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# Exotic detrital pyrope-almandine garnets in the Jurassic sediments of the Pieniny Klippen Belt and Tatric Zone: where did they come from?

ROMAN AUBRECHT[1] and ŠTEFAN MÉRES[2]

[1]Department of Geology and Paleontology, Faculty of Sciences, Comenius University, Mlynská dolina – G, 842 15 Bratislava
[2]Department of Geochemistry, Faculty of Sciences, Comenius University, Mlynská dolina – G, 842 15 Bratislava

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**Abstract**

Chemical analyses of detrital garnets from the Jurassic sediments of the Pieniny Klippen Belt and from the Central Western Carpathians yielded important information with possible application in the paleogeographic investigations in Mesozoic of the Western Carpathians. From the Pieniny Klippen Belt, five samples of the Lower Jurassic rocks were analysed from localities Klape (Klape Unit?), Manín Narrows (Manín Unit), Sedliacka Dubová, Lúty Potok and Krásna Hôrka (the latter three samples are from the Nižná Unit). Along with these samples, Middle Jurassic samples from Hatné (Czorsztyn Unit), Vršatec (Czorsztyn Unit) and Horné Sŕnie – Samášky (Pruské Unit) were analysed, too. From the Central Western Carpathians, three samples were analysed from localities Malý Šiprúň (Tatric Unit of the Veľká Fatra Mts.), Čierťaže (Krížna nappe, Fatricum of the Malá Fatra Mts.) and Prašník (Nedzov nappe, Hronicum?, Čachtické Karpaty Mts.).

Along with some usual almandinic garnets, all the samples from the Pieniny Klippen Belt (including Klape and Manín units) contained predominantly garnets with higher pyrope component (Mg) which reached 30 to 50 %. Their likely source-rocks were granulites and eclogites which, however, lack in the Central Western Carpathian crystalline complexes and even in the neighbouring Brunovistulicum (easternmost zone of the Bohemian Massif). Their source can be placed to the Moldanubian Zone of the Bohemian Massif, from which also the basement crustal segments of the Pieniny Klippen Belt units (including even the Manín and Klape? units) might be derived. The closest granulite occurrences are situated in the Moldanubian Zone, only about 130–140 km west of the recent westernmost outcrops of the Pieniny Klippen Belt.

Relatively rich contents of such garnets, together with exotic granulitic pebbles, were reported also from the Flysch Belt. They also indicate a source area of detrital material with granulites and eclogites similar to the Moldanubian Zone.

In the Central Western Carpathian samples, garnets compositionally close to those from the Tatric-Veporic crystalline complexes were found (predominantly almandine, less grossular or spessartine resp.). They came from the greenschist to high-grade amphibolite metamorphic facies, which corresponds well with the Western Carpathian metamorphics, e.g. phyllites, mica-schists, gneisses amphibolites and/or amphibolitized eclogites. The most problematic, however, was a source of a few garnet grains from the Malý Šiprúň locality, which reached 35–49 % content of the pyrope component. Rocks with garnets of such a high pyrope content have never been found so far in the Central Western Carpathian crystalline complexes. They display eclogitic rather than granulitic origin. An explanation can be found, perhaps, in a source placed externally from the Central Western Carpathians as the Malý Šiprúň locality represents rocks from the most external Tatric zone, so called Šiprúň Trough. Another, though local possible source of these garnets may be the remnants of high-grade metamorphics of the Hercynian lower crust origin in the Tatric crystalline complexes (so-called leptyno-amphibolite complex of the Western Carpathians) which include amphibolitized eclogites.

**Key words:** Jurassic paleogeography, Western Carpathians, Pieniny Klippen Belt, Bohemian Massif, garnets, granulites, eclogites

## Introduction

Pieniny Klippen Belt is the most tectonically complicated zone in the Western Carpathians. Its complex structure resulted from multiphase deformation that affected this zone during its evolution. The resulting structure is a melange of numerous paleogeographically different tectonic units which originated even hundreds of kilometres away from each other and now occur commonly even in distances of several metres due to significant shortening.

The Pieniny Klippen Belt involves mostly the Oravic Units (sensu Maheľ, 1986), coming from an independent paleogeographic domain belonging to the Outer Western Carpathians (Czorsztyn, Pruské, Niedzica, Czertezik, Kysuca-Pieniny and some other units), as well as the units of unknown origin, e.g. Klape, Manín and Drietoma units which are frequently attributed to the Central Western Carpathians. However, it is necessary to stress that provenance of none unit of the recent Pieniny Klippen Belt has been reliably proved. Because of the strong crustal shortening, all the units are incomplete. Only Jurassic and Cretaceous sedimentary cover is commonly preserved; the older stratigraphic levels, together with their crystalline basement were destroyed. This crustal segment was probably subducted, together with surrounding oceanic crust, under the overriding amalgamated plate of the Central and Inner Western Carpathians. Reconstruction of the original position of the Pieniny Klippen Belt units is then very difficult. Study of their Jurassic-Cretaceous facial relationship can reveal just some aspects of their paleogeographical position, but the main question remains: where did they come from?

One of the methods, used several times in paleogeographic reconstructions of the Pieniny Klippen Belt, mainly in its convergent and collisional Cretaceous period, was the heavy mineral analysis. Recently, the heavy mineral analysis of the Western Carpathian Jurassic sediments brought interesting data which shed light on some aspects of paleogeographic reconstruction of the Western Carpathian synrift evolution stage (Aubrecht, 1993, 1994; Aubrecht and Krištín, 1995). The analyses were aimed at determination of provenance of the detrital material and the mutual relationship among the Western Carpathian units in the time of Jurassic rifting. Further sampling, together with the variation analysis (chemical and morphological division of heavy mineral grains – see Morton, 1985), revealed new facts that may play an important role in the paleogeography of the Western Carpathians.

Importance of garnet, seemingly an ordinary component of heavy mineral spectra, was for a long time underestimated in the Western Carpathians. Except of Neogene sediments, where there were some attempts to use chemistry of this mineral group as a provenance indicator (Uher and Kováč, 1993), the results from older sediments were missing.

The first information on detrital garnet compositions from the Flysch Belt of the Outer Western Carpathians was published by Otava et al. (1997, 1998). Their results showed that some portion of the detrital garnets from the Cretaceous and Paleogene sediments of the Magura Flysch Zone possess an almandine-pyrope composition that is typical for garnets coming from granulites and/or eclogites. Since these rocks are specific, the mentioned authors think the source area was similar to the Moldanubian Zone of the Bohemian Massif where they occur in huge masses.

Recently, chemical analyses of detrital garnets were carried out from the Lower and Middle Jurassic sediments at 11 West Carpathian localities, mostly from the Pieniny Klippen Belt. Their results are the topic of this paper.

