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Bohemian garnet

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Abstract. This study presents the chemical and mineralogical characteristics of garnet currently mined in the České středohoří Mts. for the production of Bohemian garnet jewellery. Pyrope samples from the Podsedice deposit range in colour from the prevalent red pyrope with a brownish hue to the rare dark violet Cr-rich pyrope. Electron microprobe analyses of the red pyrope show a consistent content (mol%) of 74.3–75.1 pyrope, 12.5–13.7 almandine, 4.3–7.2 uvarovite, 1.1–4.0 grossular, and 0.7–0.8 spessartine. Minor components include 0.44–0.77 wt% TiO_2, 0.05–0.10 wt% Na_2O, and 0.05–0.07 wt% V_2O_3. The dark violet pyrope has an elevated chromium content of 3.23–4.25 wt% Cr_2O_3. Both types of pyrope are nearly free of compositional zoning. Pargasitic amphibole, Al-Cr spinel, and iron-nickel sulphide are for the first time identified as minor inclusions in the Bohemian garnet. Pargasite forms sub-oval inclusions, 30 to 60 μm long. The Ca contents in pargasite are notably lower than in ordinary calciferous amphiboles (~1.6 Ca pfu), and the increased Na content indicates approximately 20 mol% of the magnesiotaramite end-member in the amphibole solid solution. The pargasite inclusions provide important petrologic and geotectonic information on the metamorphic state of the ultramafic host-rock prior to garnet crystallization. The red and violet garnets considered in this study generally contain a very limited amount of microscopic inclusions and impurities. Chemical data indicate that this pyrope has been primarily derived from pyrope lherzolites and peridotites in a shallow crustal position.

Key words: Bohemian garnet, chemical composition, mineral inclusions, origin, Podsedice pyrope deposit, Czech Republic

Introduction

The crystalline basement of the České středohoří Mts. is composed of gneisses, migmatites, and granulites with garnetiferous peridotites/lherzolites. Sporadic outcrops, xenoliths in the Tertiary vent breccias, and samples from borehole-drilling (Kopecký and Sattran 1962) have allowed the assessment of the extension and geologic setting of the crystalline rocks in this area, which belong to the Saxothuringian Zone of the Variscan orogenic belt. The abundant peridotites/lherzolites are tectonically emplaced in a shallow subsurface position in the upper crust, directly below sediments of the platform cover.

During the platform evolution of the area, the host rocks of the Bohemian garnet underwent strong weathering and denudation. The pyrope, derived primarily from pyrope-bearing peridotites/lherzolites, was at first deposited in enriched horizons of Carboniferous-Permian sediments, and later redeposited in Upper Cretaceous sediments. All units were subsequently affected by younger volcanic activity. These redeposition processes led to an accumulation of the highest-quality, resistant pyrope grains in Pleistocene fluvial sediments, which are currently mined for this mineral.

The extraction of pyrope, widely known as Bohemian garnet, has taken place in the southwestern part of the České středohoří Mts. mainly during the past two centuries. Among several localities of pyrope-bearing Pleistocene sediments in the area, the Podsedice deposit is the single location exploited at present. Although some reliable microprobe analyses of Bohemian garnet have been published during the past twenty years, mainly in local Czech language publications, and infrequently in journals of a wider circulation (e.g. Schlüter and Weitschat 1991), a more detailed compositional characterization of the currently exploited Bohemian garnet would seem desirable.

The present study provides detailed compositional characteristics of pyrope from the Podsedice deposit. Additionally, analyses of relatively rare and minor inclusions in pyrope have brought unexpected information on pargasite amphibole inclusions. This information is important for the petrologic and geotectonic interpretation of the Variscan history of the host garnet peridotites. This finding warrants a wider examination of pyrope inclusions in the future using a large set of grains, and a related search in peridotite samples from the primary occurrences or xenoliths in the diatreme breccias. Minor Al-Cr spinel and Fe-Ni sulphide are also identified for the first time as inclusions in the local pyrope.

Along another line of interest, the geological background of the two historical diamond finds in the pyrope-bearing gravels is discussed in light of the present knowledge of ultrahigh-pressure rocks in the Bohemian Massif, and in the context of pyrope as a prospecting tool in diamond exploration.

