-tectonic units coming from the Central Western Carpathians and from the independent Oravic Superunit which dominates the Pieniny Klippen Belt. The shallowest Oravic unit is the Czorsztyn Unit which is considered to be paleogeographically located on a swell or ridge (Fig. 2). Its sedimentary record is known from the Hettangian till the latest Cretaceous. Shallow-marine deposits dominated the Bajocian to Valanginian lithostratigraphy of this unit (Fig. 3). After the Valanginian, a hiatus encompassing the whole Hauterivian, Barremian and substantial parts of the Aptian occurred in this unit (Aubrecht et al. 2006). Tithonian to Valanginian formations of this unit are often covered by pelagic Albian to Cenomanian red marly limestones, marlstones and radiolarites (Chmielowa and Pomiedznik Formations). The cause and character of this hiatus were for a long time unclear. Submarine non-deposition and erosion were the most preferred explanations because of

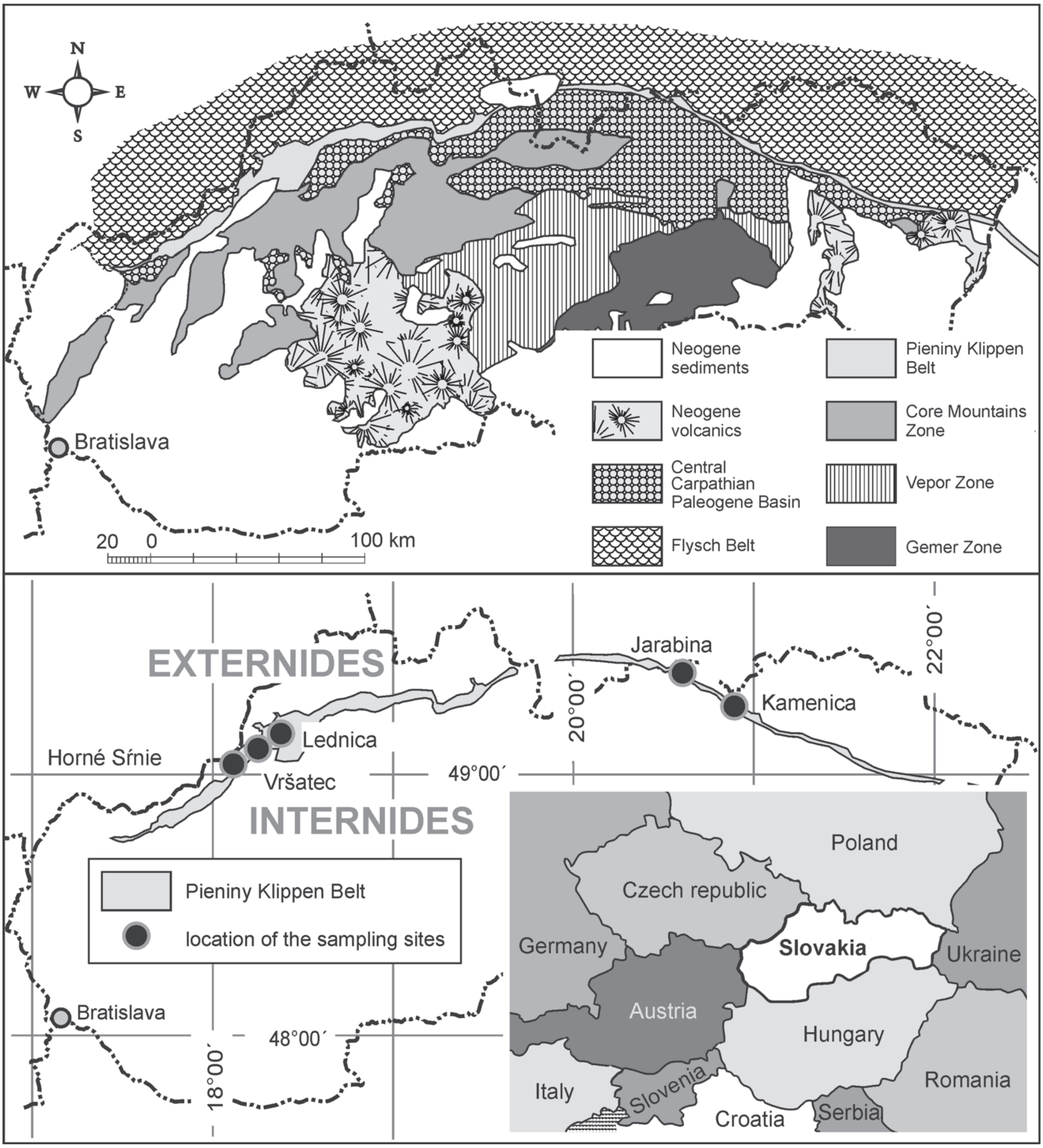

Fig. 1. Structural scheme of Slovakia (according to Lexa et al. 2000 — modified) and location of the sampling sites.

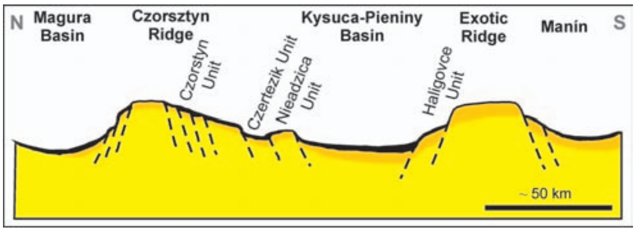

Fig. 2. Reconstruction of the paleogeographical position of the individual Oravic units after Birkenmajer (1977, slightly modified).

the pelagic character of the overlying sediments. Detailed studies, however, showed that the hiatus resulted from emersion, erosion and karstification of the older sediments (Aubrecht et al. 2006). The research also revealed that the deposition of the overlying Chmielowa Formation started in the Late Aptian in the form of red organodetritic limestones with phosphatic stromatolites and oncoids and sandy detrital admixtures which are locally preserved at the base of the formation. Already the thin-section study revealed the presence of spinel grains, together with some small basaltic pebbles in

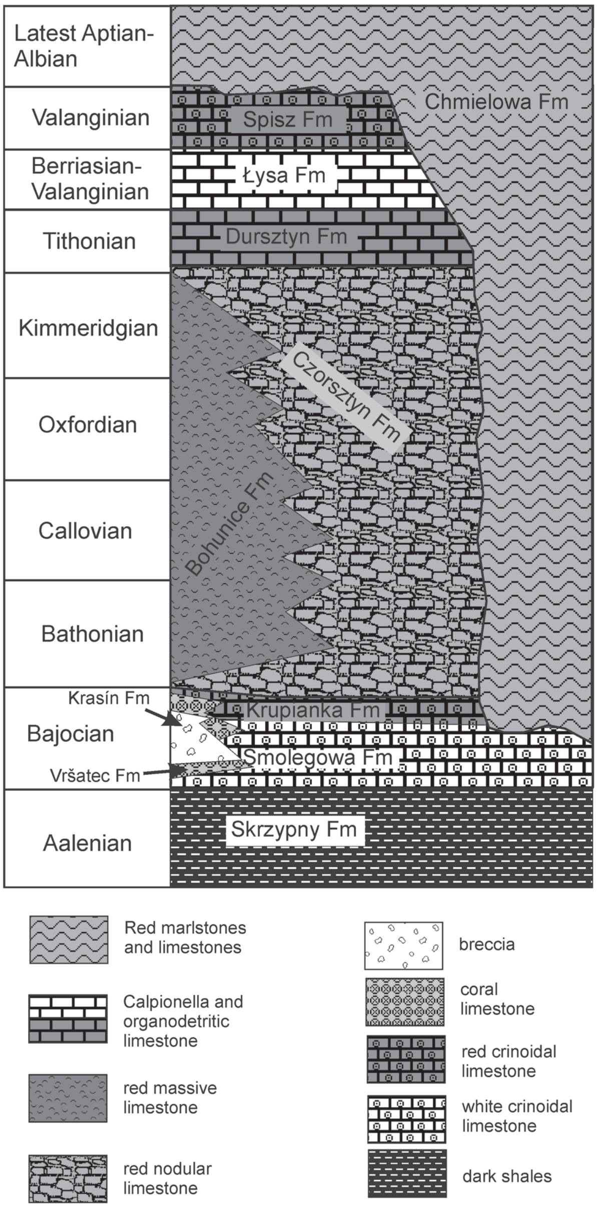

Fig. 3. Lithostratigraphic chart of the Czorsztyn Unit from Aalenian to Albian.

these limestones, and provoked detailed heavy mineral analysis which brought unexpected results with far-reaching consequences in the paleogeography of the Outer Carpathians.

Studied localities and analytical methods

Seven samples from six localities were analysed for heavy minerals: Vršatec I, Vršatec II, Horné Sŕnie (2 samples), Lednica, Jarabina and Kamenica (Fig. 1; for the detailed location of the sampling sites see Aubrecht et al. 2006). The average weight of the samples was about 2 kg. To separate the sandy siliciclastic admixture, the samples were dissolved in acetic acid and washed by water. The fraction between 0.08 and 0.71 mm was separated by sieving. Smaller grains were washed out because of the difficulty of determining by optical methods. The remaining fraction underwent separation in heavy liquids (bromoform and tetrabromethane, densities 2.8 and 2.92 respectively). The fraction 0.08–0.25 mm was studied in transmitting light, the whole fraction was also examined by a stereomicroscope. The percentages of the heavy mineral assemblages were determined by ribbon point counting. Spinels and garnets were hand-picked, then mounted in epoxy resin, polished and coated with carbon.

The spinels were analysed using a wave-dispersion (WDS) electron microprobe at the Department of Mineralogy in the Natural History Museum, London (UK). The microprobe used was Cameca SX50. The following operating conditions were used: 20 kV accelerating voltage, 20 nA beam current, beam diameter 2–5 μm, counting time 20 seconds, ZAF corrections, standards (*n-natural, sy-synthetic*) — TiO_2 (*sy*), $CaTiO_3$ (*sy*), V (*sy*), wollastonite (*n*), Cr_2O_3 (*sy*), Mn (*sy*), hematite (*sy*), Co (*sy*), Ni (*sy*), ZnS (*sy*), Al_2O_3 (*sy*), diopside (*n*), MgO_2 (*sy*). Fe^{2+} and Fe^{3+} in spinels were calculated assuming an ideal stoichiometry. The composition of garnets was determined using a CAMECA SX-100 electron microprobe at the State Geological Institute of Dionýz Štúr in Bratislava. The analytical conditions were 15 kV accelerating voltage and 20 nA beam current, with a peak counting time of 20 seconds and a beam diameter of 2–10 μm. Raw counts were corrected using a PAP routine.

Results and source rocks interpretation

Percentages of heavy minerals

In all the samples, spinels and garnets are dominant, with lesser amounts of rutile, tourmaline and zircon (Fig. 4). In some samples, increased numbers of tourmaline, anatase and magnetite were recorded (Fig. 4, Table 1). Kyanite and ilmenite grains were also found in rare cases. For provenance studies of this assemblage, chemical analyses of the two most abundant minerals, garnet and spinel, were carried out.

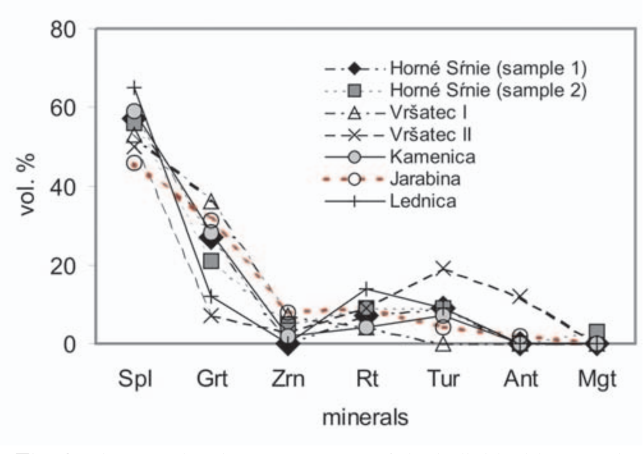

Fig. 4. Diagram showing percentages of the individual heavy minerals in the examined samples.

Table 1: Percentual ratios of heavy minerals in the examined samples.