## Location and geological setting of the sampled sites

The localities include the Early to Middle Jurassic sediments from Czorsztyn, Pruské, Nižná, Manín and Klape units of the Pieniny Klippen Belt (the latter represents just Klapy Hill of uncertain position) and Tatric, Krížna and Nedzov units of the Central Western Carpathians. As a rule, the Pieniny Klippen Belt samples were garnet-dominated, whereas the second group of samples was depleted in garnet (maximum content of detrital garnet found in the Central Western Carpathians was 12 % in the Tat-

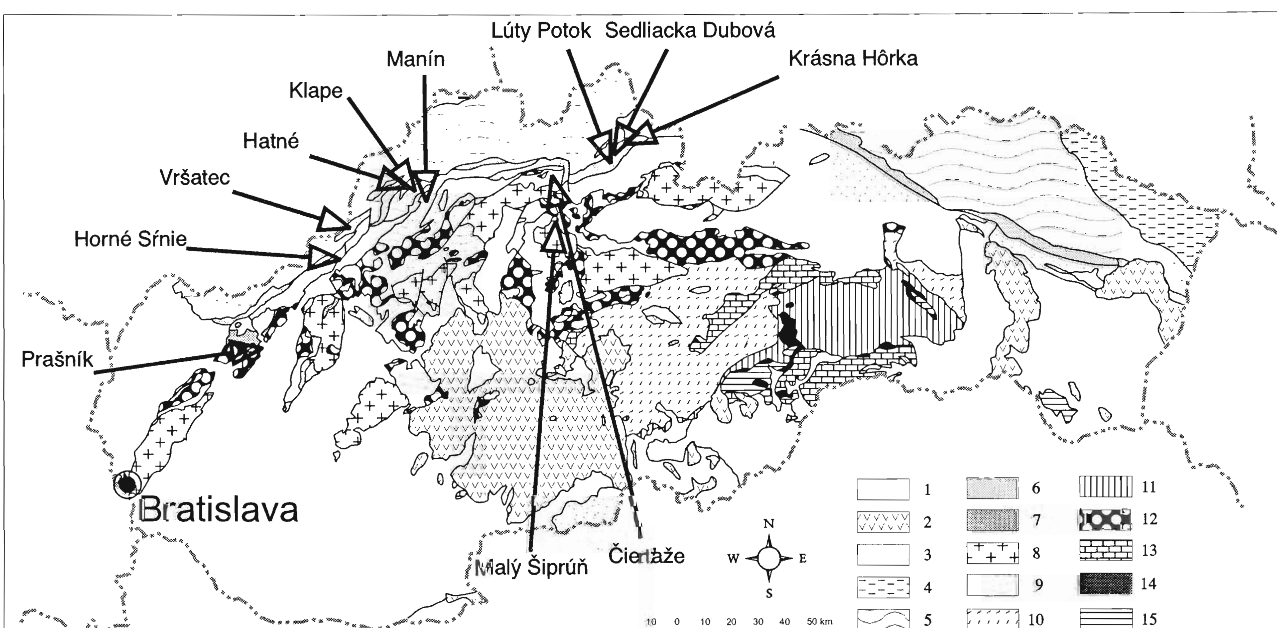


**Fig. 1.** Position of the sampled localities within the frames of the West Carpathian geological structures. Legend: 1 – fill of the Neogene basins, 2 – Neogene volcanics, 3 – Paleogene basins, 4 – Outer Flysch Belt units, 5 – Inner Flysch Belt units, 6 – Pieniny Klippen Belt – Oravic units, 7 – Sennonian of the Central and Inner Western Carpathians, 8 – Tatric units, 9 – Fatric units, 10 – Veporic Unit, 11 – Gemeric Unit, 12 – Hronic units, 13 – Silicic units s.l., 14 – Meliaticum, 15 – Turnaicum, Zemplinicum, other units of the Inner Western Carpathians.

ric Unit of the Veľká Fatra Mts.). The reason of the garnet depletion in the Jurassic deposits of the Central Western Carpathians is unknown. Either an intrastratal dissolution or resedimentation from pre-existing older rocks are the most likely possibilities (Aubrecht, 1994, Aubrecht and Krištín, 1995).

The studied localities are as follows:

### *Localities of the Pieniny Klippen Belt*

*Vršatec* – locality occurs in the area of Vršatec Klippes, 1 km NE from the village Vršatecké Podhradie at the blue-marked tourist route going to Červený Kameň. The sample represents Bajocian white sandy crinoidal limestone (Smolegowa Fm.) with small quartz pebbles in the upper slice of the Czorsztyn Unit. The locality was described by Mišík (1979; profile II.).

*Hatné* – a quarry occurring directly at the road connecting Udiča and Horná Mariková villages, near the cemetery of the Hatné village. The sample was taken from red sandy crinoidal limestones of Bathonian age (Krupianka Fm.) likely belonging to the Czorsztyn Unit. The locality was described by Aubrecht and Sýkora (1998).

*Horné Sŕnie – Samášky* – a profile of the Pruské Unit along a roadcut within the area of the local cement factory quarries near Horné Sŕnie village. The sample was taken from the Bajocian-Bathonian sandy crinoidal calciturbidite (Samášky Fm.) The locality was described by Aubrecht and Ožvoldová (1994).

*Lúty Potok* – a conspicuous klippe in the valley of Dlžniansky Cickov creek (formerly called Lúty potok), at foot of Vysoký grúň hill (849 m), W of Krivá village in Orava territory. The locality was described by Andrusov (1938) and Mišík et al. (1995). The latter authors ascribed the locality to Nižná Unit. The sample was taken from red sandy crinoidal limestone of Pliensbachian age.

*Krásna Hôrka* – an old abandoned quarry N of Nižná (Orava territory). It represents the type locality of the Nižná Unit (Scheibner, 1967). The sample was taken from arcosic sandstones to sandy crinoidal limestones of Sinemurian age.

*Sedliacka Dubová* – a conspicuous klippe Skalka behind the local farm. The sample was taken from sandy crinoidal limestones to arcosic sandstones of the Early Jurassic age.

*Manín Narrows* – the type locality of the Manín Unit. The sample was taken from sandy Lower Jurassic limestone.

*Klape* – a hill consisting of Lower to Middle Jurassic limestone block, likely representing a huge olistolite in the flysch of the Klape Unit (Marschalko, 1986). The sample was taken from sandy crinoidal limestone near the top of the hill (likely Toarcian – see Began, 1962).

### *Localities of the Central Western Carpathians*

*Malý Šiprúň* – well-known hill in the Veľká Fatra Mts. The sample was taken from Lower Jurassic sandy limestone (Trlenská Fm. - see Bujnovský et al., 1979) of Tatric Unit, near the top of the hill.

*Čierťaže* – a small ridge towards Osnica Hill in the Malá Fatra Mts., in the valley of Zázrivka creek. The sample was taken from black sandstone of the Early Jurassic age (Kopienec Fm.) of the Krížna Nappe.

*Prašník* – northern slope of Tlstá hora Hill (426 m), south of Prašník village, near Vrbové. The locality represents one of the remants of Jurassic sediments of the Nedzov Nappe. An original sedimentary area of this highest nappe (in geological continuation of the Malé Karpaty Mts.) used to be placed either to Hronic or to Silicic zone. The sample was taken from the Lower Jurassic grey organodetrital limestone with slight sandy admixture.

## Chemical composition of the detrital garnet grains

Differences in garnet compositions result from isomorphic mixing of the garnet end-members (most commonly almandine, pyrope, spessartine and grossular). Different composition of wall-rocks and wide range of PT conditions during formation of garnet cause significant differences also in their chemical compositions. Therefore, garnets are very valuable mineral group in geological reconstructions.

This was the reason we have focused on the detrital garnet composition in reconstruction of the source-rocks of the Jurassic sediments from selected localities in the Western Carpathians. We have entirely analysed 84 grains of detrital garnets from the Lower and Middle Jurassic sediments of the Western Carpathians. The microprobe analyses were carried out in CLEOM laboratory of the Comenius University, as well as in the Geological Survey of Slovak Republic. The selected representative analyses are in Tabs. 1–4.