History

Bohemian garnet has been known since the Middle Ages. Two pieces of the oldest known bronze rosette jewels with garnet, from the tenth or eleventh century, were found in the Třebenice village churchyard in 1900 (Götz et al. 1979). The use of garnet in the bishop rings and townsmen crosses is mentioned in the archival records of the Saint Vitus inventory from the fifteenth century. At the same time, garnet was used in the production of a Gothic jewel called the Elisabeth Belt (kept in the town museum of Hradec

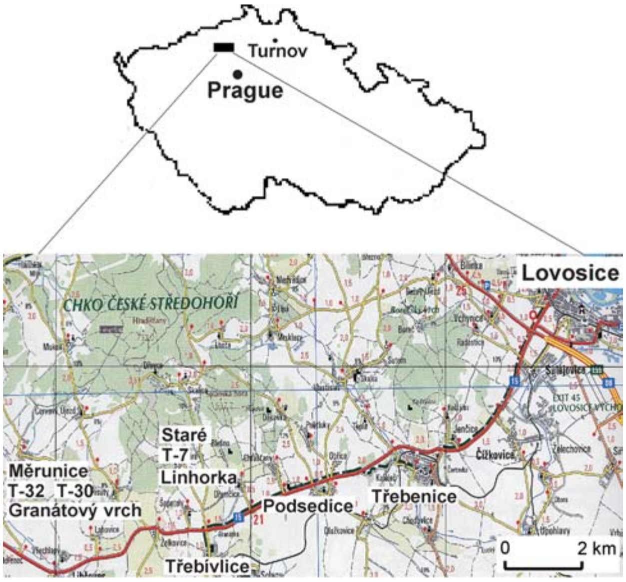

Figure 1. Location of the Podsedice Mine.

Králové), in the relics of Saint Vitus, and Loreta treasures such as Crucifixion, Pacification, Hungarian, and Gothic chalices (Winter 1893). The first written references to Bohemian red garnet (called as granatus or carchedorilus) are known from the sixteenth century (Agricola 1546).

The garnet was first given the name "Granati Bohemici" in the seventeenth century (De Boot 1609). At that time, the centre of garnet mining became the České středohoří Mts. in the surroundings of the Třebenice, Třebívlice, Podsedice, Dlažkovice, and Měrunice localities (Fig. 1), while Prague became the processing centre of the precious stones. The most beautiful garnets can be found in the Emperor Rudolph's collections of rock crystal containers, silver belts, rings, and other golden articles.

During the Baroque era, the processing industry shifted to the town of Turnov, and the whole garnet industry gave employment to about ten thousand people. The favoured faceted shapes were rose-cut, square, oblong, cabochon, and even brilliant, and later also pear, heart, and oval. Bohemian garnet was sometimes combined with locally available peridot or opal.

The greatest prosperity of the Bohemian garnet industry was recorded in Victorian times, in the nineteenth century. New rivet technology enabled the binding of small stones into a compact face, which enhanced the utilization of smaller garnet stones. Bohemian garnet started to be worked in wholesale, and jewellery (including rings, earrings, necklaces, brooches, pendants, diadems, hoods, and souvenirs) became available to the citizens.

A complex of influences caused the decline of the garnet industry in Bohemia during the twentieth century. These included an economic depression, the lower popularity of garnet jewellery, new finds of other pyrope occurrences and other garnet varieties, and disruptions due to wars. After World War II, the political and economic environment was unfavourable for the revival of garnet jewellery. However, small-scale mining continues at present, and a relatively extensive export of garnet jewels from the Granát Turnov Cooperative (Fig. 2) is currently on the rise.

Bohemian garnet and garnet jewellery have been highly esteemed for centuries, and were occasionally used as valuable gifts to important persons such as the Czar Nicholas in 1833, the Crown Prince Rudolph Habsburg in 1871, and a necklace for Sarah Bernhard in 1888. More recently, a garnet set composed of a necklace, bracelet, brooch, and earrings, containing altogether 1280 Bohemian garnets set in 18 ct. gold, was presented to the British Queen Elisabeth II on the occasion of her visit to the Czech Republic in 1990, and a silver cross in a combined setting of Bohemian garnet with local moldavite and rock crystal was presented to Pope John Paul II in 1993.

Zahálka (1884) and Ježek (1912) gave the first detailed account of mineral associations in the pyrope-bearing alluvial gravels, which were subsequently updated by Rost (1962). Hibsch (1920) was the first to realize the origin of pyrope from garnet-bearing basalt breccias. He distinguished three main pyrope-bearing belts on a map at a scale of 1 : 25,000: a western belt near Měrunice, a middle one south of Staré, and an eastern belt near Dřemčice and Chrášťany. Kopecký and Sattran (1962) provided evidence of the serpentinised pyroxene-garnet peridotite as a host rock (source) of the pyrope.