Locality	Spl	Grt	Zrn	Rt	Tur	Ant	Mgt
Horné Sŕnie 1	57	27	0	7	9	0	0
Horné Sŕnie 2	56	21	5	9	9	0	3
Vršatec 1	53	36	7	4	0	0	0
Vršatec 2	50	7	3	9	19	12	0
Lednica	65	12	0	14	9	0	0
Kamenica	59	28	2	4	7	0	0
Jarabina	46	31	8	9	4	2	0

Explanations: **Spl** — spinels, **Grt** — garnet, **Zrn** — zircon, **Rt** — rutile, **Tur** — tourmaline, **Ant** — anatase, **Mgt** — magnetite. All symbols for rock-forming minerals in this paper were used according to Kretz (1983).

Chemical composition of detrital garnets and their origin

Garnets belong to a group of rock-forming minerals with high importance for interpretations of the genesis of many types of rocks: (1) garnets are useful in defining metamorphic conditions, (2) can be utilized for the estimation of the p-T history of the host rock, (3) garnets are very good indicators of their parental rock types (mafic, felsic, Mn-rich, V-rich, Cr-rich, etc.), (4) detrital garnets are useful in paleogeography. Natural garnets grown in various metamorphic conditions were classified by Méres (2008; Figs. 5 and 6) in pyrope-almandine-grossular and pyrope-almandine-spessartine triangle diagrams. Three main groups were distinguished: (A) garnets from HP/UHP (high-pressure to ultra-high-pressure conditions), (B) garnets from eclogite and granulite facies conditions, (C) garnets from amphibolite facies conditions, with C1 — transitional subgroup between the granulite and amphibolite facies conditions and C2 — subgroup of the amphibolite facies conditions. These groups have been distinguished according to their chemical compositions and inclusions.

The garnets from HP/UHP conditions displaying typical composition $\mathrm{Prp}_{<70}\mathrm{Alm}_{\sim15}\mathrm{Grs}_{\sim10}\mathrm{Sps}_{<1}\mathrm{Uvar}_{<5}$, are homogeneous (only the B group and C1 subgroup have diffusion zoning) and contain typical inclusions of the minerals from the

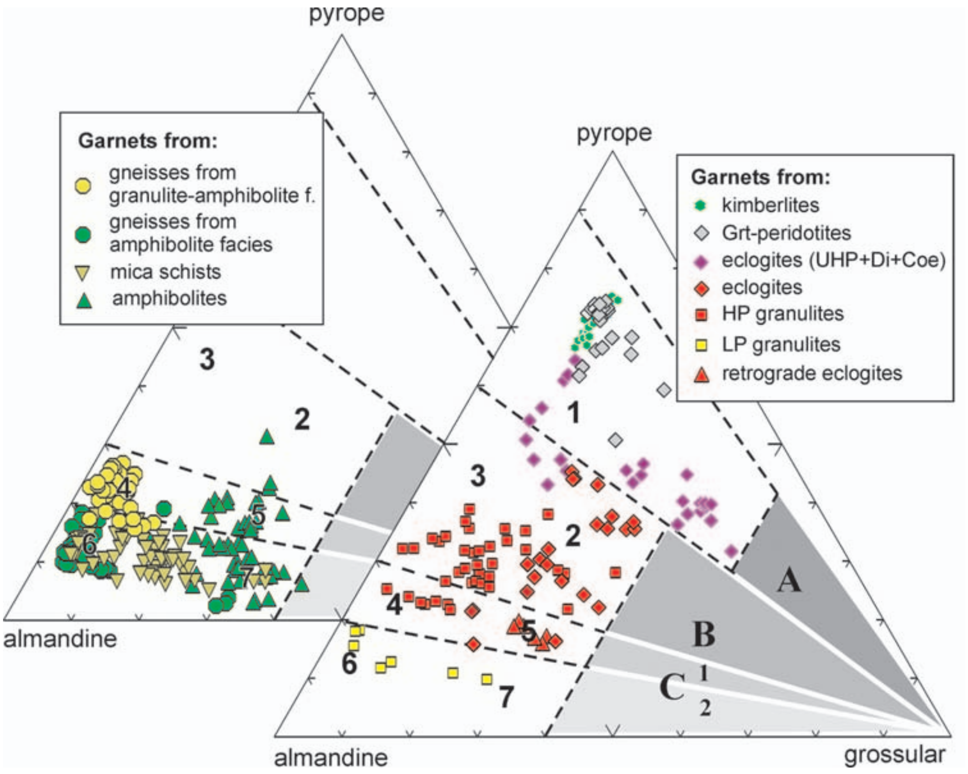

Fig. 5. Composition of the garnets from UHP/HP metamorphic conditions in the classification diagrams "pyrope-almandine-grossular" (Méres 2008). Explanations: **A** = field of Grt compositions from HP/UHP conditions; **B** = field of Grt compositions from granulite and eclogite facies conditions; **C1** = transitional field of Grt compositions from high amphibolite to granulite facies conditions; **C2** = field of Grt compositions from amphibolite facies conditions (Comment: field C2 includes many other Grts too: Grt from blue schists, Grt from skarns, Grt from serpentinites, Grt from igneous rocks, etc.). No. 1–7: Source rocks of the individual garnets (see text).

Source of the garnet compositions. Right diagram: Grt from HP granulites in the Góry Sowie Mts (Polish Sudetes; O'Brien et al. 1997), Grt from peridotites, eclogites and granulites from the Bohemian Massif (Messiga & Bettini 1990; Nakamura et al. 2004; Seifert & Vrána 2005; Vrána et al. 2005; Medaris et al. 2006a,b; Janoušek et al. 2006, 2007; Racek et al. 2008), Grt from HP and UHP eclogites and garnet peridotites from the Western Gneiss Region (WGR, Norway; Krogh Ravna & Terry 2004), Grt from kimberlites (Schulze 1997), Grt from eclogites with inclusions of diamond (Schulze 1997), Grt from HP granulites, from UHP eclogites with inclusions of coesite and Grt peridotites from the Saxonian Erzgebirge and Granulitgebirge (Massonne & Bautsch 2004). Left diagram: Grt from mica schists, gneisses and amphibolites and amphibolized eclogites occurrence in the pre-Alpine basement rocks of the Western Carpathians Mts (Hovorka et al. 1987; Méres & Hovorka 1989, 1991; Hovorka & Méres 1990, 1991; Korikovsky et al. 1990; Hovorka et al. 1992; Janák et al. 1996, 2001, 2007; Hovorka & Spišiak 1997; Vozárová & Faryad 1997; Faryad & Vozárová 1997; Janák & Lupták 1997; Méres et al. 2000; Faryad et al. 2005).

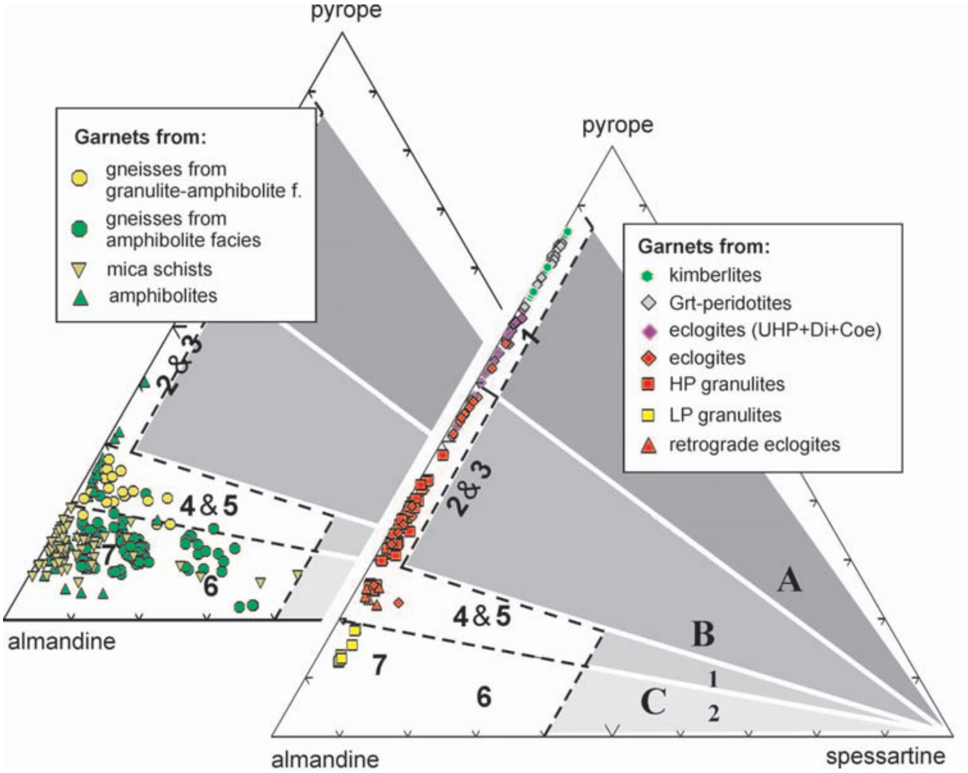

Fig. 6. Composition of the garnets from granulite and amphibolite facies conditions in the classification diagrams "pyrope-almandine-spessartine" (Méres 2008). Explanations as Fig. 5.

UHP conditions such as phengite, kyanite, coesite or diamond. The garnets from eclogite facies conditions have most commonly $\mathrm{Prp}_{30-50}\mathrm{Alm}_{35-45}\mathrm{Grs}_{\sim 10}\mathrm{Sps}_{<1}$ composition and contain inclusions of the minerals like omphacite, phengite, rutile, kyanite, zoisite and Al-Cr-spinels. The garnets from granulite facies conditions are characterized by $\mathrm{Prp}_{20-30}\mathrm{Alm}_{50-60}\mathrm{Grs}_{<30}\mathrm{Sps}_{<2}$ composition and contain inclusions of minerals such as diopside, rutile, spinel, amphibole or pargasite. The garnets from the transitional subgroup between the granulite and amphibolite facies conditions (C1) generally display $\mathrm{Prp}_{15-25}\mathrm{Alm}_{<70}\mathrm{Grs}_{<30}\mathrm{Sps}_{<3}$ composition and contain inclusions of minerals typical for high-grade amphibolite facies rocks (e.g. Cpx + Hbl + Plg symplectites). The garnets from amphibolite facies conditions (C2 subgroup) generally have $\mathrm{Prp}_{<15}\mathrm{Alm}_{\sim 75}\mathrm{Grs}_{<30}\mathrm{Sps}_{>3}$ composition. Prograde growth zonation and inclusions of the minerals like kyanite, sillimanite, andalusite, staurolite, chloritoide, biotite, plagioclase, amphibole, K-feldspar, epidote and muscovite are typical for these garnets. In the C2 subgroup, garnets from many other sources integrate, for example garnets from igneous rocks (granitoids, syenites), HP/LT metamorphic rocks, contact-metamorphosed rocks (skarns) or from serpentinites.

Some garnet grains from the examined samples showed preserved euhedral crystal shape; most of the grains were subangular, showing a low-grade of roundness (Fig. 7a). Some of the analysed garnet grains bear traces of intrastratal etching. Electron microprobe analyses of the detrital garnets (48 grains, 105 analyses) from the Vršatec I, Vršatec II, Jarabina, Horné Sŕnie, Lednica and Kamenica localities show significant variation in chemistry. Variation of garnet composition is expressed in the relative proportions of the pyrope, almandine, grossular and spessartine end member components (Table 2). The garnets were classified according to the above mentioned pyrope-almandine-grossular and pyrope-almandine-spessartine diagrams (Méres 2008). The composition of detrital garnet grains shows that they can be subdivided into 7 groups, according to their parental rocks (Fig. 8a and Fig. 8b):

(1) *Garnets derived from UHP eclogites or garnet peridotites* (Fig. 8a and Fig. 8b field A.1). This garnet assemblage is dominated by high pyrope (around and higher 50 mol %), moderate almandine (30–40 mol %) and grossular (11–17 mol %) and low spessartine components (less than 1 mol %). The garnets are relatively homogeneous due to their high-temperature equilibration above 600–650 °C. The garnets locally contain inclusions of Al_2SiO_5 (kyanite, Fig. 7—Grt 2–9).

(2) *Garnets derived from HP eclogites and HP mafic granulites* (Fig. 8a and Fig. 8b field B.2) are also homogeneous. These garnets are characterized by high pyrope (30–50 mol %), moderate almandine (40–50 mol %) and grossular (17–20 mol %) molecule and very low spessartine contents (less than 2 mol %).

(3) *Garnets derived from felsic and intermediate granulites* (Fig. 8a and Fig. 8b field B.3). These garnets are dominated by relatively high pyrope (30–40 mol %), moderate almandine (48–60 mol %), higher amounts of grossular molecules (less than 5 mol %) and very low spessartine (less than 2 mol %). These garnets are relatively homogeneous.

