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

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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 Klapa (Klapa Unit?), Manin Narrows (Manin Unit), Sedlicecka Dubová, Lúty Potok and Krásna Hôrka (the latter three samples are from the Nová Unit). Along with these samples, Middle Jurassic samples from Hajné (Czorsztyń Unit), Vršatec (Czorsztyń Unit) and Horné Srnie – Samušky (Pruské Unit) were analysed, too. From the Central Western Carpathians, three samples were analysed from localities Molý Šípniak (Tatic Unit of the Veľká Fatra Mts.), Cierža (Krásna nappe, Fatricum of the Malá Fatra Mts.) and Prašník (Nedzov nappe, Hronicium?, Cachtické Karpaty Mts.).

Along with some usual almandine garnets, all the samples from the Pieniny Klippen Belt (including Klapa and Manin 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 the basement crustal segments of the Pieniny Klippen Belt units (including even the Manin and Klapa?) 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 Hysch 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 Tatic-Veporic crystalline complexes were found (predominantly almandine, less grossular or spessartine resp.). They came from the greenschist to high-grade amphibolite metamorphic foci, 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 Molý Šípniak 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 eclogite rather than granulite origin. An explanation can be found, perhaps, in a source placed externally from the Central Western Carpathians as the Molý Šípniak locality represents rocks from the most external Tatic zone, so called Šípniak 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 Tatic crystalline complexes (so-called leptino-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 Mahel, 1986), coming from an independent paleogeographic domain belonging to the Outer Western Carpathians (Czorsztyń, Pruské, Niedzica, Czertezik, Kysuca-Pieniny and some other units), as well as the units of unknown origin, e.g. Klapa, Manin 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 Krístin, 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 under-estimated 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 Czersztyn, Pruské, Nižná, Manín and Klape units of the Pieniny Klippen Belt (the latter represents just Klapy Hill of uncertain position) and Tatran, Krížna and Nedžov 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 Tatran units.)

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 – Oravick units, 7 – Sivenovitz of the Central and Inner Western Carpathians, 8 – Tatric units, 9 – Fatric units, 10 – Veporic Unit, 11 – Ciemric Unit, 12 – Hronic units, 13 – Siliceous units s.l., 14 – Mohalicum, 15 – Tvrnicicum, Zemplitlicum, other units of the Inner Western Carpathians.
The reason of the garnet depletion in the Jurassic deposits of the Central Western Carpathians is unknown. Either an intrastratal dissolution or reevolution from pre-existing older rocks are the most likely possibilities (Aubrecht, 1994, Aubrecht and Krištin, 1995).

The studied localities are as follows:

Localities of the Pieniny Klippfen 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 Červeny Kameň. The sample represents Bajocian white sandy crinoidal limestone (Smolenogova Fm.) with small quartz pebbles in the upper slice of the Čorshzný Unit. The locality was described by Mišík (1979; profile II).

Hatné – a quarry occurring directly at the road connecting Udíča and Horná Maríková villages, near the cemetery of the Hatné village. The sample was taken from red sandy crinoidal limestones of Bathonian age (Krúpianka Fm.) likely belonging to the Čorshzný Unit. The locality was described by Aubrecht and Šykora (1998).

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

Lúty Potok – a conspicuous klippe in the valley of Dlhniansky Ciecky creek (formerly called Lúthy potok), at foot of Vysoký hřebík hill (849 m), W of Křivá 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.

Krášna 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 arcocost sandstones to sandy crinoidal limestones of Sinemurian age.

Sedlcacka Dubová – a conspicuous klippe Skalka behind the local farm. The sample was taken from sandy crinoidal limestones to arcocost 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 olistolith in the flysch of the Klape Unit (Marschalko, 1986). The sample was taken from sandy crinoidal limestone near the top of the hill (likely Tarcian – see Began, 1962).

Localities of the Central Western Carpathians

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

Čierťáž – 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 (Kőpieneck Fm.) of the Krížna Nappe.

Pravník – northern slope of Tlsta hora Hill (426 m), south of Pravník village, near Vrbík. The locality represents one of the remnants of Jurassic sediments of the Nedzov Nappe. An original sedimentary area of this highest nappe (in geological continuation of the Malé Karpathy 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 crystaline complexes (based on published literature: Spišiak and Hovorka, 1984; Mérés and Hovorka, 1989, 1991; Hovorka and Spišiak, 1986; Hovorka et al., 1987, 1990, 1992; Hovorka and Mérés, 1990, 1991; Faryad, 1995; Cambel et 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 Klippfen 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; Mereš and Hovorka, 1989, 1991; Hovorka and Spišiak, 1986; Hovorka et al., 1987, 1990, 1992, Hovorka and Mereš 1990, 1991; Faryad, 1995; Cumbel 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
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 amphibitized ecolites being the probable source-rocks.

From Lúty Potok locality, 11 garnet grains were analyzed. 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-

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mandine, depleted in pyrope (Fig. 2B) and slightly enriched in spessartine component (AI: 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 

**Krášna 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 (AI: 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 **Sedluvca 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 amounts of grossular and nearly no spessartine component (average: AI: 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: AI: 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: AI: 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 **Manin 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 (AI: 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 (AI: 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 homogenous. This fact supports our opinion about their origin in the granulite/eclogite metamorphic facies (Fig. 3C).