Location and access

The single locality currently being mined for garnet is situated on the western outskirts of Podsedice village, about 10 km southwest of the town of Lovosice. It is accessible from Prague by roads E55 and 15 from the town of Lovosice to Most. The garnet-bearing alluvial sediments occur on the southern slopes of the České středohoří Mts., between Třebenice and Měrunice villages. The owner, Granát Turnov Cooperative, operates the Podsedice mine.

Geological setting

The area is comprised of basement rocks covered by Carboniferous, Mesozoic, and Quaternary sediments, and intruded by Tertiary volcanics. The Litoměřice fault, striking NE-SW, divides the area into a northern block composed of gneisses, migmatites, and granulites with garnetiferous peridotites, and a southern block that shows a lower metamorphic grade of mica schists and phyllites. The northern block belongs to the Saxothuringian Zone of the Variscan orogenic belt.

The primary position of garnet peridotites in the northern block has been verified by boreholes T-7, T-30, and T-32, situated close to the vents near Staré and Měrunice villages. In borehole T-7, garnet peridotites were encountered between the depths of 209 and 436 m, below the platform Cretaceous sediments (Kopecký and Sattran 1962).

Earrings, size 15.5 × 38 mm each.

Brooch, size 36 × 30 mm.

Star brooch, 37 mm in diameter.

Round four-layer brooch (with large central almandine), size 38 × 33 mm.

Figure 2. Examples of Bohemian garnet jewellery set in 22 ct gold-plated silver, manufactured by the Granát Turnov Cooperative.

Two main types of peridotite can be distinguished: peridotite with abundant orange-red, dark red pyrope, and peridotite with violet pyrope (Kopecký in Fiala 1965). The first type is characterized by a fine-grained, dark green groundmass consisting of olivine, clinopyroxene, orthopyroxene, and amphibole, with pyrope grains 2–4 mm in size and of a dark red colour, and light orange-red coloured pyrope phenocrysts up to 2 cm in size, which are often cracked. The second type contains scattered grains of violet pyrope up to 2 cm in size, in a groundmass composed of olivine, with accessory orthopyroxene and clinopyroxene (Sattran in Fiala 1965).

Serpentinised garnetiferous peridotites are found as isolated, minor lens-shape bodies (with true thicknesses up to a few hundred metres) enclosed in felsic granulites that grade into granulite gneisses and migmatites (Kopecký and Sattran 1962, 1966). Their association is evidenced by angular xenoliths of pyrope peridotite in the granulites (boreholes T-30 and T-32), and by granulite rafts (borehole T-7) enclosed in peridotite (Kopecký and Sattran 1966). Kopecký and Sattran (1966) assumed that both rocks originated in a considerably deep zone where a granulite mass could be intimately associated with intrusions of peridotite. They are accompanied by less frequent ultrabasic and eclogitic rocks. According to Kopecký and Paděra (1974) the peridotites have a layered structure characterized by alternation of the predominant garnet lherzolites with wehrlites and dunites, mostly also carrying garnet. The thickness of the eclogitic rock layers varies between several cm up to tens of metres. The eclogitic rocks occur in the form of small lenses, layers, and inclusions, the largest being encountered at a depth of 408–415 m. An eclogite at a depth of 420 m is present as a 5 cm thick layer with a distinct boundary to the surrounding peridotite (Fiala and Paděra 1984). This eclogite/peridotite contact shows no signs of contact reaction and gives an impression of equilibrium between both rocks. Eclogites (at 209, 404 and 420 m depths) are characterized by round, brown-red garnet grains up to 1 cm in size (the average size is 2 mm) in the green-grey mass of pyroxene. Kopecký and Sattran

(1962) and Fiala (1965) described fragments of eclogitic rocks in the marginal parts of the garnet peridotite (borehole T-7).

The area of the České středohoří Mts. contains a Tertiary volcanic complex. Its origin is associated with a deep-seated fault zone trending NE-SW. The diatremes usually contain older tuffitic breccias composed of angular to rounded country rock xenoliths, ranging in size from 60 cm to only a few cm, set in a fine-grained matrix comprised of carbonate and clay minerals in the near-surface parts. The younger phase produced massive basaltic rocks, which penetrate the older breccias.

The serpentinised pyroxene-pyrope peridotites are also known as xenoliths from two occurrences of the Tertiary vent breccias (Granátový vrch and Linhorka hills). They are accompanied at the Linhorka vent by sporadic xenoliths of eclogitic rocks composed of diopside-omphacite, garnet, minor plagioclase, quartz, and accessory rutile (Kopecký and Sattran 1962).