(4) *Garnets derived from gneisses metamorphosed under P-T transitional to granulite and amphibolite facies condi-*

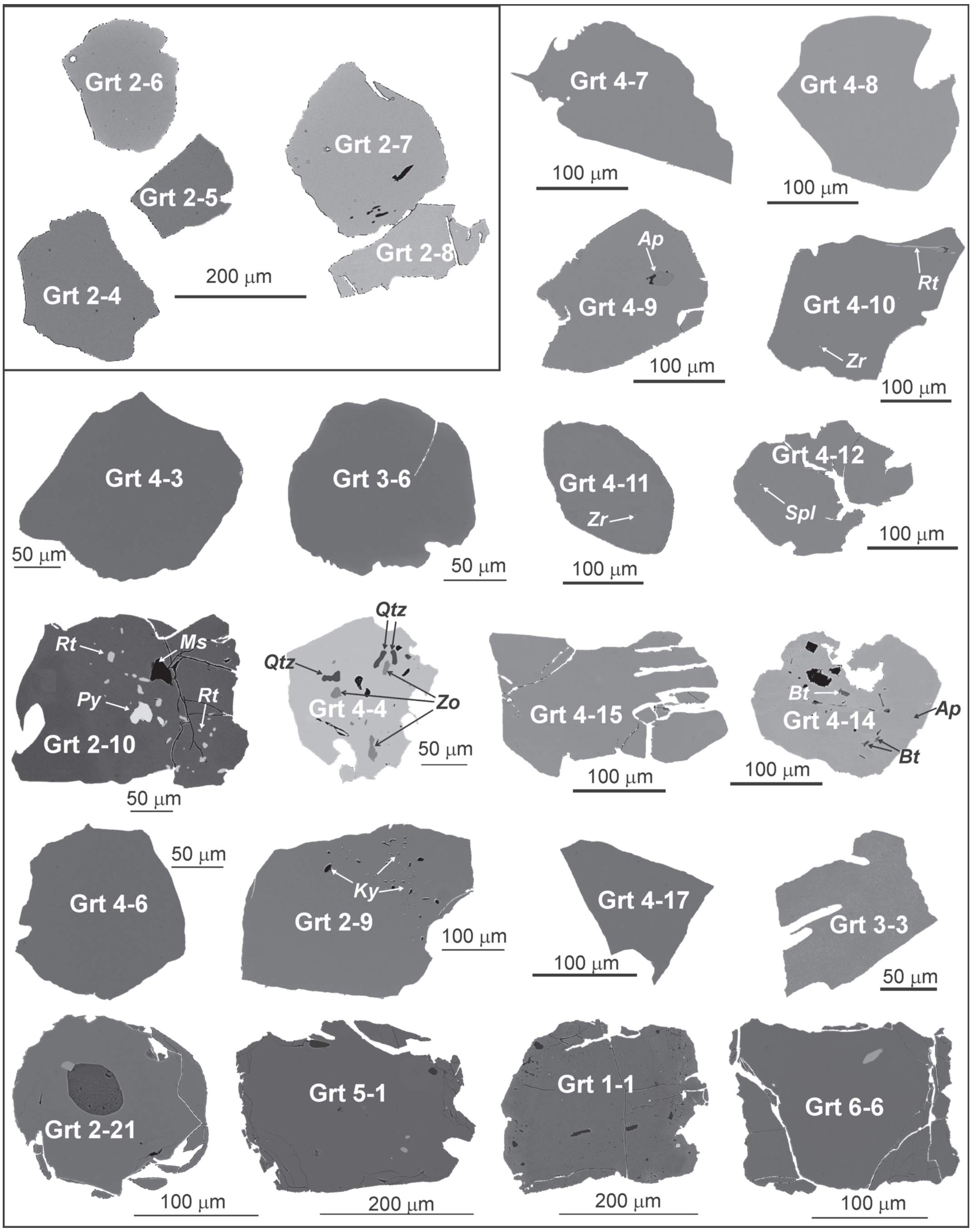

Fig. 7a. Back-scattered electron (BSE) images of the detrital garnets from the Upper Aptian/Lower Albian sediments of the Czorsztyn Unit.

tions (Fig. 8a and Fig. 8b field C1.4&5). They have higher almandine contents (60–70 mol %), lower pyrope contents (20–30 mol %) than the granulitic garnets, but low content of spessartine (<2 mol %) and grossular (<5 mol %). These garnets are homogeneous.

(5) *Garnets derived from amphibolites metamorphosed under transitional P-T granulite to amphibolite facies conditions* (Fig. 8a and Fig. 8b field C1.4&5). They differ from the 4-group garnets by having higher proportions of the grossular molecule (6–30 mol %) and relatively lower almandine contents (45–60 mol %). These garnets locally contain inclusions (Fig. 7a) of spinel (Spl in Grt 4–12), TiO_2 (Rtl in Grt 2–10), muscovite (Ms in Grt 2–10) and pyrite (Py in Grt 2–10).

(6) *Garnets derived from gneisses metamorphosed under amphibolite facies conditions* (Fig. 8a and Fig. 8b field C2.6). They have the highest almandine contents (>70 mol %), lowest pyrope contents (<20 mol %) and highest contents of spessartine (2–28 mol %) of the studied detrital garnets. Contents of grossular were less than 7 mol %.

(7) *Garnets derived from amphibolites metamorphosed under amphibolite facies conditions* (Fig. 8a and Fig. 8b field C2.7). They differ from the group 6 by having higher

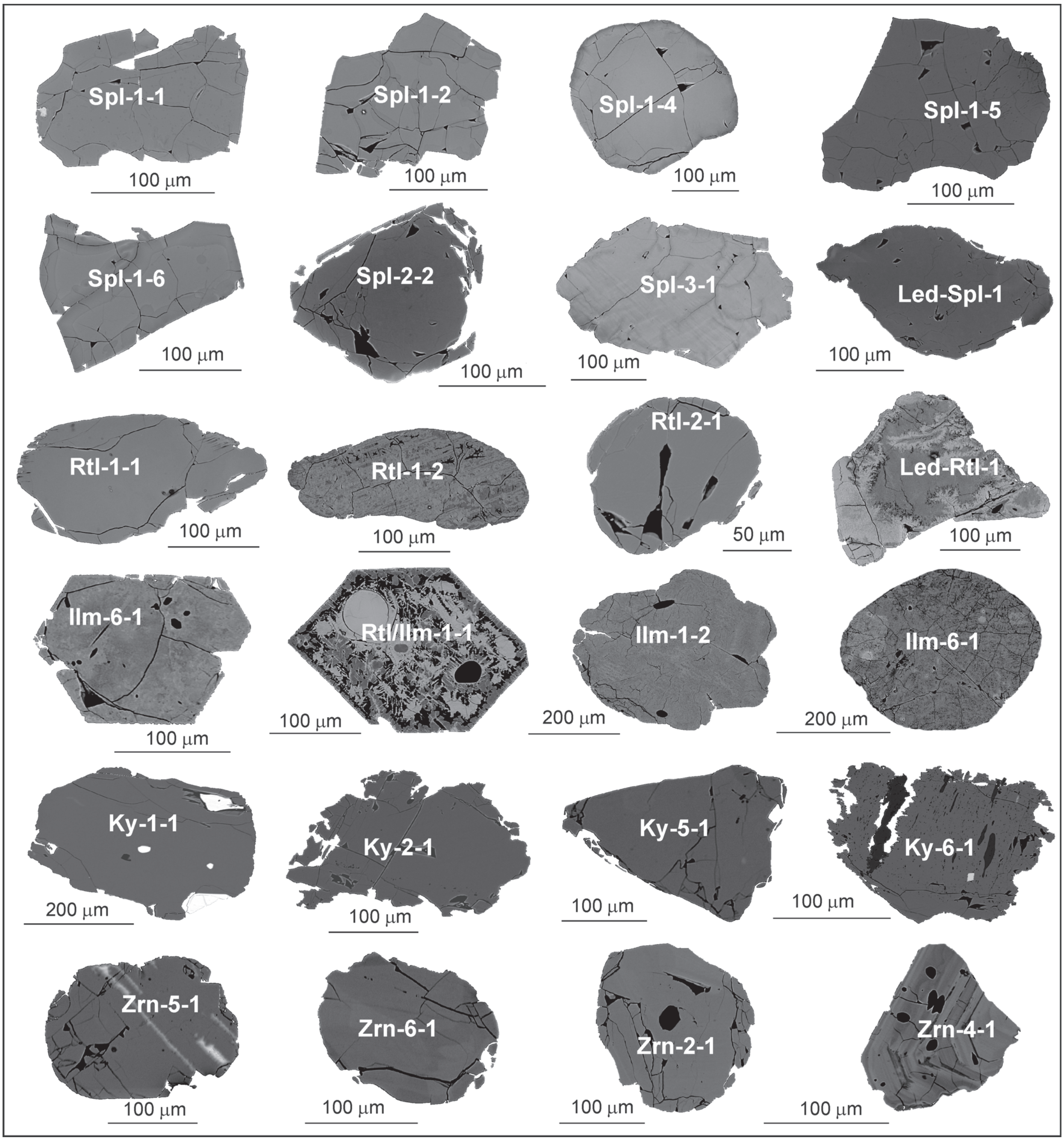

Fig. 7b. Back-scattered electron (BSE) images of the detrital spinel, rutile, ilmenite, kyanite and zircon from the Upper Aptian/Lower Albian sediments of the Czorsztyn Unit.

proportions of the grossular molecule (7–45 mol %) and lower almandine contents (45–55 mol %). These garnets (together with the garnets from the group 6) exhibit chemical growth zoning characterized by Ca- and Mn-richer cores and Fe- and Mg-richer rims (Fig. 7a—Grt 4-4; Table 2). Occurrence of the growth zoning in the garnets indicates their origin in the temperature field below 600 °C. The inclusions (Fig. 7a) in the detrital garnets of the 6 and 7 groups are mainly apatite (Ap in Grt 4-9, Grt 4-14), biotite (Bt in Grt 4-14), zoisite (Zo in Grt 4-4), SiO_2 (Qtz in Grt 4-4) and zircon (Zr in Grt 4-10 and in Grt 4-11). Part of the garnets belonging to this group which has higher grossular (27–48 mol %) and spessartine contents (3–30 mol %) was most likely derived from HP/LT metaultramafites (number 7* in Table 2).

The variable compositions of the analysed detrital garnets suggest, that the source area comprised predominantly large complexes of the metamorphic parental rocks formed under medium to high-grade conditions. Garnets from the rocks like garnet peridotite, eclogite and granulite (Fig. 8a,b field A and field B) indicate that their source area was initially metamorphosed under HP(UHP?)/HT conditions. Garnets from the rocks such as gneisses and amphibolites (Fig. 8a,b field C2) indicate the amphibolite facies metamorphism. The garnet compositions show continuous distribution between the two