All the analysed garnet grains represent chemical mixtures of four components: almandine (Al), pyrope (Py), spessartine (Sp) and grossular (Gr). Their chemical compositions are plotted in Py-Al-Gr and Py-Al-Sp ternary diagrams (Fig. 2 A-D) with dotted areas summarizing the garnet compositions from the Western Carpathian crystalline complexes (based on published literature: Spišiak and Hovorka, 1984; Méres and Hovorka, 1989, 1991; Hovorka and Spišiak, 1986; Hovorka et al., 1987, 1990, 1992; Hovorka and Méres, 1990, 1991; Faryad, 1995; Cambel at al., 1990). Moreover, the FeO-MgO-MnO ternary diagram (Miyashiro and Kuculu, in Antipin, 1977) was used to display genesis of the garnets. In this diagram, four areas of metamorphic conditions are distinguished, in which the garnets might originate: I – greenschist facies, II – low-temperature amphibolite facies, III – amphibolite facies and IV – granulite facies (Fig. 3).

### *Localities of the Pieniny Klippen Belt*

From *Vršatec* locality, 14 garnet grains were analysed. Garnets from this locality are relatively uniform in composition (Al: 45–54 %, Py: 36–49 %, Gr: 3–7 %, Sp: 0.6–3 %), with pyrope-almandine components being dominant (Fig. 2A, Tab. 1). Lesser amount of grossular is always present, spessartine component is negligible. Garnets of

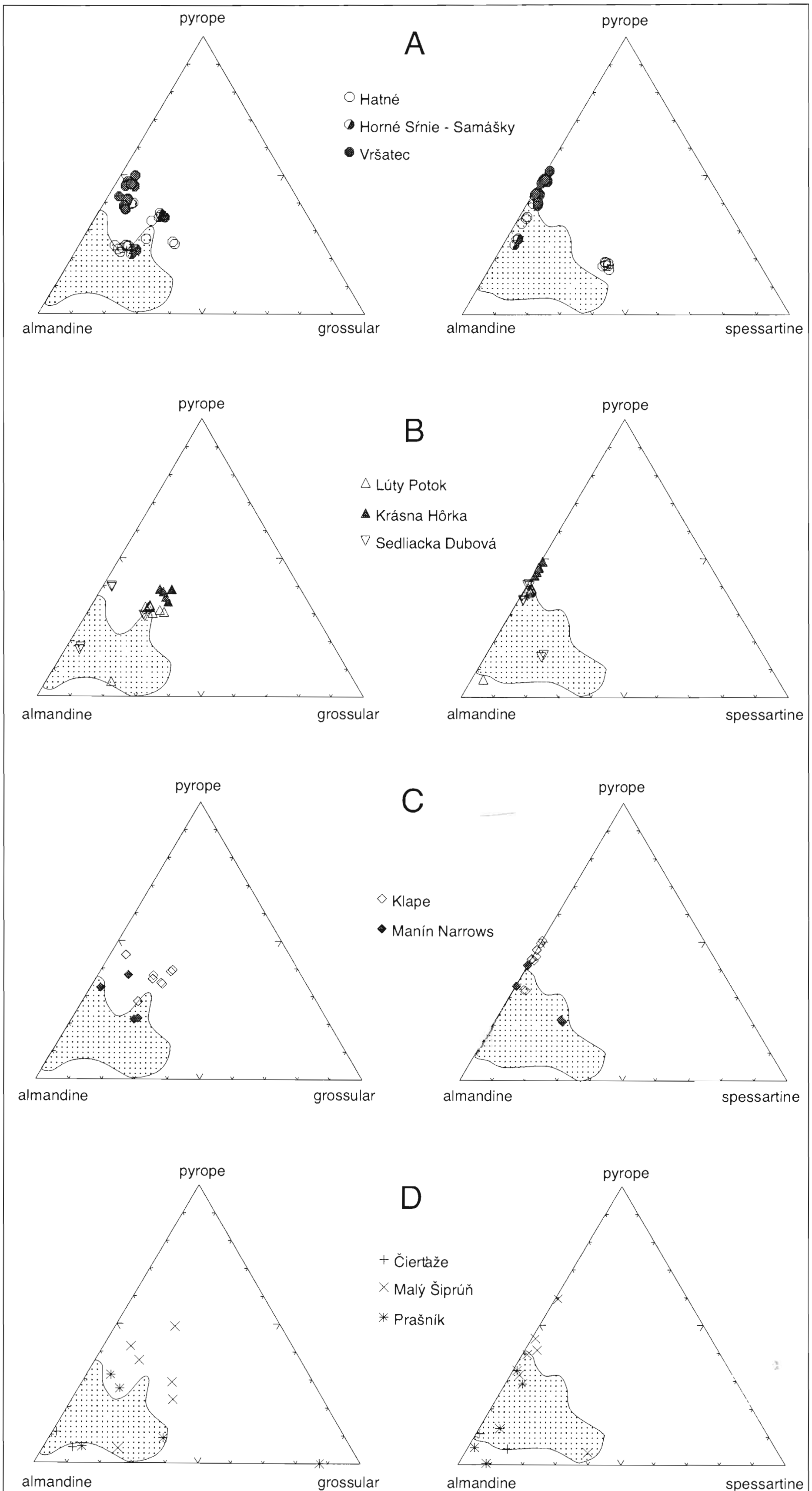


**Fig. 2.** Py-Al-Gr and Py-Al-Sp ternary diagrams of chemical compositions of the detrital garnets from the Jurassic sediments from the Western Carpathian localities. The dotted area represents chemical composition of garnets from the pre-Upper Carboniferous metamorphosed complexes of the Western Carpathians (adopted from Spišiak and Hovorka, 1984; Méres and Hovorka, 1989, 1991; Hovorka and Spišiak, 1986; Hovorka, et al., 1987, 1990, 1992, Hovorka and Méres 1990, 1991; Faryad, 1995; Cambel et al., 1990).

such composition are typical for the rocks metamorphosed in granulite or eclogite facies (Fig. 3A). Relative depletion in grossular component favours the granulitic origin.

From *Hatné* locality, 16 garnet grains were analysed. These garnets can be compositionally divided into three groups (Fig. 2A).

The first one (e.g. Tab. 1, sample H15) represents relatively uniform pyrope-almandine garnets with small portion of grossular and almost no spessartine components (Al: 51–52 %, Py: 39–40 %, Gr: 8–9 %, Sp: 0.7–0.8 %). This group of garnets possess composition identical to those from the Vršatec locality (Fig.2A). Their source-rocks were granulites.

The second group (e.g. Tab. 1, sample H12) is dominated by almandine, with pyrope and grossular in lesser amounts and with negligible portion of spessartine component (Al: 45–53 %, Py: 25–33 %, Gr: 17– 28 %, Sp: 1.5–1.8 %). This group is again similar to the garnets from Vršatec locality (Fig. 2A) but it differs by a higher content of grossular component. Therefore, the most likely source-rocks of these garnets were eclogites.

The third group (e.g. Tab. 1, sample H2) consists of spessartine-almandine, with lesser amounts of pyrope and