Mining, production and recovery

Agricola (1546) and Reuss (1838) gave first written data concerning the pyrope mining of Quaternary deposits. In the eighteenth century the primary deposits were found in the volcanic breccias at Granátový Hill near Měrunice village, and in the Linhorka Hill by Staré village. These were mined by shafts sunk to a depth of 60 m. The primitive mining methods were not economical, and production ceased at the end of nineteenth century.

Since that time the mining of pyrope has been only focused on the pyrope-bearing sediments of Pleistocene age. Local miners sunk a pit about 5 m into the layer of pyrope-bearing gravel and drove side tunnels along the productive zone in every direction for about 5–10 m, leaving only small security pillars behind. The size fraction over 3 mm was collected and the pyrope was sorted by hand. There is no information on the extension and production of pyrope mining at that time. The mining was carried out randomly throughout the garnet-bearing territory, and it had not been controlled until 1959 when the government took over the mining rights.

In the 1970s the area's pyrope potential was systematically explored by shallow boreholes, trenches, and pits (Götz and Turnovec 1975). It was found that economic quantities of pyrope had accumulated only in the Pleistocene sediments, and that more than 60% of the productive layers had already been mined out. The remaining reserves of pyrope were estimated at 800 tons, however the economically viable reserves are considerably lower, currently reaching about 8 tons.

Current mining operations at the Podsedice locality cover an area of approximately 1.5 ha. Clayey sediments that originated during the Quaternary interglacial weathering period separate two productive gravel horizons at the mine. The upper horizon, of highly variable thickness, occurs at a depth of 2–2.5 m (on average 15–20 cm). The lower gravel horizon is found at 5 m depth, showing laterally variable thicknesses ranging from a few tens of cm up to 1.5 m (on average 40 cm, see Fig. 3). The productive horizons differ from the other sediments by their dark colour with white carbonate patches. The garnet-bearing gravel horizons are covered by 3–5 m of barren hanging wall composed of fine-grained, brown-yellow, clayey sediments.

Approximately 210 tons of gravel is mined per day, with average garnet content of 12.5 grams per ton, i.e. a daily garnet production of 2.6 kg. The productive material is processed in a nearby treatment plant. The material is sieved using 20 cm and 6 cm screens. The fraction under 6 cm is processed by rotor washer and conveyed to a screening sorter. The productive size fraction of 2 to 8 mm is run through a system of jigs for density separation. The top size is transported to a stockpile while the undersized fraction is pumped directly back to the worked-out mining site. Altogether, about 99% of the processed material goes back to the mine. After the technical and subsequent biological recultivation and remediation, the mining site is returned to the landowner.

The bulk concentrate is sent to the Granát Turnov Cooperative for hand grading. The concentrate of the 2 to 5 mm size fraction contains on average 19% garnet. Of this, about 65% of the garnet grains are of adequate grade for faceting, the rest being characterized by many inclusions, fissures, unusable shapes, or corroded surfaces. Garnet occurs only sporadically in the 5 to 6 mm

Figure 3. The currently mined Podsedice open pit.

size fraction. The residual concentrate material is mostly comprised of chips of pyroxene-olivine basalt rocks with some accessory heavy minerals.

Since the early 1990s the small-scale mining of another alluvial pyrope deposit in the Vestřev locality (50 km east of Turnov) has sorted 60 tons of gravel per day, with an average pyrope recovery of 18 grams per ton.

These are currently the only two areas in the Czech Republic approved by the state for the exclusive mining of Bohemian garnet by the Granát Turnov Cooperative.

Composition of the Bohemian garnet

Samples and methods

The samples analysed for this study were obtained in 2003 from concentrate at the Granát Turnov treatment plant at Podsedice. Rounded garnet grains, including some broken pieces (bulk sample of 47 grams), show a prevalent dark red colour with a very slight brownish hue. Chromium-rich pyrope garnets of a dark violet colour are rare (less than 2% of the lot). Individual garnet grains, 3–5 mm in diameter, were selected from the concentrate, mounted in resin, cut and polished. A preliminary examination was carried out under a polarizing microscope in reflected light. This observation permitted the accurate location of rare mineral inclusions in the garnet. A total of six red garnet grains and three violet grains have been analyzed. Several grains were analyzed along profile lines consisting of 10 to 20 spots located at regular intervals. The analyses were conducted using a CAMECA SX 100 (15 kV, 10 nA) WDS electron microprobe at Masaryk University, Brno, Czech Republic. Natural minerals of known composition were used as standards for Cr (chromite), Mg, Al, Si (almandine), Fe, Ca (andradite), Na (jadeite), and Mn (rhodonite).