**Localties of the Central Western Carpathians**

From **Malý Štiprít** 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 (AI: 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 **Ciertaže** 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-

### Table 3

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<td>MgO</td>
<td>1.3</td>
<td>0.0</td>
<td>8.1</td>
<td>2.2</td>
<td>0.9</td>
<td>13.3</td>
<td>5.9</td>
</tr>
<tr>
<td>CaO</td>
<td>3.1</td>
<td>34.6</td>
<td>2.6</td>
<td>11.8</td>
<td>5.4</td>
<td>6.9</td>
<td>11.1</td>
</tr>
<tr>
<td>Total</td>
<td>100.4</td>
<td>99.5</td>
<td>100.4</td>
<td>101.0</td>
<td>100.4</td>
<td>100.3</td>
<td>99.8</td>
</tr>
</tbody>
</table>

| Pyrope          | 5        | 0    | 31   | 9    | 4    | 49  | 23  |
| Almandine       | 75       | 13   | 60   | 54   | 49   | 32  | 45  |
| Spessartine     | 11       | 1    | 4    | 32   | 1    | 2   | 1   |
| Grossular       | 9        | 86   | 8    | 33   | 16   | 18  | 30  |
garnets are typical for phyllites, mica-schists or, eventually, gneisses.

From Prašnik 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 grossular (5 %) and spessartine (about 10 %). These garnets correspond to high-grade amphibolite to granulite metamorphic facies (Fig. 3D). Their source-rocks might 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 5%).

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 5%).

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.
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 Sfnie-Samisťky, Vršatec, Krásna Hôrka and Klapo 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. Lúčky Potočok, Sedílecká Dubová and Manin 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 Míra, 1989, 1993; Hovorka et al., 1990, 1992; Janáč et al., 1994, 1996, 1997; Janáč and Lupták, 1997). However, the published chemical analyses of garnets from these metamorphic rocks possess pyrope 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 granites, 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 Fedulová, 1974; Missaš et al., 1983; Fiala et al., 1987; O'Brien and Carswell, 1993; O'Brien and Vránka, 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 Śnieżnik area complex – Obere, 1972; Smaliowski, 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 (Ota-
va, 1998) which may provoke a speculation on resedimentation of the Pieniny Klippen Belt garnets from this source. This would lead, 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 cratonic 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 Vašček et al. (1994). The northeastward movement of the Oravice crustal segment after Jurassic would be consistent with the presumed general movement of the Central Western Carpathian segment. However, placing the Oravice segment at the Moldanubic margin contradicts to the data obtained from pebble analysis (Birkenmajer et al., 1960; Krawczyk and Smolka, 1987; Mišik and Aubrecht, 1994). Neither granulitic, nor eclogite detritus has been reported from the Oravice 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 Oravice provenance still remains open.

The common presence of the pyrope-almandine garnets also in the Manin Narrows and Klapa localities is striking. Though the original paleogeographic position of the Manin and Klapa units is uncertain, they are commonly attributed to the Central Western Carpathians. The Manin Unit was considered to be related to the Tatra domain by Andrusov (1938), then to the Pieniny Klippen Belt s.s. by Salaj and Samuel (1966) and later to the Tatra by Mahrer (1978). The Klapa Unit was considered to represent an accretionary wedge in front of, or better along, the overriding Central Western Carpathian plate (Marschalko, 1986; Mišik and Varschalko, 1988; Birkenmajer, 1988; Sořák, 1992). On the contrary, Plàšieczka (1995) stated that Klapa Unit originated in the Tatra sedimentary area and it represents the highest part of the Kráľova Nappe, detached and slid to its present position where it was subsequently tectonically involved into the Pieniny Klippen belt structure. There is also a problem of position of the Klapa Hill itself. This single large Jurassic klippe occurs amidst the Cretaceous flyschs that form the main portion of the Klapa Unit. It is not clear whether it represents a block tectonically involved into this zone (Kysela, 1984) or it is a huge olistolith that slid into the flysch basin from the Andrusov Exotic Ridge (Marschalko, 1986). Anyhow, the data obtained from the Klapa Hill are not automatically valid for the entire Klapa Unit. There were some findings of eclogites among the exotic pebbles in the Klapa Unit but with different composition of garnets (Šimová, 1982; Šimová 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 Manin Narrows and Klapa localities) are garnet-dominated, whereas the Central and Inner Carpathian units are dominated by the most stable heavy mineral group - tourmaline, 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 Manin and Klapa units to the Tatra 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 (Stiel 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 Špičný, Prašník and Cieržáče) is widely dispersed (Fig. 2 D). They include garnets coming from the green schist 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 Špičný 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 Armorica in the Triassic-Early Jurassic time. Indeed, there is some exotic material, especially detrital tourmaline grains and tourmalineic rocks which occur in higher amounts in the Mesozoic sediments of the Central Western Carpathians, but are very scarce in the Tatra-Veporic crystalline complexes (Mišik and Jablonský, 1978; Aubrecht, 1994; Aubrecht and Krištín, 1995). The transport directions measured in Perno-Seythian quartzites of the Lúžna Formation in the Malé Karpaty Mts., where even exotic tourmalineic rocks occur, pointed to transport from NW to SE, i.e. from the outer zones inward (Mišik and Jablonský, 1978). The Malý Špičný locality represents rocks from the most external Tatra zone, so called Špičný Trough. This trough was presumably adjacent to the Penninic domain, i.e. in the Triassic-Early Jurassic time it was situated at the very neighbourhood to the North European Platform at Armoracia (Michalík, 1994). This zone might represent also a source-area of Tatra 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 Tariat crystalline complexes (Hovorka and Měřes, 1989, 1993; Hovorka et al., 1990, 1992; Janáč et al., 1996, 1997; Janáč and Lupták, 1997). However, this question deserves a special treatment. Further sampling and analyses are planned to be done in the Tariat Jurassic rocks.