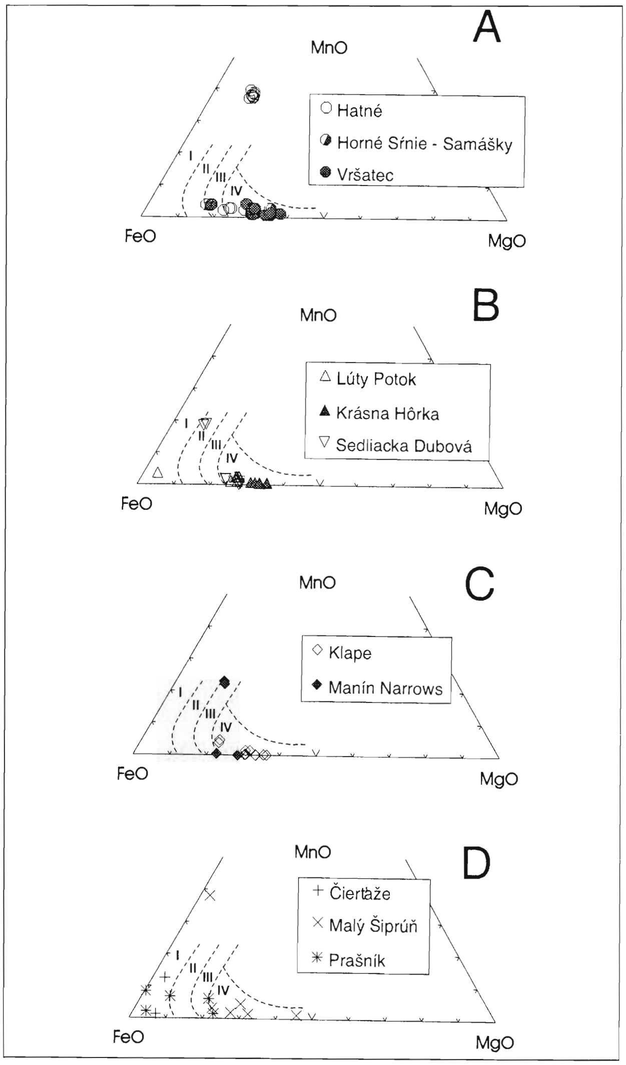


**Fig. 3.** Chemical composition of the detrital garnets from the Jurassic sediments from the Western Carpathian localities in FeO-MgO-MnO ternary diagrams. The individual fields represent various metamorphic zones (according Miyashiro and Kuculu in Antipin, 1977). I – garnets from greenschist and epidote amphibolite facies, II – garnets from epidote amphibolite facies and low-temperature subfacies of garnet amphibolite facies, III – garnets from amphibolite facies, IV – garnets from granulite facies.

grossular (Al: 41–44 %, Py: 15–17 %, Gr: 7–11 %, Sp: 31–34 %). Such garnets are typical for rocks metamorphosed in low-temperature amphibolite facies (Fig. 3A). Their probable source rocks were mica-schists or gneisses.

From *Horné Sŕnie – Samášky* locality, 12 garnet grains were analysed. These garnets can be again divided into 3 groups (Fig. 2A). They have commonly pyrope-grossular-almandine composition, with negligible spessartine component. However, these groups differ by the ratio of the dominant components.

The first group (2 grains – Fig. 2, Tab. 1, sample HS 7) differs by increased pyrope and decreased grossular component (Al: 46–47 %, Py: 44–45 %, Gr: 5–6 %, Sp: 2 %). This composition of garnets is typical for granulites.

Tab. 1
Selected representative analyses of detrital garnets from the Jurassic sediments of the Pieniny Klippen Belt

| Locality | | Hatné | | Vršatec | Horné Sŕnie–Samášky | | |
|---|---|---|---|---|---|---|---|
| Sample | H2 | H12 | H15 | V10 | HS-3 | HS-7 | HS-10 |
| $SiO_2$ | 38.2 | 39.6 | 39.4 | 39.5 | 39.1 | 40.3 | 38.8 |
| $Al_2O_3$ | 21.4 | 22.1 | 22.2 | 23.1 | 22.6 | 22.3 | 22.5 |
| FeO | 19.6 | 20.3 | 23.5 | 22.9 | 20.8 | 23.4 | 25.8 |
| MnO | 15.0 | 0.8 | 0.3 | 0.5 | 0.4 | 1.0 | 1.3 |
| MgO | 4.2 | 6.2 | 10.3 | 12.4 | 9.3 | 12.7 | 5.7 |
| CaO | 2.6 | 10.0 | 3.2 | 1.8 | 7.0 | 2.3 | 6.1 |
| Total | 101.0 | 99.0 | 98.9 | 100.2 | 99.2 | 102.0 | 100.2 |
| Pyrope | 17 | 25 | 40 | 46 | 35 | 45 | 23 |
| Almandine | 43 | 45 | 51 | 48 | 45 | 47 | 57 |
| Spessartine | 33 | 2 | 1 | 1 | 1 | 2 | 3 |
| Grossular | 7 | 28 | 8 | 5 | 19 | 6 | 17 |

The second group (6 grains – Fig. 2, Tab. 1, sample HS 3) is dominated by almandine, followed by pyrope and grossular and negligible spessartine component (Al: 44–46 %, Py: 34–36 %, Gr: 18–21 %, Sp: 0.9–1.2 %). This composition is consistent with those of the Vršatec and Hatné localities (second group) and represents eclogitic source-rocks.

The third group (4 grains Fig. 2, Tab. 1, sample HS 10) differs from the first one by its enrichment in almandine and depletion in pyrope component (Al: 57–59 %, Py: 21–23 %, Gr: 16–18 %, Sp: 2.7–3 %). Such garnets are typical for rocks metamorphosed in amphibolite facies (Fig. 3A). The relative depletion of pyrope with respect to the first group of garnets from this locality can indicate amphibolites to amphibolitized eclogites being the probable source-rocks.

From *Lúty Potok* locality, 11 garnet grains were analysed. These garnets show relative uniformity (except one grain), being dominated by almandine, followed by pyrope and grossular components (Fig. 2B, Tab. 2). The spessartine component is negligible (Al: 46–50 %, Py: 30–33 %, Gr: 16–23 %, Sp: 0.7–1.8 %). The garnet composition points to eclogitic source-rocks. The mentioned exceptional single garnet grain is enriched in al-

Tab. 2
Selected representative analyses of detrital garnets from the Jurassic sediments of the Pieniny Klippen Belt

| Locality | Sedliacka Dubová | | | Lúty Potok | | Krásna Hôrka | |
|---|---|---|---|---|---|---|---|
| Sample | SD1-c | SD2-c | SD3-m | LP5 | LP7 | KH5 | KH6 |
| $SiO_2$ | 39.1 | 39.4 | 37.6 | 41.0 | 39.9 | 42.4 | 41.4 |
| $Al_2O_3$ | 21.8 | 21.6 | 21.1 | 21.8 | 22.2 | 24.9 | 24.6 |
| FeO | 27.7 | 25.0 | 30.5 | 21.9 | 22.2 | 18.6 | 18.4 |
| MnO | 0.5 | 0.7 | 8.0 | 0.8 | 0.8 | 0.1 | 0.2 |
| MgO | 10.6 | 7.7 | 3.9 | 8.2 | 8.1 | 9.4 | 9.2 |
| CaO | 1.1 | 6.8 | 1.3 | 6.2 | 6.4 | 6.0 | 6.6 |
| Total | 100.8 | 101.2 | 102.4 | 99.9 | 99.6 | 101.4 | 100.4 |
| Pyrope | 39 | 29 | 15 | 32 | 31 | 39 | 38 |
| Almandine | 57 | 52 | 64 | 48 | 49 | 43 | 43 |
| Spessartine | 1 | 1 | 17 | 2 | 2 | 0 | 0 |
| Grossular | 3 | 18 | 4 | 18 | 18 | 18 | 19 |

mandine, depleted in pyrope (Fig. 2B) and slightly enriched in spessartine component (Al: 72 %, Py: 5 %, Gr: 19 %, Sp: 2.9 %). This grain originated in rocks metamorphosed in the greenschist facies or in low-temperature amphibolite facies (Fig. 3B), i.e. phyllites, mica-schists or, eventually, amphibolites.

From *Krásna Hôrka* locality, 6 garnet grains were analysed (Fig. 2B). They display relative compositional uniformity, with almandine-pyrope components being dominant (Tab. 2). These components are followed by grossular; the spessartine component is almost missing (Al: 39–43 %, Py: 34–37 %, Gr: 18–23 %, Sp: 0.3–0.5 %). The chemical composition of the garnets points to eclogitic source-rocks.