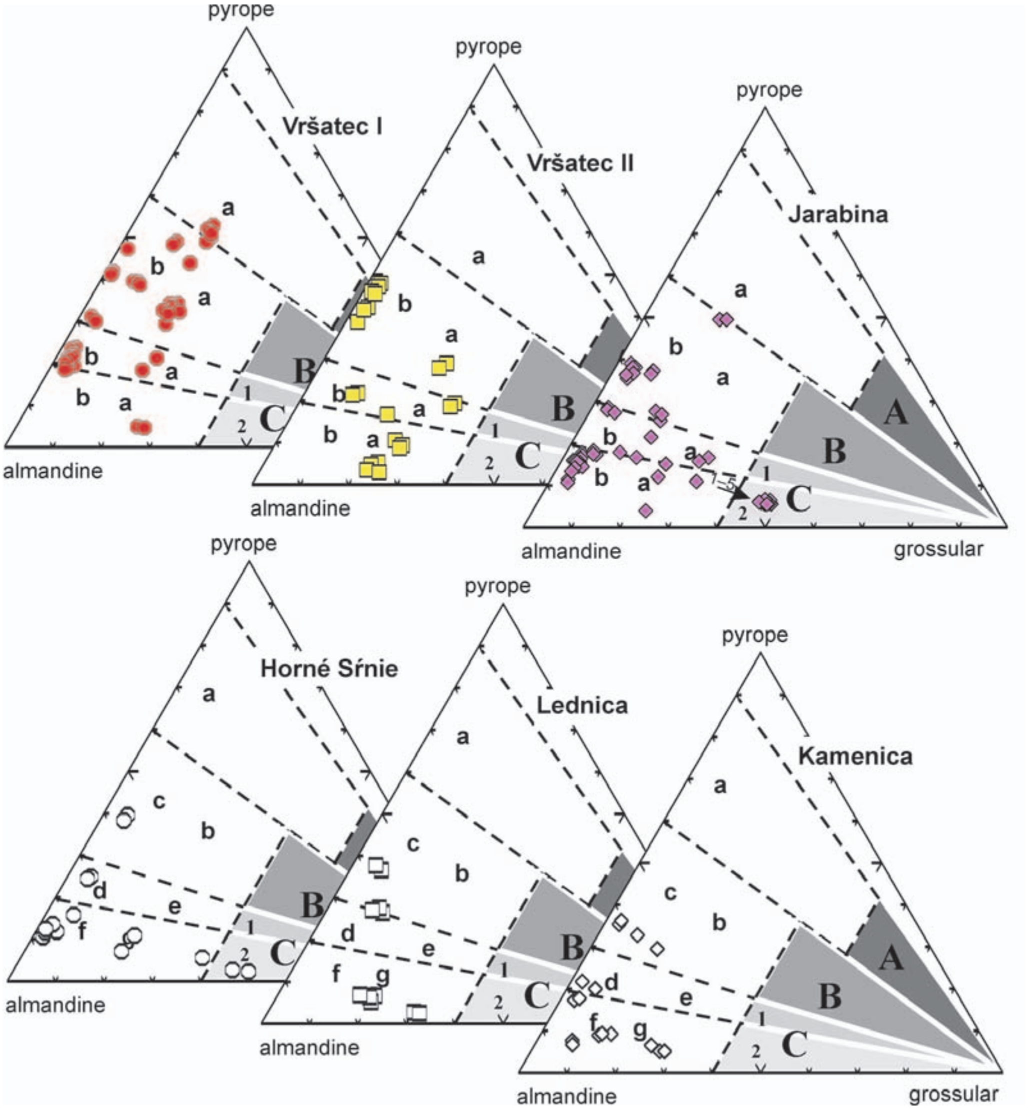

Fig. 8a. Ternary diagrams of the almandine-pyrope-grossular ratios, classifying the source rocks of the studied detrital garnets from Upper Aptian/Lower Albian sediments of the Czorsztyn Unit according to their origin. Explanations see Fig. 5 and Fig. 6.

end-members (represented by the fields C1 and C2). It suggests that the initial HP/UHP complex of the parental rocks was exhumed and *retrogressively recrystallized* under granulite and amphibolite facies conditions. Population of the detrital garnets (Fig. 8a,b) from Vršatec I, Vršatec II and Jarabina localities indicates a relatively high proportion of garnets derived from HP/UHP parental rocks, and suggests erosion of the lower part of the metamorphic rock complex. Relatively high amount of garnets from amphibolite facies conditions found at Horné Sŕnie, Lednica and partly Jarabina localities suggests a rock source from the upper parts of the metamorphic rock complexes.

Chemical composition of spinels and their origin

The spinel grains were mostly fragmented (Fig. 7b); their roundness is low (the grains are mostly subangular). The analysed spinels (Table 3) show some chemical variability, mainly in the most important parameters, such as Mg# (Mg/Mg + Fe^{2+}), Cr# (Cr/Cr + Al), TiO_2 and Fe^{2+}/Fe^{3+}. This variability points to different sources of spinels. To distinguish the spinels derived from peridotites and volcanics, a diagram of TiO_2 vs. Al_2O_3 is used (Fig. 9; Lenaz et al. 2000; Kamenetsky et al. 2001). To estimate diversity of the original tectonic position of ophiolites, classification of peridotites on the basis of spinel chemistry is used (Fig. 10; Dick & Bullen 1984). On the basis of the spinel chemistry, three main groups can be distinguished: mantle peridotite spinels, volcanic spinels and rare altered spinels.

Peridotite spinels have variable composition resulting from Al_2O_3 contents, which enables us to distinguish two different groups. The first group is characterized by increased Al_2O_3 contents (40–56.99 mol %) and MgO contents (18.54–19.48 wt. %). Their Cr# ranges from 10 to 30 mol % and Mg# from 66 to 78 mol %. This composition is typical for MORB (mid-oceanic ridge basalts) peridotites. According to Dick & Bullen's (1984) classification, these spinels correspond to the I-type peridotites (lherzolites). The second group is composed of spinels with lower Al_2O_3 contents (12.82–26.09 wt. %) and also lower MgO contents (9.29–14.02 wt. %). Their Cr# is higher (51–74 mol %) and Mg# lower (47–69 mol %) than in the first group. Such spinels correspond to SSZ peridotites

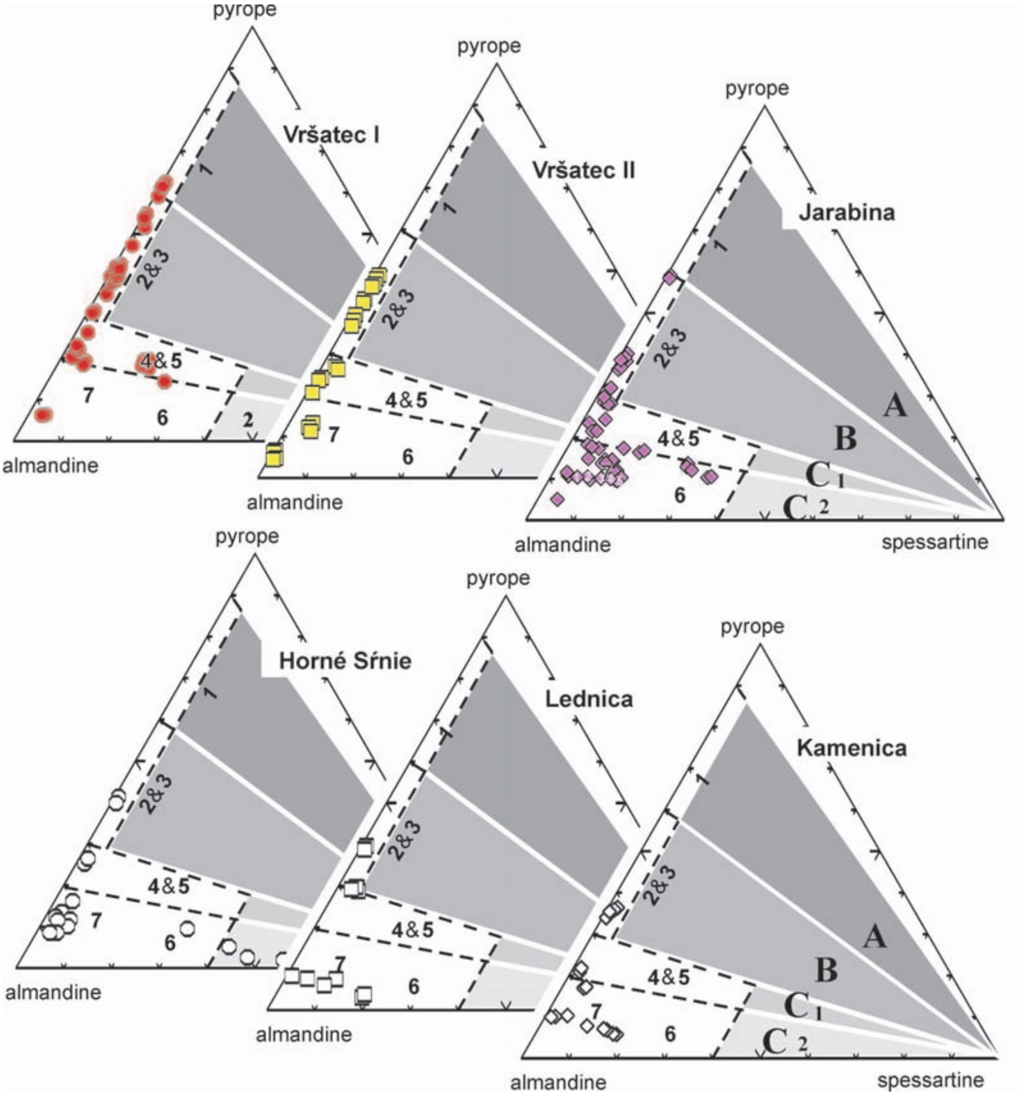

Fig. 8b. Ternary diagrams of the almandine-pyrope-spessartine ratios, classifying the source rocks of the studied detrital garnets from the Upper Aptian/Lower Albian sediments of the Czorsztyn Unit according to their origin. Explanations see Fig. 5 and Fig. 6.

(supra-subduction zone) and after Dick & Bullen (1984) they fall within the ranges of II-type and III-type ophiolites (harzburgites).

Spinels of volcanic origin were found rarely (only 10.6 % of the analysed grains). They were found only at Kamenica and Vršatec localities. The TiO_2 contents range from 0.22 to 0.44 wt. %. The Al_2O_3 contents are more variable (15.39–29.06 wt. %), as are Cr# (46–70 mol %) in comparison with Mg# (55–64 mol %). The volcanic spinels chemically correspond to the back-arc basin basalts (BABB).

Altered spinels were found only at the Kamenica and Vršatec localities. Their characteristic properties are high Cr_2O_3 contents (51–63 wt. %) and FeO contents (20–24 wt. %). The Fe_2O_3 contents are also increased, whereas the MgO contents have a relatively narrow range (3.56–7.95 wt. %).

Chemical composition of the peridotitic detrital spinels of the Czorsztyn Unit can be compared with Cr-spinels from Mesozoic ultramafic bodies of the Meliata Unit (localities: Dobšiná, Jaklovce, Hodkovce, Sedlice etc.; Mikuš & Spišiak 2007). The first group with higher Al_2O_3 and MgO contents, corresponding to MORB peridotites (lherzolites), has the same composition as the spinels from the Meliata Unit (Fig. 9). The second group with lower Al_2O_3 and MgO contents has different composition than the spinels from the Meliata Unit (their composition shows lower Al_2O_3 content, Fig. 9). Some spinels from the Vršatec I and Horné Sŕnie localities have similar composition to the spinels from the Penninic units in the Tauern Window in the Eastern Alps (Mikuš & Spišiak 2007).

The studied spinels can also be compared with the spinels from recent adjacent tectonic areas of the Klape and Manín Units (Fig. 11). Majority of them are plotted within Klape and Manín compositional fields except for the Lednica locality, which has the same composition as the spinels from the Meliata Unit.

Paleogeographical interpretation and discussion

On the basis of previous knowledge about the heavy mineral assemblages in the Jurassic and Cretaceous sediments of the Pieniny Klippen Belt, the examined heavy mineral associa-

Table 2: Representative microprobe analyses of detrital garnets from the Czorstyn Unit. *Continued on next pages.*