Chemical composition

The compositional homogeneity of the Podsedice garnets is supported by the present analyses of profile lines. The chemical compositions of 7 selected grains are documented by individual spot analyses in Table 1 and Fig. 4. In addition to major elements (Si, Al, Mg, Fe, Ca), the new analyses present the first extensive and accurate database of the contents of Ti, Cr, Na, and V. The relations of minor components Na_2O, TiO_2, Cr_2O_3 and CaO, based on 61 analyses, are shown in Fig. 5. The analyses with relatively high CaO and Cr_2O_3 correspond to the violet, chromium-rich pyrope. Nickel abundances are below or equal to the detection limit, and vanadium contents are also low (0.05–0.06 wt.% V_2O_3).

Due to their high-temperature equilibration, pyrope garnets from peridotites, lherzolites, and related ultramafic rocks in the Bohemian Massif are usually free of compositional zoning, with the exception of a narrow rim modified by decompression reactions with the olivine-rich matrix (Medaris et al. 1990). However, the outer rims seem to be absent in the detrital and abraded garnets. This is not surprising, as the pyrope rims, affected by diffusion during cooling in their host rocks, are usually only 50 µm wide (Medaris et al. 1990).

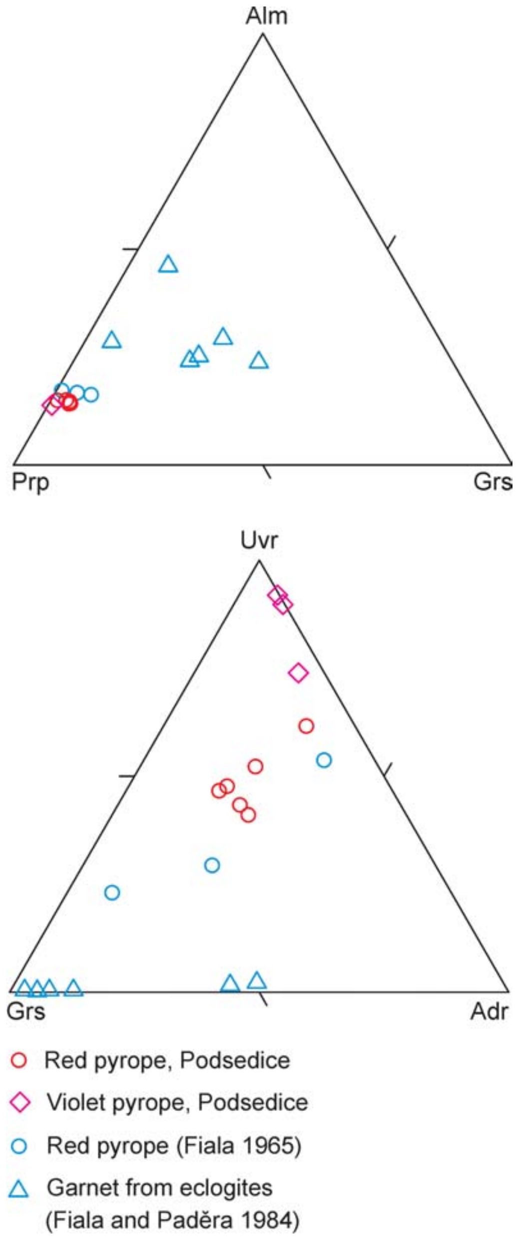

Figure 4. Comparison of pyrope composition from the Podsedice deposit (red and magenta symbols) with published analyses of pyrope and eclogitic garnet from primary occurrences (blue symbols).

Physical properties of the pyrope

The pyrope colour varieties in the peridotites from the T-7 borehole (Fiala 1965) show a refractive index (RI) of 1.740–1.744 and specific gravity (SG) of 3.688–3.704 for orange-red pyrope, RI = 1.748, SG = 3.718 for red pyrope, and RI = 1.765, SG = 3.720 for violet pyrope. Pyropes from the Carboniferous sediments in the Tř-1 borehole display RI = 1.745 and SG = 3.704 for orange-red pyrope, RI = 1.747 and SG = 3.710 for red pyrope, and RI = 1.762 and