From *Sedliacka Dubová* locality, only 3 garnet grains were analysed (7 analyses). They possess variable composition (Tab. 2, Fig. 2B). The first grain (3 analyses) is of almandine-pyrope composition, with only minor amount of grossular and nearly no spessartine component (average: Al: 57 %, Py: 40 %, Gr: 2.7 %, Sp: 0.4 %). The high pyrope and low grossular contents point to granulitic source-rocks (Fig. 3B).

The second grain (2 analyses) is dominated by almandine, followed by pyrope and grossular components. Spessartine component is in minor amount (average: Al: 52 %, Py: 29 %, Gr: 18 %, Sp: 1.3 %). This grain might come from eclogites.

The third sample (2 analyses) is also dominated by almandine, but with increased spessartine component and decreased pyrope and grossular components (average: Al: 65 %, Py: 14 %, Gr: 3.6 %, Sp: 17 %) which corresponds to low-temperature amphibolite facies (Fig. 3B) and is typical for mica-schists and gneisses.

From *Manín Narrows,* 4 garnet grains were analysed. They can be grouped into 2 groups according to their compositions (Fig. 2C). The first group (2 analyses) is of almandine-pyrope composition, with lesser amount of grossular component; spessartine molecule is missing (Al: 53–64 %, Py: 33–37 %, Gr: 3–9 %, Sp: 0–4 %), which is typical for granulites (Tab. 3, sample M1).

The second group is dominated by almandine (Tab. 3, sample M3), followed by relatively equal proportions of pyrope, spessartine and grossular (Al: 48 %, Py: 18 %, Gr: 16 %, Sp: 17 %). Such composition is typical for rocks metamorphosed in amphibolite facies (Fig. 3C), i.e. mica-schists, gneisses or amphibolites.

From locality Klape, 5 garnet grains were analysed (11 analyses). They can be grouped into 2 groups according to their compositions. Both groups correspond to the garnets from rocks metamorphosed in granulite/eclogite facies (Fig. 3C). The difference between them is just in lower amount of grossular (about 5 %) in one grain (two analyses, Fig. 2C), whereas the pyrope component is still high (up to 45 %). This single grain came from granulites, whereas the others are typical for eclogites.

The ratios of almandine, pyrope, grossular and spessartine in various parts of analysed garnet grains (centre – c, margin – m) differ just in the range of 1–2 % which indicates that the grains are homogeneous. This fact supports our opinion about their origin in the granulite/eclogite metamorphic facies (Fig. 3C).

### *Localities of the Central Western Carpathians*

From *Malý Šiprúň* locality, 6 garnet grains were analysed. They possess very variable compositions that allow no strict grouping.

Five grains represent variable pyrope-almandine-grossular garnets (Fig. 2D), with minor amount of spessartine (Al: 32–49 %, Py: 22–49 %, Gr: 8–30 %, Sp: 0.7–3 %). Their composition indicates origin in the granulite/eclogite metamorphic facies; the source-rocks were eclogites.

A single grain represents spessartine-grossular-almandine garnet, with minor amount of pyrope component (Tab. 4, sample S1) corresponding to the greenschist facies of metamorphism (Fig. 3D). Possible source-rocks were phyllites, mica-schists or, eventually, rocks of the low-temperature amphibolite facies.

From *Čierťaže* locality, only 2 garnet grains were analysed (very low primary content of garnet in the sample). Both of them are dominated by almandine with minor but variable content of pyrope, spessartine and grossular components (Fig. 2D, Tab. 4 sample C1). They correspond to greenschist metamorphic facies (Fig. 3D). Such gar-

Tab. 3
Selected representative analyses of detrital garnets from the Jurassic sediments of the Pieniny Klippen Belt

| Locality | | Klape | | | | Manín Narrows | |
|---|---|---|---|---|---|---|---|
| Sample | K2-c | K3-c | K3-m | K4-c | K5-c | M1 | M3 |
| $SiO_2$ | 39.0 | 39.3 | 39.4 | 39.2 | 39.6 | 37.9 | 36.7 |
| $Al_2O_3$ | 23.7 | 23.6 | 24.3 | 22.4 | 22.5 | 23.3 | 22.9 |
| FeO | 20.8 | 23.7 | 23.9 | 25.0 | 18.4 | 24.8 | 22.3 |
| MnO | 0.1 | 0.1 | 0.0 | 1.6 | 0.0 | 0.0 | 7.7 |
| MgO | 9.2 | 11.9 | 12.0 | 7.2 | 10.5 | 9.9 | 4.7 |
| CaO | 7.5 | 1.8 | 1.8 | 6.0 | 8.1 | 3.3 | 6.0 |
| Total | 100.3 | 100.4 | 101.4 | 101.4 | 99.1 | 99.2 | 100.3 |
| Pyrope | 35 | 45 | 45 | 27 | 39 | 38 | 18 |
| Almandine | 44 | 50 | 50 | 53 | 39 | 53 | 48 |
| Spessartine | 0 | 0 | 0 | 3 | 0 | 0 | 17 |
| Grossular | 21 | 5 | 5 | 17 | 22 | 9 | 17 |

Tab. 4
Selected representative analyses of detrital garnets from the Jurassic sediments of the Central Western Carpathians

| Locality | Čierťaže | | Prašník | | | Malý Šiprúň | |
|---|---|---|---|---|---|---|---|
| Sample | C1 | P1 | P2 | P4 | S1 | S5 | S6 |
| $SiO_2$ | 37.7 | 39.2 | 39.6 | 39.0 | 37.5 | 40.8 | 38.6 |
| $Al_2O_3$ | 21.1 | 18.7 | 21.9 | 21.7 | 21.1 | 23.1 | 21.9 |
| FeO | 32.4 | 6.4 | 27.7 | 24.4 | 21.6 | 15.8 | 21.4 |
| MnO | 4.8 | 0.6 | 0.5 | 1.9 | 13.9 | 0.4 | 0.9 |
| MgO | 1.3 | 0.0 | 8.1 | 2.2 | 0.9 | 13.3 | 5.9 |
| CaO | 3.1 | 34.6 | 2.6 | 11.8 | 5.4 | 6.9 | 11.1 |
| Total | 100.4 | 99.5 | 100.4 | 101.0 | 100.4 | 100.3 | 99.8 |
| Pyrope | 5 | 0 | 31 | 9 | 4 | 49 | 23 |
| Almandine | 75 | 13 | 60 | 54 | 49 | 32 | 45 |
| Spessartine | 11 | 1 | 1 | 4 | 32 | 1 | 2 |
| Grossular | 9 | 86 | 8 | 33 | 16 | 18 | 30 |

nets are typical for phyllites, mica-schists or, eventually, gneisses.

From *Prašník* locality, 5 garnet grains were analysed (garnets in the sample were also very scarce) with quite variable composition that allows only approximate grouping into three groups (Fig. 2D).

The first group of garnets (Tab. 4, sample P2) is dominated by almandine (around 60 %) and a relatively high content of pyrope (up to 31 %) and low portion of spessartine (5 %) and grossular (about 10 %). These garnets correspond to high-grade amphibolite to granulite metamorphic facies (Fig. 3D). Their source-rocks migh be high-temperature amphibolites, granulites, eclogites or amphibolitized eclogites resp.

The second group involves just two garnet grains corresponding to greenschist metamorphic facies or low-temperature amphibolite facies resp. (Fig. 3D, Tab. 4, sample P4). Their source might be mica-schists or amphibolites.

A single grain is grossular with minor amount of almandine component (Fig. 2D). The spessartine and pyrope components are negligible (Tab. 4 sample P1). Such garnets are typical for erlans or scarns.