Locality	**Vršatec I**									**Vršatec II**					
Grt No.	**2-2**	**2-5**	**2-6**	**2-7**	**2-8**	**2-9**	**2-9**	**2-10**	**2-10**	**3-3**	**3-6**	**3-6**	**3-6**	**3-8**	**3-8**
Position	core	rim	core	rim	core	core	rim	rim	core	rim	core	rim	rim	rim	core
Grt type	**2**	**2**	**3**	**7**	**1**	**1**	**1**	**5**	**5**	**7**	**3**	**3**	**3**	**5**	**5**
SiO_2	40.23	39.76	39.26	37.67	40.90	40.45	40.94	38.62	38.41	37.70	40.07	39.47	39.75	39.10	39.00
TiO_2	0.01	0.02	0.01	0.14	0.03	0.08	0.03	0.03	0.02	0.12	0.00	0.01	0.00	0.07	0.08
Al_2O_3	21.97	22.34	22.16	21.26	22.91	21.27	22.24	21.84	21.69	20.86	21.58	21.75	21.42	21.89	21.44
Cr_2O_3	0.01	0.00	0.00	0.02	0.07	0.08	0.07	0.00	0.00	0.06	0.04	0.05	0.02	0.02	0.06
Fe_2O_{3calc}	1.21	0.22	0.00	0.01	0.27	2.50	1.37	0.02	0.00	0.76	1.65	0.84	1.62	0.31	0.82
FeO_{calc}	22.39	23.95	25.82	29.89	19.13	13.72	14.08	25.64	27.50	31.97	23.77	27.08	25.59	22.52	22.15
MnO	0.33	0.51	0.51	1.04	0.32	0.30	0.34	0.99	1.06	0.40	0.50	0.46	0.54	1.08	0.97
MgO	9.32	10.77	11.13	1.25	13.50	14.58	14.66	5.55	4.76	0.91	12.46	10.34	11.33	4.83	4.95
CaO	6.85	3.06	0.61	9.37	4.23	6.58	6.57	7.54	6.94	8.73	1.11	0.97	0.94	11.39	11.51
V_2O_3	0.01	0.00	0.01	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.01	0.00	0.00
Total	102.33	100.63	99.51	100.64	101.37	99.55	100.29	100.23	100.37	101.51	101.20	100.96	101.22	101.20	100.97
Formula normalization to 12 oxygens and 8 cations															
Si	3.000	2.999	3.001	2.995	2.999	2.995	2.999	2.999	3.000	2.993	3.000	3.000	3.000	2.998	2.999
Ti	0.001	0.001	0.001	0.008	0.002	0.004	0.001	0.001	0.001	0.007	0.000	0.001	0.000	0.004	0.004
Al	1.931	1.986	1.996	1.992	1.980	1.856	1.920	1.998	1.997	1.952	1.904	1.948	1.906	1.978	1.943
Cr	0.000	0.000	0.000	0.001	0.004	0.005	0.004	0.000	0.000	0.004	0.002	0.003	0.001	0.001	0.003
Fe^{3+}	0.068	0.013	0.000	0.001	0.015	0.140	0.075	0.001	0.000	0.045	0.093	0.048	0.092	0.018	0.047
Fe^{2+}	1.396	1.510	1.651	1.987	1.173	0.850	0.862	1.665	1.797	2.123	1.488	1.721	1.616	1.444	1.424
Mn	0.021	0.033	0.033	0.070	0.020	0.019	0.021	0.065	0.070	0.027	0.032	0.029	0.034	0.070	0.063
Mg	1.036	1.211	1.269	0.148	1.476	1.609	1.601	0.642	0.554	0.108	1.391	1.171	1.275	0.552	0.567
Ca	0.547	0.247	0.050	0.798	0.332	0.522	0.516	0.628	0.581	0.742	0.089	0.079	0.076	0.936	0.949
tot. cat.	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
tot. oxy.	12.000	12.000	12.000	12.000	12.000	12.000	12.000	12.000	12.000	12.000	12.000	12.000	12.000	12.000	12.000
Grt end members (mol %)															
almandine	46.54	50.34	54.99	66.17	39.10	28.34	28.74	55.51	59.86	70.76	49.61	57.36	53.85	48.11	47.43
pyrope	34.53	40.34	42.26	4.92	49.18	53.65	53.37	21.41	18.46	3.60	46.36	39.04	42.48	18.39	18.88
grossular	17.61	8.17	1.65	26.45	10.95	16.10	16.50	20.89	19.33	24.06	2.82	2.55	2.41	30.81	30.71
spessartine	0.70	1.09	1.09	2.32	0.66	0.62	0.69	2.17	2.33	0.90	1.06	0.98	1.15	2.33	2.11
uvarovite	0.00	0.00	0.00	0.02	0.02	0.04	0.03	0.00	0.00	0.04	0.00	0.00	0.00	0.01	0.05
andradite	0.62	0.05	0.00	0.01	0.08	1.21	0.65	0.01	0.00	0.56	0.14	0.06	0.12	0.28	0.75
Ca–Ti Gt	0.01	0.01	0.00	0.11	0.01	0.04	0.01	0.02	0.01	0.09	0.00	0.00	0.00	0.06	0.07

Fe_2O_{3calc} and FeO_{calc} calculated from stoichiometry, Grt type = number of the parental rocks in the Fig. 8a,b.

Table 2: *Continued.*

Locality	**Jarabina**														
Grt No.	**4-3**	**4-4**	**4-5**	**4-6**	**4-7**	**4-8**	**4-9**	**4-10**	**4-11**	**4-11**	**4-4-1**	**4-4-2**	**4-4-3**	**4-4-4**	**4-4-5**
Position	**rim**	**rim**	**rim**	**rim**	**rim**	**core**	**core**	**core**	**core**	**rim**	**rim → profile → core**				
Grt type	**3**	**7***	**3**	**2**	**6**	**6**	**6**	**6**	**7**	**7**	**7***	**7***	**7***	**7***	**7***
SiO_2	38.64	37.99	39.20	38.91	37.58	37.74	37.79	37.43	38.36	38.66	38.71	38.89	38.77	39.22	38.49
TiO_2	0.02	0.11	0.04	0.04	0.00	0.03	0.04	0.05	0.06	0.06	0.06	0.08	0.11	0.06	0.13
Al_2O_3	21.20	21.27	21.69	21.61	21.21	21.49	21.31	21.04	21.68	21.89	21.75	21.71	21.85	22.23	21.73
Cr_2O_3	0.02	0.01	0.05	0.02	0.09	0.00	0.07	0.00	0.01	0.00	0.00	0.00	0.04	0.00	0.00
Fe_2O_{3calc}	0.98	0.23	0.69	0.57	0.00	0.00	0.00	0.14	0.00	0.06	0.00	0.14	0.00	0.00	0.00
FeO_{calc}	29.79	19.03	25.49	26.63	33.13	32.52	25.91	36.73	27.56	28.19	20.55	20.59	20.08	20.10	19.29
MnO	1.41	2.23	0.64	0.57	3.94	4.73	12.44	1.59	6.75	4.74	1.41	1.97	2.72	3.33	3.82
MgO	7.03	1.47	10.46	7.27	3.36	3.61	3.03	2.64	3.95	3.92	1.47	1.51	1.48	1.49	1.53
CaO	1.92	16.87	1.66	5.00	1.41	0.95	1.00	1.38	3.41	4.93	16.97	16.62	16.38	16.17	15.63
V_2O_3	0.01	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.01	0.01	0.00	0.00	0.01
Total	101.03	99.20	99.91	100.62	100.71	101.08	101.59	101.01	101.80	102.44	100.93	101.52	101.44	102.61	100.62
Formula normalization to 12 oxygens and 8 cations															
Si	3.000	2.998	2.999	2.999	3.000	2.999	3.000	2.999	3.000	2.995	3.003	3.003	2.997	2.998	3.002
Ti	0.001	0.006	0.002	0.003	0.000	0.002	0.002	0.003	0.004	0.004	0.003	0.005	0.007	0.004	0.007
Al	1.940	1.978	1.956	1.963	1.996	2.012	1.994	1.987	1.999	1.999	1.988	1.976	1.990	2.002	1.997
Cr	0.001	0.001	0.003	0.001	0.006	0.000	0.004	0.000	0.001	0.000	0.000	0.000	0.002	0.000	0.000
Fe^{3+}	0.057	0.014	0.040	0.033	0.000	0.000	0.000	0.009	0.000	0.003	0.000	0.008	0.000	0.000	0.000
Fe^{2+}	1.934	1.256	1.631	1.717	2.212	2.161	1.720	2.461	1.803	1.826	1.333	1.330	1.298	1.285	1.258
Mn	0.093	0.149	0.042	0.037	0.266	0.318	0.837	0.108	0.447	0.311	0.092	0.129	0.178	0.216	0.252
Mg	0.814	0.173	1.193	0.835	0.400	0.427	0.358	0.315	0.461	0.453	0.169	0.174	0.170	0.170	0.177
Ca	0.160	1.426	0.136	0.413	0.120	0.081	0.085	0.118	0.286	0.409	1.410	1.375	1.357	1.325	1.306
tot. cat.	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
tot. oxy.	12.000	12.000	12.000	12.000	12.001	12.007	12.002	12.000	12.003	12.000	12.000	12.000	12.000	12.003	12.008
Grt end members (mol %)															
almandine	64.45	41.81	54.33	57.19	73.77	72.34	57.34	81.97	60.16	60.89	44.36	44.21	43.22	42.89	42.03
pyrope	27.13	5.76	39.75	27.82	13.34	14.30	11.94	10.51	15.38	15.11	5.64	5.79	5.67	5.69	5.93
grossular	5.17	46.99	4.43	13.50	4.01	2.70	2.82	3.91	9.52	13.59	46.85	45.43	44.97	44.14	43.45
spessartine	3.10	4.96	1.39	1.24	8.88	10.66	27.89	3.59	14.91	10.36	3.07	4.28	5.94	7.20	8.42
uvarovite	0.00	0.01	0.01	0.01	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.00
andradite	0.15	0.32	0.09	0.23	0.00	0.00	0.00	0.02	0.00	0.02	0.00	0.18	0.00	0.00	0.00
Ca-Ti Gt	0.00	0.15	0.00	0.02	0.00	0.00	0.00	0.01	0.02	0.03	0.08	0.11	0.15	0.08	0.16

Fe_2O_{3calc} and FeO_{calc} calculated from stoichiometry, Grt type = number of the parental rocks in the Figs. 8a,b, 7* — Grt probably from HP/LT metaultramafites.

Table 2: *Continued from previous pages.*

Locality	Horné Sŕnie					Lednica				Kamenica					
Grt No.	1	3	5	7	7	1	1	2	5	2	2	5	6	7	7
Position	rim	core	rim	core	rim	core	rim	core	core	core	core	core	core	core	rim
Grt type	3	6	7	7*	7	7*	7*	4	3	7	6	7	2	3	3
SiO_2	39.57	37.73	37.56	37.96	37.55	37.53	37.81	39.40	39.49	37.69	38.15	38.18	39.66	39.48	38.98
TiO_2	0.03	0.02	0.09	0.01	0.01	0.18	0.16	0.01	0.00	0.04	0.02	0.00	0.00	0.05	0.08
Al_2O_3	22.29	21.36	21.24	21.18	21.19	21.23	21.13	21.79	22.20	21.25	21.57	21.58	22.21	22.13	21.93
Cr_2O_3	0.06	0.00	0.01	0.03	0.00	0.03	0.04	0.00	0.06	0.04	0.02	0.08	0.01	0.02	0.08
Fe_2O_{3calc}	0.00	0.00	0.00	0.40	0.12	0.00	0.08	0.74	0.09	0.00	0.00	0.00	0.37	0.19	0.00
FeO_{calc}	26.47	36.93	31.32	13.61	22.46	25.69	25.76	27.78	26.42	32.82	34.56	33.05	27.63	28.49	27.93
MnO	0.52	2.58	1.58	17.12	11.67	6.11	5.99	1.77	0.53	1.80	2.08	0.86	0.41	0.77	0.84
MgO	10.06	2.56	1.78	0.40	2.06	0.65	0.61	6.76	9.60	2.29	4.26	5.06	8.66	9.23	9.15
CaO	1.87	0.77	6.82	10.73	5.43	9.12	9.71	4.31	2.44	4.94	1.04	2.11	3.07	1.20	1.19
V_2O_3	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00
Total	100.87	101.94	100.40	101.44	100.48	100.56	101.28	102.56	100.84	100.88	101.69	100.92	102.03	101.55	100.19
Formula normalization to 12 oxygens and 8 cations															
Si	3.001	3.000	3.000	3.000	2.999	2.999	2.999	3.000	3.001	3.000	3.000	2.999	2.999	3.000	3.000
Ti	0.002	0.001	0.006	0.001	0.001	0.011	0.009	0.001	0.000	0.003	0.001	0.000	0.000	0.003	0.005
Al	1.992	2.001	1.999	1.973	1.994	1.999	1.975	1.956	1.989	1.994	1.999	1.997	1.980	1.982	1.990
Cr	0.003	0.000	0.001	0.002	0.000	0.002	0.003	0.000	0.003	0.003	0.001	0.005	0.001	0.001	0.005
Fe^{3+}	0.000	0.000	0.000	0.024	0.007	0.000	0.005	0.043	0.005	0.000	0.000	0.000	0.021	0.011	0.000
Fe^{2+}	1.679	2.455	2.092	0.900	1.500	1.717	1.709	1.769	1.680	2.185	2.273	2.171	1.747	1.811	1.798
Mn	0.034	0.174	0.107	1.146	0.789	0.414	0.403	0.114	0.034	0.121	0.138	0.057	0.026	0.050	0.055
Mg	1.137	0.303	0.212	0.047	0.245	0.078	0.072	0.767	1.088	0.272	0.499	0.593	0.977	1.045	1.050
Ca	0.152	0.066	0.584	0.908	0.464	0.781	0.825	0.351	0.199	0.422	0.088	0.177	0.249	0.098	0.098
tot. cat.	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
tot. oxy.	12.000	12.002	12.006	12.000	12.000	12.011	12.000	12.000	12.000	12.002	12.001	12.000	12.000	12.000	12.002
Grt end members (mol %)															
almandine	55.93	81.91	69.86	29.98	50.02	57.44	56.79	58.94	55.97	72.83	75.80	72.41	58.26	60.29	59.91
pyrope	37.88	10.11	7.07	1.56	8.18	2.60	2.41	25.55	36.26	9.07	16.65	19.77	32.56	34.80	35.00
grossular	5.06	2.18	19.44	29.86	15.42	25.95	27.19	11.45	6.60	14.02	2.92	5.90	8.21	3.23	3.25
spessartine	1.12	5.79	3.58	38.19	26.31	13.84	13.38	3.80	1.14	4.04	4.62	1.91	0.88	1.65	1.83
uvarovite	0.01	0.00	0.01	0.03	0.00	0.03	0.04	0.00	0.01	0.02	0.00	0.02	0.00	0.00	0.01
andradite	0.00	0.00	0.00	0.36	0.06	0.00	0.06	0.25	0.02	0.00	0.00	0.00	0.09	0.02	0.00
Ca-Ti Gt	0.00	0.00	0.05	0.01	0.00	0.14	0.13	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.01