Table 1. Representative analyses of pyrope from the Podsedice locality

Mineral	Red pyrope				Violet pyrope		
Grain	11	12	13	23	31	32	33
Analysis No.	12c**	22c	25r	38c	42c	64c	75c
SiO_2	42.66	43.10	42.57	42.88	42.78	42.86	42.93
TiO_2	0.66	0.49	0.48	0.53	0.45	0.39	0.32
Al_2O_3	21.55	21.81	21.15	21.94	20.08	20.21	20.70
Cr_2O_3	1.60	1.86	2.52	1.75	4.07	4.08	3.30
V_2O_3	0.05	0.05	0.06	0.05	0.05	0.06	0.05
FeO*	9.09	8.48	8.87	8.53	8.00	8.10	8.04
MnO	0.32	0.35	0.37	0.33	0.33	0.33	0.31
MgO	20.65	20.88	20.82	21.13	20.65	20.61	20.84
CaO	4.31	4.42	4.52	4.46	4.99	4.89	4.94
Na_2O	0.09	0.06	0.05	0.08	0.05	0.05	0.03
Total	100.98	101.48	101.40	101.68	101.43	101.57	101.46
Number of ions (8 cats.)							
Si	3.012	3.021	3.000	3.001	3.020	3.022	3.020
Al	1.797	1.804	1.761	1.813	1.674	1.683	1.720
Ti	0.035	0.026	0.025	0.028	0.024	0.021	0.017
Cr	0.089	0.103	0.140	0.097	0.227	0.227	0.184
Fe^{3+}	0.059	0.041	0.065	0.055	0.049	0.042	0.052
Fe^{2+}	0.477	0.456	0.457	0.445	0.423	0.436	0.421
Mn	0.019	0.020	0.022	0.019	0.020	0.020	0.018
Mg	2.173	2.182	2.187	2.204	2.173	2.167	2.186
Ca	0.326	0.332	0.341	0.334	0.378	0.370	0.372
End-members (mol%)							
Alm	13.53	13.16	13.32	13.01	10.85	11.52	11.99
Sps	0.65	0.70	0.76	0.66	0.69	0.68	0.63
Prp	74.64	74.77	74.33	74.96	75.36	75.01	73.81
Grs	3.54	3.95	1.13	3.66	0.00	0.00	0.66
Adr	3.05	2.12	3.32	2.78	1.30	0.99	2.66
Uvr	4.59	5.30	7.14	4.93	11.8	11.80	9.40

* all iron given as FeO
** c and r denote core and rim position of the analysis, respectively

SG = 3.722 for violet pyrope (Fiala and Kopecký 1964). The continuous series from red to violet colour demonstrates the close linkage between colour, Cr_2O_3 content, and RI (Fiala 1965). Schlüter and Weitschat (1991) examined six representative pyrope grains from the concentrate in the Podsedice locality. RI ranged from 1.748 to 1.750, three samples displayed anomalous birefringence, and all were inert to UV radiation.

Light coloured garnets accompanying red pyrope in the Pleistocene sediments show various rose and yellow-brown tints (Králová and Bauer 1960). X-ray analysis has identified the garnet as pyrope with an elementary cell dimension a_0 = 11.540 Å, which is close to the value for red pyropes from the primary peridotite xenoliths in the Linhorka Hill. An average of three measurements gave RI = 1.789 and SG = 4.147 for oval grains of light-rose pyrope, and RI = 1.773 and SG = 4.149 for yellowish pyrope.

Mineral inclusions in garnet

In the present article pargasitic amphibole, chromium-aluminium spinel, and iron-nickel sulphide are for the first time identified as minor inclusions in the Bohemian garnet. Bauer and Králová (1960) studied zircon inclusions in pyrope from Podsedice; however, no zircon has been detected among inclusions in our material.

Pargasite forms sub-oval inclusions, 30 to 60 μm long, in three garnet grains (Fig. 6a). One Cr-rich violet pyrope contained more than 10 pargasite inclusions located at a distance of approximately 1/3 of the grain radius from the surface. Pargasite analyses are presented in Table 2, and the numbers of Ca and Na atoms per formula unit (pfu) are shown in Fig. 7. The Ca contents are notably lower than in ordinary calciferous amphiboles (~1.6 Ca pfu), and the increased Na content indicates approximately 20 mol% of the magnesiotaramite end-member (Leake et al. 1997) in the