## Interpretation and discussion – possible provenance of the garnets

According to the chemical composition, the studied garnets from the Jurassic sediments of the Pieniny Klippen Belt and the Central Western Carpathians can be divided into four groups:

A group – garnets with a high pyrope content (more than 30 %), a relatively low content of grossular (less than 10 %) and a very low content of spessartine (less than 3 %).

B group – to this group belong the garnets with high pyrope content (more than 25 %), relatively high ratio of grossular (exceeding 15 %) and very low content of spessartine (less than 3 %).

C group – garnets with contents of pyrope ranging between 20 and 30 %, grossular from 10 to 30 % and spessartine less than 5 %.

D group – connects garnets with less than 20 % of pyrope component and variable amounts of the other components (spessartine, grossular, almandine).

The chemical compositions of all analysed garnets plotted in ternary diagrams is in Fig. 4. The studied garnets form four independent fields in the Py-Al-Gr ternary diagram. In the Py-Al-Sp diagram, the A and B fields largely overlap each other, due to low contents of spessartine. It is evident that most of the studied garnet grains occur in the fields A and B. Characteristic feature of these garnets is high content of pyrope in their composition. Such garnets are typical for high-grade metamorphosed rocks - granulites and eclogites (Fig. 3). The difference between the groups A and B is in the content of grossular component. The A group garnets, with relatively lower grossular content, are typical for granulites, whereas the B group, with higher content of grossular, represents eclogitic source rock.

The lesser amount of studied garnets fell into the field C. The garnets of this group differ from the previous two groups by their lower ratio of pyrope, with moderate content of grossular. Garnets of such composition occur either in the rocks metamorphosed in high-grade amphibolite to granulite metamorphic facies (gneisses, amphibolites, granulites, eclogites) or in originally high-grade metamorphosed rocks (eclogites) later recrystallized in the amphibolite metamorphic facies (e.g. amphibolitized eclogites).

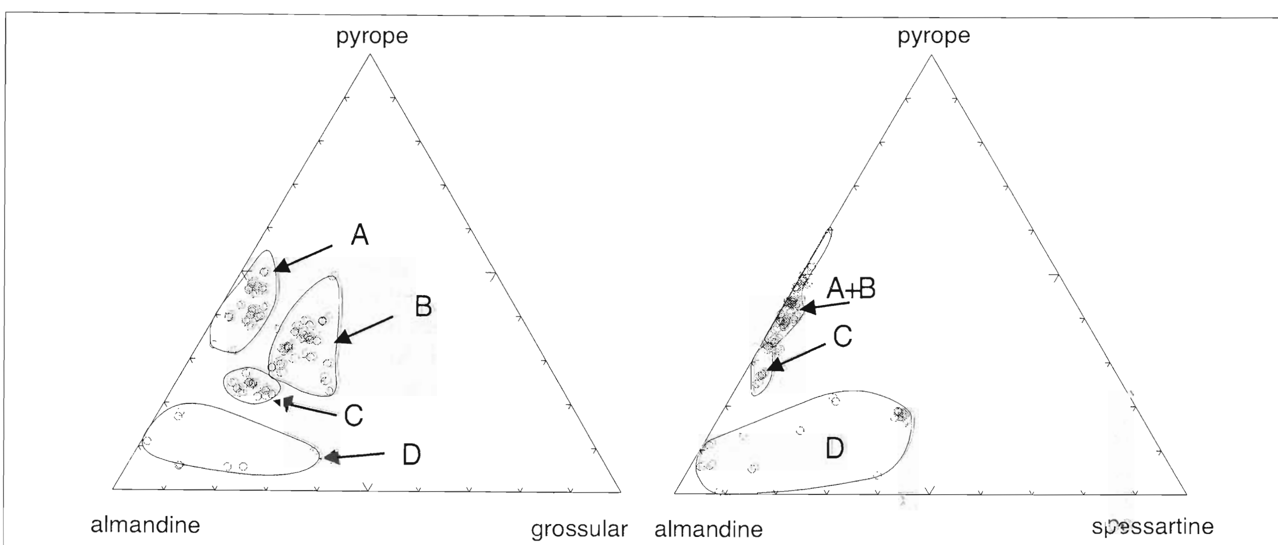


**Fig. 4.** Chemical composition of the detrital garnets from the Jurassic sediments from the Western Carpathian localities (circles) in Py-Al-Gr and Py-Al-Sp ternary diagrams with distinguished four principal groups of garnets: A – garnets coming from granulitic source-rocks, B – garnets coming from eclogitic source-rocks, C – garnets coming from gneisses, amphibolites, granulites, eclogites or amphibolitized eclogites resp., D – garnets coming from phyllites, mica-schists, gneisses and amphibolites.

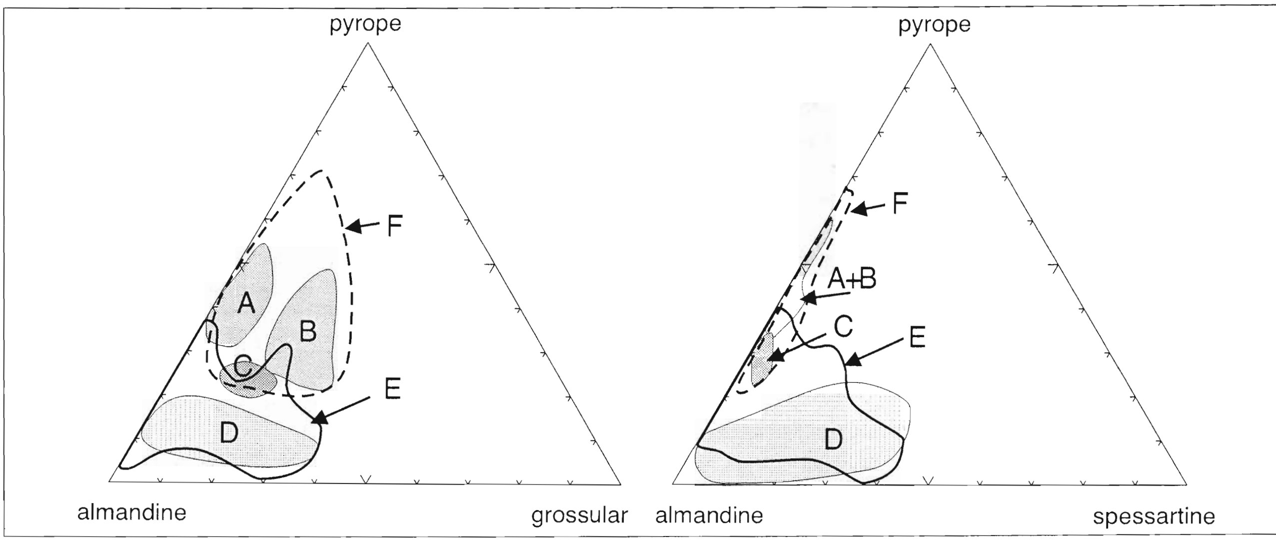


**Fig. 5.** Py-Al-Gr and Py-Al-Sp ternary diagrams with A, B, C, D fields of detrital garnets from the Jurassic sediments of the Western Carpathians (see Fig. 4), E field of pre-Upper Carboniferous metamorphosed rocks of the Western Carpathians (see Fig. 2), F field of granulites and eclogites of the Moldanubian Zone (adopted from Dudek 1971, O'Brien and Vrána 1995; Beard et al., 1992, Carswell and O'Brien, 1993; Medaris et al., 1995; Medaris et al., 1998).

The least of the studied garnets belongs to the D group. They have variable ratios of Py, Al, Sp and Gr. Such garnets are typical for rocks metamorphosed in the greenschist to amphibolite facies, e.g. phyllites, mica-schists, gneisses and amphibolites.