Fe_2O_{3calc} and FeO_{calc} calculated from stoichiometry, Grt type = number of the parental rocks in the Figs. 8a,b, 7* — Grt probably from HP/LT metaultramafites.

tions can be interpreted as derived from at least two separate sources. The first source supplied the detritic material earlier, as it is identical with the source of Jurassic clastics in the Czorsztyn Unit. The source most likely represented magmatic and metamorphic rocks forming the Czorsztyn elevation. The heavy mineral assemblage derived from this source is dominated by garnet, with decreasing amounts of zircon, rutile and tourmaline (Aubrecht 1993, 2001). Composition of the detrital garnets is the same as of those presented in this paper (cf. Aubrecht & Méres 2001).

The second source is similar to the source of exotic clastics in the Albian of the Klape Unit and the Tatric and Fatric units of the Central Western Carpathians (Jablonský 1978, 1986; Mišík et al. 1980, 1981; Jablonský et al. 2001). The heavy mineral assemblages derived from this source are characterized by strong prevalence of spinels (mainly Cr-spinels) and zircon, followed by tourmaline and rutile. The sources of both assemblages are the subjects of long-lasting debates. The solution of this problem would provide answers to the crucial questions which remain in the Mesozoic paleogeography of the Western Carpathians.

Source of the garnets

Composition of the detrital garnets shows that they were derived from parental rocks such as UHP eclogites or garnet peridotites, HP eclogites and HP mafic granulites, felsic and intermediate granulites, gneisses and amphibolites metamorphosed under the transitional, granulite to amphibolite facies conditions and gneisses and amphibolites metamorphosed under amphibolite facies conditions. These rock types are typical of the polymetamorphosed complexes, in which the first metamorphic event took place under HP/UHP conditions. The metamorphic complex was then exhumed and *retrogressively recrystallized* under the granulite and amphibolite facies conditions. Such metamorphosed complexes are known in the European Variscides (e.g. Dora Maira Massif of the Western Alps, Bohemian Massif,

Table 3: Representative microprobe analyses of Cr-spinels from the Czorstyn Unit (in wt. %). Formula is based on 3 cations.

Locality	**Kamenica**						**Horné Sŕnie**			**Lednica**		**Jarabina**			**Vršatec**					
Sample	Kam-1						Hos-1			Led-1		Jar-1			Vrs-1			Vrs-2		
Analyse	#2	#6	#12	#15	#7	#8	#17	#19	#21	#22	#23	#17	#19	#21	#59	#60	#64	#24	#26	#30
SiO_2	0.02	0.00	0.02	0.03	0.06	0.05	0.06	0.06	0.07	0.06	0.04	0.03	0.07	0.03	0.05	0.09	0.03	0.04	0.03	0.02
TiO_2	0.07	0.03	0.03	0.07	0.23	0.22	0.09	0.08	0.17	0.07	0.06	0.05	0.29	0.06	0.27	0.44	0.08	0.12	0.31	0.07
Al_2O_3	17.31	56.99	56.80	20.04	15.41	15.39	17.12	24.13	15.17	44.79	52.29	17.83	12.82	25.35	21.04	29.06	22.27	10.42	17.44	42.33
Cr_2O_3	50.45	9.18	10.36	49.33	52.37	51.61	52.05	44.43	53.31	21.12	13.22	50.74	54.57	42.76	46.18	36.80	46.33	60.63	49.24	24.31
$^*Fe_2O_3$	3.59	2.22	1.08	2.35	3.53	4.39	2.22	2.89	0.95	1.68	4.04	2.39	2.03	1.13	4.69	5.08	2.23	1.27	4.34	3.27
FeO	14.51	9.84	11.43	13.49	15.18	16.22	14.97	14.28	18.28	13.51	9.51	15.58	17.89	16.54	14.05	14.35	15.44	13.55	16.72	10.43
MnO	0.23	0.12	0.14	0.23	0.21	0.27	0.27	0.23	0.27	0.14	0.13	0.25	0.28	0.21	0.22	0.21	0.22	0.36	0.27	0.15
MgO	12.34	19.48	18.54	13.42	11.85	11.27	12.14	13.40	9.56	15.66	19.38	11.75	9.62	11.71	13.30	14.09	12.36	11.89	11.24	17.63
ZnO	0.15	0.21	0.17	0.13	0.13	0.13	0.10	0.25	0.16	0.24	0.10	0.16	0.15	0.14	0.09	0.07	0.13	1.03	0.14	0.16
V_2O_3	0.32	0.06	0.10	0.32	0.27	0.26	0.31	0.29	0.30	0.14	0.11	0.32	0.14	0.34	0.32	0.19	0.34	0.26	0.20	0.21
NiO	0.13	0.44	0.41	0.07	0.11	0.08	0.09	0.08	0.06	0.23	0.40	0.06	0.09	0.16	0.13	0.21	0.09	0.04	0.08	0.22
Total	99.20	98.66	99.15	99.57	99.42	99.95	99.49	100.22	98.36	97.73	99.36	99.21	98.04	98.48	100.43	100.68	99.60	99.70	100.07	98.86
Si	0.001	0.000	0.001	0.001	0.002	0.002	0.002	0.002	0.002	0.002	0.001	0.001	0.002	0.001	0.002	0.003	0.001	0.001	0.001	0.001
Ti	0.002	0.001	0.001	0.002	0.006	0.005	0.002	0.002	0.004	0.001	0.001	0.001	0.007	0.001	0.006	0.010	0.002	0.003	0.007	0.001
Al	0.649	1.766	1.763	0.735	0.583	0.582	0.641	0.866	0.589	1.492	1.640	0.669	0.504	0.928	0.764	1.015	0.815	0.402	0.654	1.395
Cr	1.269	0.191	0.216	1.214	1.330	1.310	1.308	1.070	1.388	0.472	0.278	1.278	1.439	1.050	1.126	0.863	1.137	1.568	1.238	0.538
Fe^{3+}	0.086	0.044	0.021	0.055	0.085	0.106	0.053	0.066	0.024	0.036	0.081	0.057	0.051	0.027	0.109	0.113	0.052	0.031	0.104	0.069
V	0.007	0.001	0.002	0.007	0.006	0.006	0.007	0.006	0.007	0.003	0.002	0.007	0.003	0.007	0.007	0.004	0.007	0.006	0.004	0.004
Sum B	2.013	2.002	2.003	2.013	2.011	2.011	2.013	2.012	2.013	2.005	2.004	2.013	2.006	2.014	2.013	2.007	2.014	2.011	2.008	2.008
Fe^{2+}	0.386	0.216	0.252	0.351	0.408	0.436	0.398	0.364	0.503	0.319	0.212	0.415	0.499	0.430	0.362	0.356	0.401	0.371	0.445	0.244
Mn	0.006	0.003	0.003	0.006	0.006	0.007	0.007	0.006	0.008	0.003	0.003	0.007	0.008	0.006	0.006	0.005	0.006	0.010	0.007	0.004
Mg	0.585	0.763	0.728	0.623	0.567	0.539	0.575	0.608	0.469	0.660	0.769	0.558	0.478	0.542	0.611	0.623	0.572	0.580	0.533	0.735
Zn	0.004	0.004	0.003	0.003	0.003	0.003	0.002	0.006	0.004	0.005	0.002	0.004	0.004	0.003	0.002	0.002	0.003	0.025	0.003	0.003
Ni	0.003	0.009	0.009	0.002	0.003	0.002	0.002	0.002	0.002	0.005	0.009	0.002	0.002	0.004	0.003	0.005	0.002	0.001	0.002	0.005
Sum A	0.985	0.996	0.995	0.985	0.987	0.987	0.985	0.986	0.986	0.993	0.994	0.985	0.991	0.985	0.985	0.990	0.984	0.987	0.990	0.991
Cr#	66	10	11	62	70	69	67	55	70	24	15	66	74	53	60	46	58	80	65	28
Mg#	60	78	74	64	58	55	59	63	48	67	78	57	49	56	63	64	59	61	55	75

$^*Fe_2O_3$ calculated from stoichiometry. Cr# = Cr/(Cr+Al); Mg# = Mg/(Mg+Fe^{2+}).

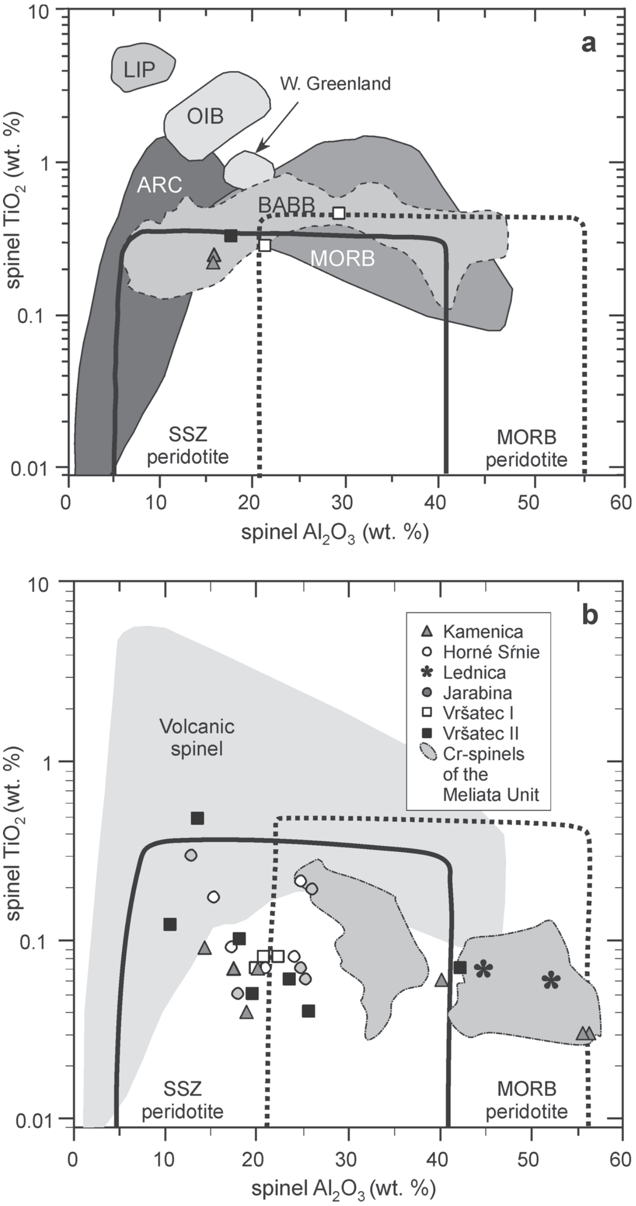

Fig. 9. Al_2O_3 vs. TiO_2 compositional relationships of the analysed spinel grains. For comparison, Cr-spinels from (grey fields with dot-and dashed line) the Mesozoic ultramafic bodies of the Western Carpathians (Meliata Unit) are plotted (Mikuš & Spišiak 2007). The spinels are compared with compositional fields of spinel from volcanic rocks and mantle peridotites (according to Kamenetsky et al. 2001). **a** — peridotite spinels; **b** — volcanic spinels (MORB = mid-oceanic ridge basalts, SSZ peridotite = supra-subduction zone peridotite).