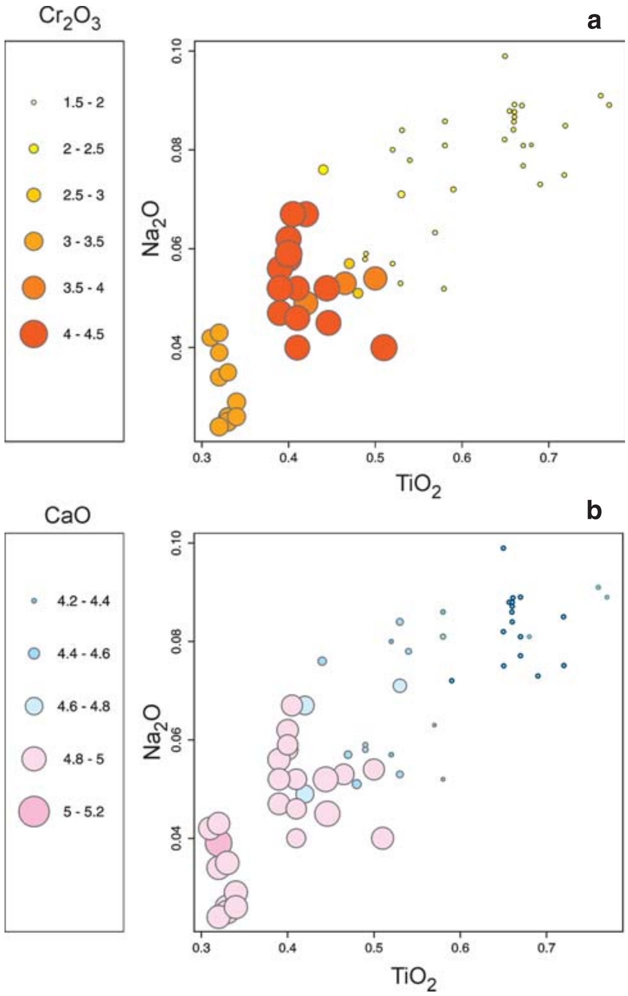

Figure 5. a – comparison of Cr_2O_3 content with TiO_2 and Na_2O variation in the analysed pyrope. b – comparison of CaO content with TiO_2 and Na_2O variation. A third variable, Cr_2O_3 and CaO, respectively, is shown by the size of the circles.

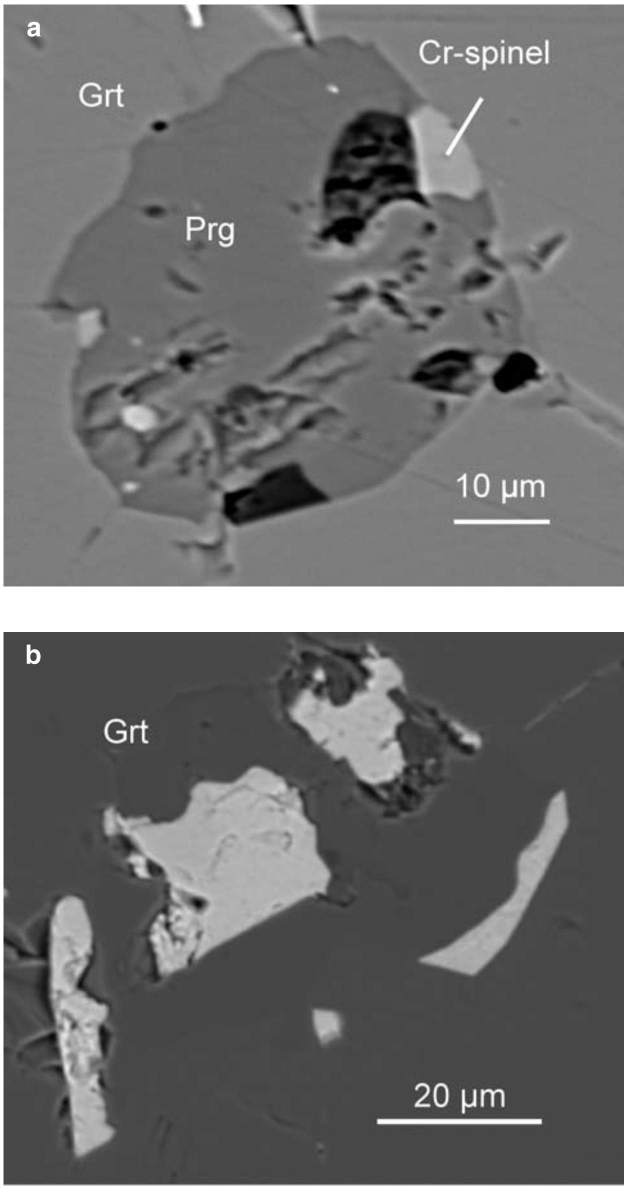

Figure 6. a – pargasite-amphibole inclusion in the violet Cr-rich pyrope. b – Fe-Ni sulphide inclusions in the violet Cr-rich pyrope. Grt – garnet, Prg – pargasite.