The samples from the Jurassic sediments from the localities Horné Sŕnie-Samášky, Vršatec, Krásna Hôrka and Klape yielded garnets coming evidently from the high-metamorphosed rocks – granulites and eclogites (Fig. 2 A, B and C, Fig. 3 A, B, and C). The samples from the other localities of the Pieniny Klippen Belt, i.e. Lúty Potok, Sedliacka Dubová and Manín Narrows, are dominated by similar garnets, with lesser amounts of garnets coming from mica-schists, gneisses, amphibolites and/or amphibolitized eclogites.

In the pre-Upper Carboniferous metamorphic complexes of the Western Carpathians, rocks metamorphosed in the greenschist to amphibolite facies (phyllites, mica-schists, gneisses and amphibolites) are most common (Kamenický, 1967). Rocks of the high-temperature amphibolite to granulite/eclogite facies occur sparsely, just in the leptyno-amphibolite complex of the Western Carpathians (Hovorka et al., 1992, 1994, 1997). In this complex, garnet-pyroxene metabasalts, amphibolitized eclogites and high-grade metamorphosed gneisses occur as xenoliths (Hovorka and Méres, 1989, 1993; Hovorka et al., 1990, 1992; Janák et al., 1994, 1996, 1997; Janák and Lupták, 1997). However, the published chemical analyses of garnets from these metamorphic rocks possess pyrop component less than 30 %. The chemical composition of the pre-Upper Carboniferous metamorphic rocks of the Western Carpathians is in Figs. 2 and 5.

Comparison of the garnet composition from the Jurassic sediments with those from the Western Carpathian metamorphics shows following facts:

a) all the studied garnets of the A and B groups from the Jurassic sediments are significantly different in their composition, namely in their high content of pyrope component,

b) the composition of garnets from the C and D groups is comparable with that of the Western Carpathian metamorphics.

This considerable difference (Fig. 5) excludes the Western Carpathian pre-Upper Carboniferous crystalline complexes as a possible source area of most of the analysed detrital granets, especially from the Pieniny Klippen Belt units. High content of pyrope component in these garnets indicates that their source rocks were granulites and eclogites. From the regional point of view, their most likely source was Bohemian Massif. In the Moldanubian Zone of the Bohemian Massif, there are numerous occurrences of granulites and eclogites (Dudek and Fediuková, 1974; Mísař et al., 1983; Fiala et al., 1987; O'Brien and Carswell, 1993; O'Brien and Vrána, 1995; Medaris et al., 1995; Beard et al., 1992). The nearest granulites occur in the Moldanubian Zone of the Bohemian Massif in Austria, about 130–140 km west of the recent westernmost occurrences of the Pieniny Klippen Belt.

The most important is that rocks as granulites were reported neither from other zones of the Bohemian Massif (except two small occurrences in the Western Sudetes – Góry Sowie Block and the Śnieźnik area complex – Oberc, 1972; Smulikowski, 1967; Kryza et al., 1996), nor from the Western Carpathian crystalline complexes. Granulites are frequent among the exotic pebble material in the Silesian Unit (Wieser, 1985), which suggests that the exotic Silesian Cordillera represented also a crustal segment similar to the Moldanubian Zone. However, the detrital pyrope-almandine garnets, coming most probably from the Moldanubian Zone, have been found also in the easternmost zones of the Early Carboniferous sediments in Moravia (Otava, 1998) which may provoke a speculation on resedimentation of the Pieniny Klippen Belt garnets from this source. This would led, however, to considerable decrease of garnet amounts in the final sediment, which is not the case. In our opinion, the source of the garnets was primary.

Chemical composition of garnets from the Moldanubic granulites and eclogites is summarized in Fig. 5 (field F). Their perfect correspondence to the composition of most of the studied detrital garnets from the Jurassic sediments of the Pieniny Klippen Belt (namely the groups A and B) is evident and suggests that the crustal segment representing the basement of most of the Pieniny Klippen Belt Units was derived from this Hercynian zone. It is consistent with paleogeographic evolution of the Western Carpathians presented by Vašíček et al. (1994). The northeastward movement of the Oravic crustal segment after Jurassic would be consistent with the presumed general movement of the Central Western Carpathian segment. However, placing the Oravic segment at the Moldanubic margin contradicts to the data obtained from pebble analysis (Birkenmajer et al., 1960; Krawczyk and Słomka, 1987; Mišík and Aubrecht, 1994). Neither granulitic, nor eclogitic detritus has been reported from the Oravic units. However, many of the reported rocks (e.g. various types of gneisses, porphyries etc.) do occur in the Moldanubicum, hence the question of the Oravic provenance still remains open.

The common presence of the pyrope-almandine garnets also in the Manín Narrows and Klape localities is striking. Though the original paleogeographic position of the Manín and Klape units is uncertain, they are commonly attributed to the Central Western Carpathians. The Manín Unit was considered to be related to the Tatric domain by Andrusov (1938), then to the Pieniny Klippen Belt s. s. by Salaj and Samuel (1966) and later to Fatric by Mahel' (1978). The Klape Unit was considered to represent an accretionary wedge in front of, or better along, the overriding Central Western Carpathian plate (Marschalko, 1986; Mišík and Marschalko, 1988; Birkenmajer, 1988; Soták, 1992). On the contrary, Plašienka (1995) stated that Klape Unit originated in the Fatric sedimentary area and it represents the highest part of the Krížna Nappe, detached and slided to its present position where it was subsequently tectonically involved into the Pieniny Klippen belt structure. There is also a problem of position of Klape Hill itself. This single large Jurassic klippe occurs amidst the Cretaceous flysches that form the main portion of the Klape Unit. It is not clear whether it represents a block tectonically involved into this zone (Kysela, 1984) or it is a huge olistolith that slided into the flysch basin from the Andrusov Exotic Ridge (Marschalko, 1986). Anyhow, the data obtained from the Klape Hill are not automatically valid for the entire Klape Unit. There were some findings of eclogites among the exotic pebbles in the Klape Unit but with different composition of garnets (Šímová, 1982; Šímová and Šamajová, 1981). They contain only 28 % of pyrope component which is depleted with respect to our results.

Our results of the heavy mineral analysis display principal differences in composition of the heavy mineral spectra in the Jurassic sediments of the Pieniny Klippen Belt and the Central Western Carpathians. All the units in the Pieniny Klippen Belt (including Manín Narrows and Klape localities) are garnet-dominated, whereas the Central and Inner Carpathian units are dominated by the most stable heavy mineral group - turmaline, zircon and rutile (Aubrecht, 1993; Aubrecht et al., 1997 and unpublished reports). Moreover, the results of chemical composition of the garnets presented in this paper are in favour of the theory about attribution of the Manín and Klape units to the Oravic domain. The garnet-dominated heavy mineral spectra in the Pieniny Klippen Belt are consistent with those from the Gresten Zone of the Eastern Alps (Faupl, 1975) and from the autochthonous Jurassic cover of the Bohemian Massif below the overthrust Carpathians (Štelcl et al., 1972, 1977). In our opinion, all these domains represent a single heavy mineral province, independent from the Central and Inner Western Carpathians.