Conclusions

1. New results of chemical analyses of detrital garnets from the Western Carpathian Jurassic sediments showed that the Piešťany Klippen Belt Units (Oravic units, Manin 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 Moldanubian Zone.

3. Based on our results, Manin 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 Tariat-Veporic type of crystalline complexes, except three garnet grains found in Tariat 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 Měřes (1993) and Hovorka et al. (1992, 1994, 1997). However, there are further investigations needed to resolve this problem.

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Hovorka, D. & Měřes, S., 1991: Pre-Upper Carboniferous gneisses of
Odkud pocházejí exotické klastické pyropovo-almandínové granáty v jurských sedimentoch pienského bradlového pásma a tatríku?

Chemicke analýzy klastických granátů z jurských sedimentů bradlového pásma a centrálních Západních Karpát poskytly závazné informace aplikovatelné v paleogeografickém výzkumu mezozoika Západních Karpát.

Z bradlového pásma sa analyzovali vzorky liasových hornín z lokalit Klapy (klapská jednotka?), Manínska ticháva (manínska jednotka), Sedička Dubová, Lúpy potok a Krásna hôrka (všetky riešianska jednotka). Okrem toho boli analyzovali aj vzorky z dogerských lokalít pienských jednotiek, ako je Hatin (rozsozstovská jednotka), Višatce (rozsozstovská jednotka) a Horné Šmírany (pruská jednotka). Z centrálnych Západných Karpát sa skúmali vzorky z Malého Spišu (tatrská Veľke Fatry), Čierlže (tatrské Malej Fatry) a Prašnika (nedvozovský príkrov, Čachtické Karpaty).

Z analýz vychádza nasledujúce výsledky. Všetky vzorky jurských sedimentov z bradlového pásma obsahovali pyropovo-almandínové, resp. pyropovo-grossulárovo-almandínové granáty s vyšším obsahom pyropovej molekuly (prejavujú sa zvyšeným obsahom Mg), a to 30 až 50 %. Ich zdrojovými horninami boli pravdepodobne granulity a eklogity, ktoré sa však v centrálnokarpatskom krystalínu, no ani v príahrom burovistiku nevyskytujú. Ich zdroj predbežne klademe do oblasti moldanubika Českého masív, z ktorého sa mohli derivovať kórové sedimenty podložia jednotiek bradlového pásma, a to vrátane manínskej a klapskej jednotky (resp. iha bradla Klapy). Najbližšie výsledky granulitov a eklogitov sa nachádzajú v moldanubiku Českého masívu, asi 130–140 km na Z od dnešných najzadápsnejších lokalít pienského bradlového pásma.

Umestnenie oravického krystalínskeho podložia do moldanubiku je však v rozpor s niektorými údajmi z analýzy obliakov z jury jednotiek oravika (Birkenmajer et al., 1960; Krawczyk a Slomka, 1987; Mišák a Aubrecht, 1994), v ktorých sa granulitické ani eklogitické klasty nezistili. Vefa opísaných hornín (napr. rozličné typy rul, porfýry a pod.) sa v moldanubiku vyskytuje, ale otázka proveniencie týchto jednotiek je stále otvorená.


Vo vzorkoch z centrálnych Západných Karpát sa zaznamenali prevážne granáty zložené blízke granátom z tatromorického krystalínu (prevážne almandínové, v menšej miere grossulárové, príp. spessartinové), ale istým prvkom sú tiez lokálovne zaradené granulity a eklogity z centrálnych Západných Karpát, ktoré majú zaujímavé vlastnosti, ktoré sa nesú v súvislosti s tiež zo jurských obdobií. Vznik vzniku pri hranici medzi centrálnymi Západnými Karpátami, v ktorých bol spišský horstok okrajovou zónou, bolo toto zdroja pravdepodobne aj výsledkom eklogitových procesov v exotickom krystalíne, ktoré sa vznikli v úseku materiálnej časti západných Západných Karpát, v ktorom sme pravdepodobne analyzovali napríklad západné časti západných Západných Karpát.