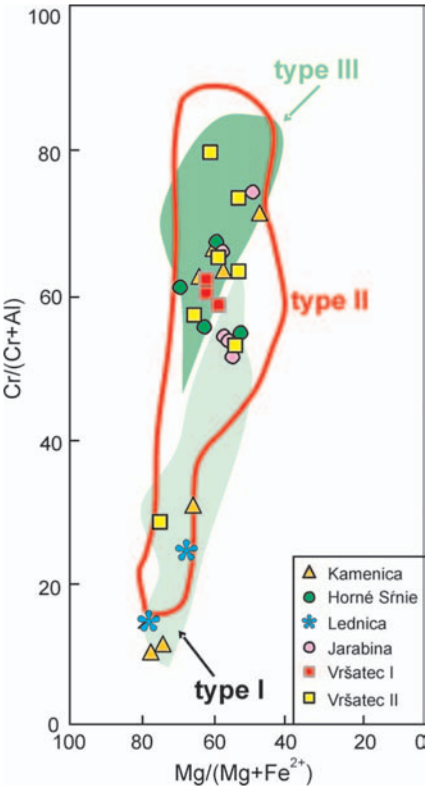

Fig. 10. $Mg/(Mg+Fe^{2+})$ vs. $Cr/(Cr+Al)$ diagram of the analysed spinels (after Dick & Bullen 1984).

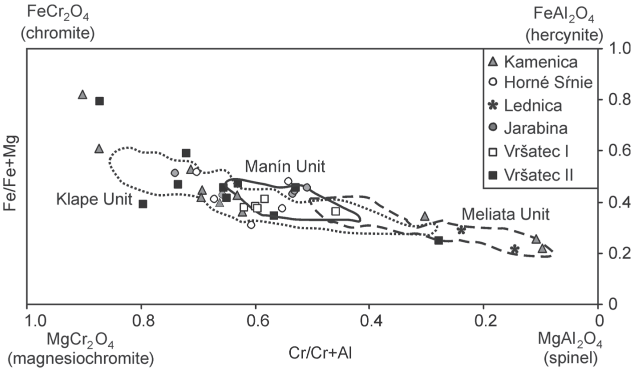

Fig. 11. Nomenclature and composition of spinels based on the classification of Deer et al. (1992). The studied spinels are compared with spinels of the Meliata Unit and adjacent tectonic units (Klape and Manín Units). The compared compositional fields are according to Mikuš (2005).

Massif Central, leptyno-amphibolite complex in the Western Carpathians) and in the Western Gneiss Region of the Norwegian Caledonides.

The detrital garnets presented in this paper have predominantly specific composition (almandine-pyrope and grossular-pyrope-almandine) which corresponds well with the detrital garnets from the Jurassic sandy limestones of the Czorsztyn Unit, but they were also found in the Jurassic limestones of the Klape Klippe and in the Manín Unit of the Pieniny Klippen Belt (Aubrecht & Méres 2000). Except for this zone, almandine-pyrope garnets are also characteristic for other zones of the Western Carpathian externides. They were reported from the Cretaceous to Paleogene sediments of the Carpathian Flysch Zone (Otava et al. 1997, 1998; Salata 2004; Oszczypko & Salata 2005; Grzebyk & Leszczyński 2006). The data from the Flysch Zone are not restricted solely to garnets from heavy mineral assemblages but exotic granulitic pebbles (one of the potential source rocks) were reported from the Silesian Unit by Wieser (1985). Almandine-pyrope garnets are lacking in the crystalline rocks of the Western Carpathian internides

(Aubrecht & Méres 2000). Very similar pyrope-rich garnets are known from the metamorphic rocks (garnet peridotites, garnet pyroxenites, kyanite eclogites and granulites) of the Bohemian Massif (Scharbert & Carswell 1983; O'Brien & Vrána 1995; Medaris et al. 1995a,b, 1998, 2005, 2006a,b; O'Brien et al. 1997; Nakamura et al. 2004). Because of the presence of granulite-derived detritus, the crustal segments of the Western Carpathian externides, including the Pieniny Klippen Belt, were interpreted as being derived from the Moldanubian Zone of the Bohemian Massif (Aubrecht & Méres 1999, 2000). However, almandine-pyrope to garnets very rich in pyrope contents are also abundant in the Bathonian-Lower Callovian sands in the Cracow-Wieluń Upland which is an epi-Hercynian platform and was relatively stable during the Mesozoic (Aubrecht et al. 2007). These occurrences are too distant from the Moldanubian Zone. Apart from this zone, there are only two other known proximal occurrences of granulites and eclogites — the Góry Sowie Block and the Śnieźnik area complex in the Western Sudetes (Smulikowski 1967; Oberc 1972; Kryza et al. 1996; O'Brien et al. 1997). They are, however, too small to be a regionally important source of clastic material. Exotic, pyrope-almandinic garnets were also reported from the Carboniferous of the Moravo-Silesian Culm Basin (Otava & Sulovský 1998; Otava et al. 2000; Hartley & Otava 2001; Čopjaková et al. 2001, 2005). Some granulitic pebbles were also found in the Carboniferous sediments of the Upper Silesia Coal Basin (Paszkowski et al. 1995). In the Carboniferous clastics of the Moravo-Silesian Zone, the authors invariably derive the clastic material from the Moldanubian Zone of the Bohemian Massif (Paszkowski et al. 1995; Hartley & Otava 2001).

Source of the spinels

The presence and overall dominance of spinels in the heavy mineral assemblage of the Chmielowa Formation is surprising. They most likely represent clastics from a source which was different from the garnet source, although small part of the spinels might also be derived from the same metamorphic complex as the high-pyrope garnets, because Cr and Al spinels usually occur also in the metaperidotites, eclogites and polymetamorphosed equivalents of the granulite facies. However, such spinels would appear already in the Jurassic or Lower Cretaceous detritus-bearing sediments of the Czorsztyn units (Middle Jurassic and Valanginian crinoidal limestones) which is not the case (Łoziński 1959; Aubrecht 1993, 2001). Similarly unlikely is the possibility that originally rare, but resistant spinels were enriched by reworking and dissolution in the condensed facies overlying the paleokarst surface. The previous inherited assemblage, also containing less stable minerals, such as garnet and kyanite, bears no signs of depletion. Therefore, most of the spinels were probably derived from the source which could have been identical to the source of the Albian exotics in the Klape Unit of the Pieniny Klippen Belt and in the Tatric and Fatric units of the Central Western Carpathians. However, this source is unknown to date and many publications were already dedicated to this topic. The first research concerning West Carpathian exotics was made by Matějka & Andrusov (1931), Zoubek (1931) and Andrusov (1938) who investigated the "Upohlav" conglomerates in the Pieniny Klippen Belt. Their source was interpreted as an exotic Pieniny Ridge (Andrusov 1938, 1945) which was later renamed by Birkenmajer (1988) as the Andrusov Ridge. According to Birkenmajer (1977, 1988), the Andrusov Ridge was placed south of the Kysuca-Pieniny Basin (passing to an oceanic crust) and north of the Central Western Carpathians. According to Marschalko (1986), the transport direction of the exotics in the Klape Unit was from south and south east. That would indicate position of the Klape Unit north of the Andrusov Ridge. This opinion was challenged by Birkenmajer (1988) who placed this unit south of the ridge. From the beginning, the researchers considered that all the exotic conglomerates were Senonian, but later works brought data about the earlier, Albian onset of the exotic sedimentation (e.g. Began et al. 1965; Samuel et al. 1972). The first Cr-rich spinels were even reported from the Barremian-Aptian limestone pebbles from the exotic conglomerates (Mišík et al. 1980), the same was reported from the Eastern Alps (Wagreich et al. 1995). Albian-Cenomanian exotic flysch (including exotic conglomerates) is also widespread in the Tatric and Fatric units of the Central Western Carpathians where it is named the Poruba Formation (Jablonský 1978, 1986). The transport directions in this unit, however, largely differ from those in the Klape Unit (Jablonský 1986). The data in the Tatric units are largely scattered but generally trough-parallel transport dominated, with some lateral transport directions coming from the south (in Nízke Tatry Mts). In the Fatric units (Krížna Nappe) there were both, southern and northern sources indicated by the measurements. Because of these facts, Mišík et al. (1980) suggested the presence of two additional exotic sources, the Ultratatric and the Ultrakrížna ridges, which made the paleogeographical situation quite complicated. Even earlier occurrences of exotic ophiolitic detritus (Cr-rich spinels) were indicated in the Hauterivian sandstone turbidites in the Fatric and Hronic (Choč Nappe) units (Jablonský 1992). Further to the south, Hauterivian to Albian flysches with Cr-rich spinels occur in the northern part of the Transdanubian Central Range (Árgyelán 1992, 1996; Császár & Árgyelán 1994), where the first Cr-rich spinels appeared already in the Upper Jurassic limestones of the Gerecse Mountains (Árgyelán & Császár 1998). This ophiolitic detritus was invariably derived from the suture of the Meliata Ocean which was open in the Middle Triassic and closed in the Late Jurassic. Even in the Middle Jurassic matrix of the Meliatic subduction melange, chrome spinels are present, although in minor amounts (Mock et al. 1998). The Meliata suture zone is situated south of the Central Western Carpathians and is considered to be a boundary between them and the Inner Western Carpathians further to the south. The Andrusov Ridge was supposed to be situated north of the Central Western Carpathians and was considered to be an accretionary wedge formed by subduction of the younger, Penninic-Vahic Ocean (e.g. Maheľ 1981, 1989; Birkenmajer 1988). The resedimented ophiolitic remnants in the Pieniny Klippen Belt were then considered to represent another important suture zone in the Western Carpathians. However, the situation with the Andrusov Ridge is more complex. Pebbles of basaltic volcanics of the Late Jurassic–Early Cretaceous K-Ar age (Rybár & Kantor 1978; Birkenmajer & Pécskay 2000) would fit the Penninic ophiolites. Some exotics were apparently derived from the Carpathian Foreland, for example Namurian black coal (Havlena 1956; Šilar 1956) or non-metamorphosed Devonian limestone (Tomaś et al. 2004). Along with the above mentioned rock types, there are many exotics which seem to be derived from more southern zones representing the Inner Western Carpathians and even Dinarides. There are pebbles from blocks of southern types of Triassic, such as the Wetterstein-type platform limestones typical for the Silicic units; exotic granitic pebbles (the so-called Upohlav-type) are the most similar to those of A-type granites, as in the Turčok or Velence Massif (Uher & Marschalko 1993; Uher & Pushkarev 1994; Uher et al. 1994; Uher & Broska 1996). The Devonian limestone pebbles mentioned above might be alternatively derived from a more southern source, such as the Transdanubian Central Range. Very characteristic are deep-water to oceanic Triassic sediments indicating their relationship with the Meliata Ocean (Mišík et al. 1977; Birkenmajer et al. 1990). The Triassic deep-sea deposits are even older (Lower Anisian) than those found in the Meliata Unit. Moreover, radiometric datings of some glaucophanite pebbles showed Jurassic age of metamorphism which is in accordance with the closure of the Meliata Ocean (Dal Piaz et al. 1995). Meliata-like elements in the exotic conglomerates led to speculations about proximity of the Meliata and Oravic domains (e.g. Mišík 1978; Mišík & Sýkora 1981), although later some authors favoured an alternative explanation about two different Triassic troughs south and north of the Central Western Carpathians (Birkenmajer et al. 1990). In the Eastern Alps, where the situation of the exotics is very similar to the Western Carpathians, there is also a long lasting debate about the northern (Penninic) and southern (Meliata–Vardar) sources of ophiolite detritus in Cretaceous sediments (e.g. Decker et al. 1987; Pober & Faupl 1988; Faupl & Pober 1991; Faupl & Wagreich 1992; Wagreich et al. 1995; Eynatten & Gaupp 1999). An attempt to unify both sources led Plašienka (1995, 1996) to a radical opinion that the Klape Unit belongs to the Fatric domain and its exotic flysches represent just a proximal part of the Poruba Formation turbiditic fan. There are, however, many counterarguments against this opinion (Mišík 1996). The data presented in this paper also contradict this theory.