Chemical composition of the detrital garnets from the Jurassic sediments of the Central Western Carpathians (Malý Šiprúň, Prašník and Čierťaže) is widely dispersed (Fig. 2 D). They include garnets coming from the greenschist to high-grade amphibolite metamorphic facies (Fig. 3 D), which corresponds well with the West Carpathian metamorphics, e.g. phyllites, mica-schists, gneisses amphibolites and/or amphibolitized eclogites. Just one grain of grossular garnet from the Prašník locality came most likely from an erlan or scarn. The most problematic, however, was a source of three garnet grains from the Malý Šiprúň locality, which reached 35–49 % content of the pyrope component. Rocks with garnets of such a high pyrope content have never been found so far in the Central Western Carpathian crystalline complexes. These detrital garnets are similar to those from the Pieniny Klippen Belt, but they display eclogitic rather than granulitic origin (higher portion of grossular). An explanation can be found, perhaps, in a source placed externally from the Central Western Carpathians. According to Michalík (1994), the Central Western Carpathians were originally situated much more westward opposite to Armoricia in the Triassic-Early Jurassic time. Indeed, there is some exotic material, especially detrital tourmaline grains and tourmalinic rocks which occur in higher amounts in the Mesozoic sediments of the Central Western Carpathians, but are very scarce in the Tatro-Veporic crystalline complexes (Mišík and Jablonský, 1978; Aubrecht, 1994; Aubrecht and Krištín, 1995). The transport directions measured in Permo-Scythian quartzites of the Lúžna Formation in the Malé Karpaty Mts., where even exotic tourmalinic rocks occur, pointed to transport from NW to SE, i.e. from the outer zones inward (Mišík and Jablonský, 1978). The Malý Šiprúň locality represents rocks from the most external Tatric zone, so called Šiprúň Trough. This trough was presumably adjacent to the Penninic domain, i.e. in the Triassic-Early Jurassic time it was situated at the very neigbourhood to the North European Platform at Armoricia (Michalík, 1994). This zone might represent also a source-area of Tatric tourmalinic exotics and the rare eclogitic garnets, too. Another possible source of these garnets may be the remnants of high-grade metamorphics including amphibolitized eclogites in the Tatric crystalline complexes (Hovorka and Méres, 1989, 1993; Hovorka et al., 1990,1992; Janák et al., 1996, 1997; Janák and Lupták, 1997). However, this question deserves a special treatment. Further sampling and analyses are planned to be done in the Tatric Jurassic rocks.

## Conclusions

1. New results of chemical analyses of detrital garnets from the Western Carpathian Jurassic sediments showed that the Pieniny Klippen Belt Units (Oravic units, Manín and Klape units) contain common pyrope-almandine garnets originated in high-grade metamorphic rocks of granulitic and eclogitic character.

2. Their probable source was similar to the Moldanubian Zone of the Bohemian Massif. In our opinion, the Oravic crustal segment was derived from this Hercynian zone. There are, however, some contradictions opposing the Moldanubian origin, such as absence of granulitic pebble-sized detritus in the Oravic sediments and presence of the Permian acid volcanics that are absent in the Moldanubic Zone.

3. Based on our results, Manín and Klape units (Klape Hill) were related to the Oravic crustal segment rather than to the Central Western Carpathians.

4. The samples from the Central Western Carpathians reflect provenance from normal Tatric-Veporic type of crystalline complexes, except three garnet grains found in Tatric Unit coming from eclogites that are of exotic origin. Their source might be located either externally of the Jurassic position of the Central Western Carpathian crustal block or in eclogitic remnants embedded in the high-grade metamorphic complexes of the Central Western Carpathians, such as LACWECA of Hovorka and Méres (1993) and Hovorka et al. (1992, 1994, 1997). However, there are further investigations needed to resolve this problem.

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# Odkiaľ pochádzajú exotické klastické pyropovo-almandínové granáty v jurských sedimentoch pieninského bradlového pásma a tatrika?

Chemické analýzy klastických granátov z jurských sedimentov bradlového pásma a centrálnych Západných Karpát poskytli závažné informácie aplikovateľné v paleogeografickom výskume mezozoika Západných Karpát.

Z bradlového pásma sa analyzovali vzorky liasových hornín z lokality Klapy (klapská jednotka?), Manínska tiesňava (manínska jednotka), Sedliacka Dubová, Lúty potok a Krásna hôrka (všetky nižnianska jednotka). Okrem toho boli analyzované aj vzorky z dogerských lokalít pieninských jednotiek, ako je Hatné (czorsztynská jednotka), Vršatec (czorsztynská jednotka) a Horné Srnie-Samášky (pruská jednotka). Z centrálnych Západných Karpát sa skúmali vzorky z Malého Šiprúňa (tatrikum Veľkej Fatry), Čierťaže (fatrikum Malej Fatry) a Prašníka (nedzovský príkrov, Čachtické Karpaty).

Z analýz vychodia nasledujúce výsledky. Všetky vzorky jurských sedimentov z bradlového pásma obsahovali pyropovo-almandínové, resp. pyropovo-grossulárovo-almandínové granáty s vyšším obsahom pyropovej molekuly (prejavuje sa zvýšeným obsahom Mg), a to 30 až 50 %. Ich zdrojovými horninami boli pravdepodobne granulity a eklogity, ktoré sa však v centrálnokarpatskom kryštaliniku, no ani v priľahlom brunovistuliku nevyskytujú. Ich zdroj predbežne kladieme do oblasti moldanubika Českého masívu, z ktorého sa mohli derivovať kôrové segmenty podložia jednotiek bradlového pásma, a to vrátane manínskej a klapskej jednotky (resp. iba bradla Klapy). Najbližšie výskyty granulitov a eklogitov sa nachádzajú v moldanubiku Českého masívu, asi 130–140 km na Z od dnešných najzápadnejších lokalít pieninského bradlového pásma.

Umiestnenie oravického kryštalinického podložia do moldanubika je však v rozpore s niektorými údajmi z analýzy obliakov z jury jednotiek oravika (Birkenmajer et al., 1960; Krawczyk a Słomka, 1987; Mišík a Aubrecht, 1994), v ktorých sa granulitické ani eklogitické klasty nezistili. Veľa opísaných hornín (napr. rozličné typy rúl, porfýry a pod.) sa v moldanubiku vyskytuje, ale otázka proveniencie týchto jednotiek je stále otvorená.

Pomerne veľa takýchto granátov sa našlo aj vo flyšovom pásme (Otava et al., 1997, 1998). Aj ony signalizujú osobitný zdroj klastík, v ktorom boli podstatne zastúpené granulity, resp. eklogity. Granulity sú časté aj v exotickom obliakovom materiáli zo sliezskej kordiléry (Wieser, 1985), čo svedčí o tom, že aj exotická sliezska kordiléra bola kôrovým segmentom podobným moldanubiku.

Vo vzorkách z centrálnych Západných Karpát sa zaznamenali prevažne granáty zložením blízke granátom z tatrovepορického kryštalinika (prevažne almandinické, v menšej miere grossulárové, príp. spessartínové), ale istým prekvapením boli tri analyzované zrná z Malého Šiprúňa, ktoré tiež majú vyšší podiel pyropovej molekuly. Pravdepodobne pochádzajú z eklogitov exotického pôvodu, azda zo zdroja v jurskom období mimo centrálnych Západných Karpát, v ktorých bol šiprúnsky trog okrajovou zónou. Do tohto zdroja kladieme aj pôvod exotických turmalínických klastík a detritického turmalínu (Mišík a Jablonský, 1978; Aubrecht, 1994; Aubrecht a Krištín, 1995). Potenciálnym zdrojom týchto granátov mohol byť aj spodnokôrový hercýnsky leptynitovo-amfibolitový komplex (LACWECA – Hovorka a Méres, 1993; Hovorka et al., 1992, 1994, 1997), v ktorom sa zistila rula metamorfovaná vo vysokej amfibolitovej až granulitovej fácii a enklávy amfibolitizovaných eklogitov (Hovorka and Méres, 1989, 1993; Hovorka et al., 1990, 1992; Janák et al., 1994, 1996, 1997; Janák and Lupták, 1997). Ale odpoveď na túto otázku môžu dať až ďalšie analýzy z tejto, ako aj z iných lokalít centrálnych Západných Karpát.