New paleogeographical model of the Pieniny Klippen Belt

In spite of the still unknown source of the ophiolite detritus, in most reconstructions it is placed much further south than the presumed sedimentary area of the Czorsztyn Unit. The reconstruction of the Oravic (Pienidic) domain made by Birkenmajer (1977) was accepted with small modifications up to the present time. However, in the light of the presence of the Cr-rich spinels in the Albian sediments of the Czorsztyn Unit, this reconstruction is problematic. According to this concept, the Czorsztyn Unit sedimented on an isolated swell which was separated in the Cretaceous from the Carpathian internides by the so-called Kysuca-Pieniny Trough, which in later interpretations of Birkenmajer (1988) was considered one of the branches of the Penninic Ocean. In the Albian, the input of exotics (including ophiolite detritus) was concentrated only in the more southern units (in the sense of previous reconstructions), such as the Klape Unit, Tatric and Fatric units (see above). Moreover, the first sandstone turbidites also appeared in the Upper Albian of the Manín Unit (Marschalko & Rakús 1997). However from the Oravic units they were known only from the Coniacian-Santonian Sromowce Formation of the Kysuca-Pieniny Unit. Although there is a rare occurrence of Albian flysch (Trawne Member) mentioned from the Kysuca Unit by Birkenmajer (1987) it is not clear whether it bears some exotics. In the Turonian sandstone flysch (Snežnica Formation), there is still lack of Cr-rich spinels (Łoziński 1959; Aubrecht — unpublished data). This is the reason why the latest Aptian appearance of ophiolitic detritus in the Czorsztyn Unit is so surprising. The question is: How can this detritus, derived from the south, reach an isolated elevation surrounded by deep troughs? The Czorsztyn Unit in the Cretaceous was still situated on an elevated area, as indicated by Aubrecht et al. (2006). However, the presence of exotic ophiolitic detritus indicates that it was not an isolated elevation but this sedimentary area must have been adjacent to the exotic source.

For these reasons, we propose an alternative paleogeographical model of the Pieniny Klippen Belt evolution (Figs. 12, 13). Middle Jurassic Penninic rifting caused detachment of the Oravic segment from its position in continuation of the Moldanubian Zone of the Bohemian Massif. The SW-NE orientation of the initial rifting corresponds to many paleogeographical reconstructions (see discussion in Aubrecht & Túnyi 2001). Derivation from the Moldanubian Zone is based on the garnet compositions presented by Aubrecht & Méres (2000) and in this paper. The Oravic segment was originally situated in lateral continuation of the Central and Inner West Carpathian segments (Michalík 1994). In an earlier period the Triassic Meliata Ocean was situated south of both segments. This ocean was closed in the Late Jurassic when the crustal segments derived from the North-European Platform collided with South-Alpine/Dinaridic segments. Remnants of the ocean were arranged in subduction melange along the Meliata suture zone. During the Cretaceous, the amalgamated blocks were further rotated clockwise to the final NW-SE orientation (for the pre-Paleogene orientation of the Central Western Carpathians, see Túnyi & Márton 2002 and Csontos & Vörös 2004). The rotation caused detachment of the Oravic segment from its lateral position and its relative lateral shift along the northern margin of the Central Western Carpathians. The Meliatic melange was then secondarily placed in the zone between the Oravic segment and the Central Western Carpathians where it formed an elevated ridge (the exotic Andrusov Ridge) which was the source of exotic pebbles and ophiolitic detritus, feeding simultaneously the Klape, Tatric and Fatric units on the SW and the Oravic units on the NE. Such arrangement of the exotic source fits well with the conclusions of Marschalko (1986) who suggested that the exotic ridge represented a long-lasting elevation formed in a strike-slip zone rather than compressional wedge which would be destroyed in a short time. Early presence of the ophiolitic detritus in the Czorsztyn Unit indicates that it was closer to the exotic ridge and no depression occurred between them, which would prevent transport of this material to the Czorsztyn sedimentary area. The ophiolitic material (dominated by spinels) was mixed with the material from the still emerged Czorsztyn

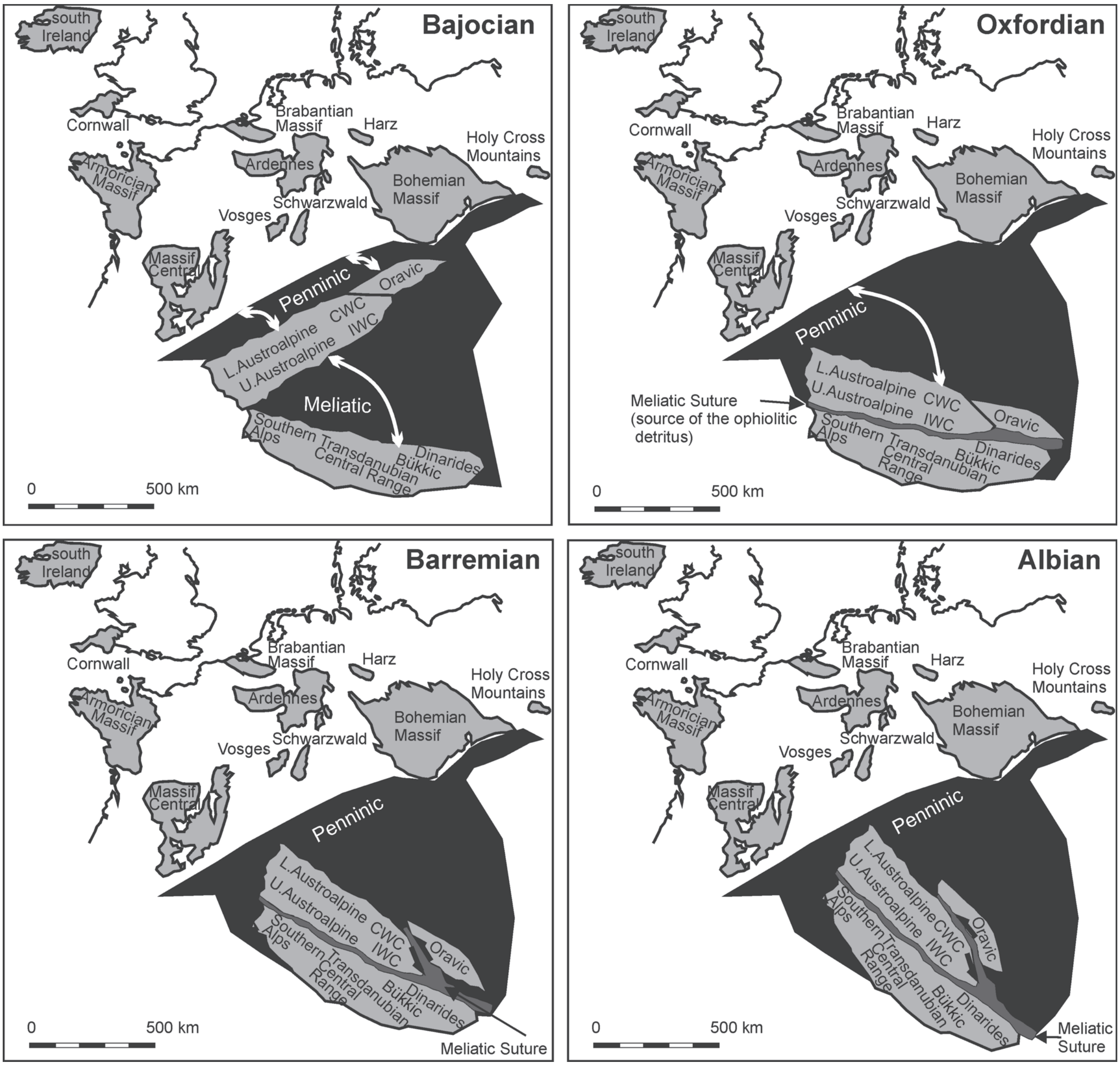

Fig. 12. New proposed paleogeographical scheme of the Pieniny Klippen Belt (Middle Jurassic to Early Cretaceous) evolution in the context of the other Alpine-Carpathian units (see the comments in the text). Abbreviations: **L. Austroalpine** = Lower Austroalpine, **U. Austroalpine** = Upper Austroalpine, **CWC** = Central Western Carpathians, **IWC** = Inner Western Carpathians.

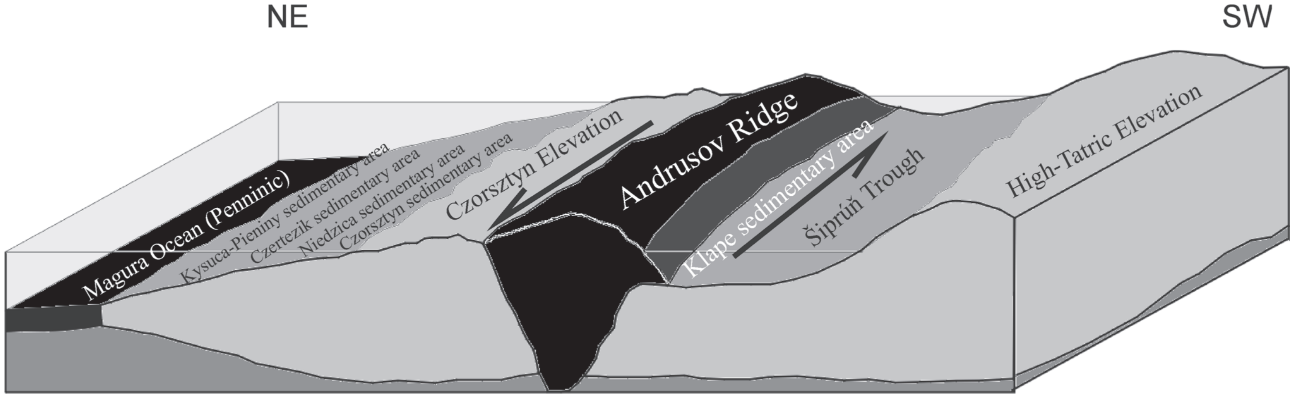

Fig. 13. New proposed paleogeographical reconstruction of the Pieniny Klippen Belt units in the Albian.

Swell (garnet-dominated heavy mineral assemblages). The elevation difference between the Czorsztyn and the exotic Andrusov Ridge was not big and only relatively fine detritus was transported to the Czorsztyn sedimentary area (both, Jurassic and Cretaceous clastics in the Czorsztyn Unit are of the same size — maximum 2–3 cm pebbles). On the contrary, the exotic pebbles in the Klape and Tatric units reach size from some decimeters to meters.

This paleogeographical reconstruction requires radical change in the interpretation of the Oravic zonation (Fig. 13). In the new interpretation we keep the original arrangement of Birkenmajer (1977) (with slight modification of Wierzbowski et al. 2004) but the entire orientation of the Oravic segment should be reversed by 180°. This means that the Kysuca-Pieniny sedimentary area would continue to the Magura Ocean and no trough existed between the Central Western Carpathians and the Czorsztyn Swell. The northward arrangement of the Oravic units is more logical as the SE-NW oriented extension (rifting) usually causes crustal block tilting in which the riftward side is steeper and the landward side dips more gently (the reconstruction of Birkenmajer 1977 shows the opposite). Therefore, there was much larger space on the landward (generally northern) side to arrange all the gradually deepening Oravic units.

Conclusions

1. Heavy mineral analysis of the Upper Aptian-Albian sediments from the Chmielowa Formation of the Czorsztyn Unit of the Pieniny Klippen Belt shows a dominance of spinels and garnets over zircon, rutile and tourmaline.
2. The composition of majority of the detrital garnets shows that they were derived from primary HP/UHP parental rocks which were recrystallized under granulite and amphibolite facies conditions. Such garnets are of exotic origin but the same were found in the Jurassic clastics of the Czorsztyn Unit. Therefore, garnets despite being exotic, are considered to be derived from the presently non-existing crystalline rocks of the Oravic crustal segment.
3. Detrital spinels are a new element in the Aptian/Albian Oravic paleogeography. They were most likely derived from the same exotic sources as clastics of the Klape, Tatric and Fatric units. The presence of ophiolitic detritus in the sediments which sedimented on the Czorsztyn Elevation infer that this elevation was not isolated from the exotic source by deeper troughs but it was in close vicinity to it. A small part of the spinels might also be derived from the same metamorphic complex as the high-pyrope garnets.
4. A new paleogeographical model for the Pieniny Klippen Belt is proposed: The Oravic segment was derived from the Moldanubian Zone of the Bohemian Massif by the Middle Jurassic rifting. The rifting caused block tilting where most of the Oravic units were arranged north of the Czorsztyn Swell, dipping to the Magura (Penninic) Ocean. The Oravic segment was situated in the lateral continuation of the Central and Inner Western Carpathians. Later clockwise rotation caused detachment of the Oravic segment, which was laterally shifted in front of the Central Western Carpathians, together with remnants of the Meliata suture zone. The latter served as a source of the exotics to the Klape, Tatric, Fatric and Oravic units.

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