amphibole solid solution (Fig. 7, Table 2). The chlorine content determined in two spot analyses was 0.27 and 0.28 wt%, while the fluorine content was below the detection limit. This indirectly shows that the amphibole contains significant (OH) groups. The numbers of ions for pargasite (Table 2) are calculated without the low chlorine content. The pargasite inclusions may provide important petrological and geotectonic information on the metamorphic state of the ultramafic host-rock prior to garnet crystallization.

Al-Cr spinel has been identified as a minute inclusion associated with pargasite (Fig. 6a). The iron-nickel sulphide with Fe/Ni ratio near unity forms a small cluster of inclusions enclosed in garnet (Fig. 6b). The studied red and violet garnet generally contains only minor microscopic inner inclusions and impurities.

Discussion and conclusions

Analytical data

The new analytical data provide the compositional characteristics of the pyrope currently mined at the Podsedice deposit. They document the prevalent red pyrope used in jewellery and a minor component of Cr-rich violet pyrope, which is not utilized in jewellery due to colour distinction.

Electron microprobe analyses of the red pyrope (6 grains, 39 analyses) show a consistent content (mol%) of 74.3–75.1 pyrope, 12.5–13.7 almandine, 4.3–7.2 uvarovite, 1.1–4.0 grossular, and 0.7–0.8 spessartine. Minor components include 0.44–0.77 wt% TiO_2, 0.05–0.10 wt% Na_2O, and 0.05–0.07 wt% V_2O_3. The dark violet pyrope has an elevated chromium content of 3.23–4.25 wt% Cr_2O_3.

In comparison of both varieties, the violet pyrope shows twice the Cr_2O_3 content, a higher CaO content, lower FeO_{tot} and TiO_2 contents, and half Na_2O content compared to red pyrope, while the contents of MgO, MnO, and V_2O_3 are almost the same. The NiO and Y_2O_3 contents were under the detection limit.

An approximately linear dependence between Na_2O

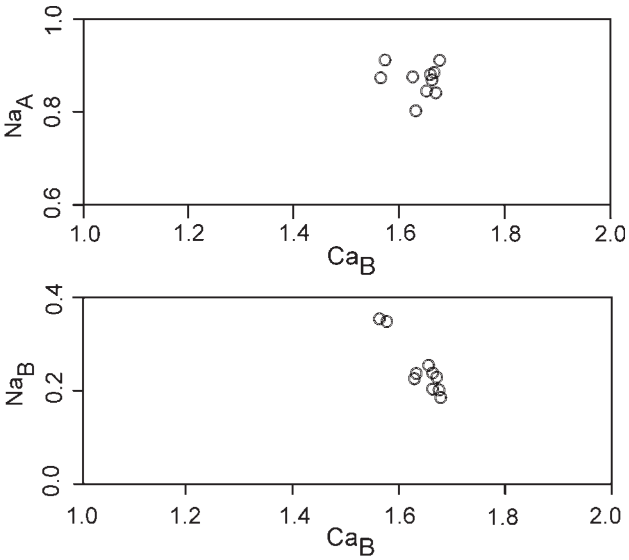

Figure 7. Occupancy of B and A sites in pargasite by Ca and Na ions.

and TiO_2 contents in the analyzed set of garnets is shown in Fig. 5.

An attempt to correlate the newly obtained data with published information on pyrope composition in crustal ultramafic and eclogitic rocks of upper mantle derivation from primary occurrences (mainly boreholes) in northern Bohemia (Fig. 4) shows that information on primary samples (Fiala 1965, Fiala and Paděra 1984) is as yet too limited. The most extensive analytical set of 170 pyrope grains from Carboniferous sandstones in the Staré region (near Podsedice) and more than 50 pyrope crystals from peridotite xenoliths in the Linhorka diatreme (Chopin and Sobolev 1995) indicates a chromium range of 1.1 to 8.6 wt% Cr_2O_3, CaO content between 3.7 and 6.6 wt%, and 1.5–11.1 wt% of Cr_2O_3 with 3.5–7.6 wt% of CaO, respectively. These data show a significantly wider range of pyrope composition in the general area of the Variscan crustal garnet ultramafic rocks in northern Bohemia, than that predominating at the Podsedice deposit. This is in agreement with the known variability of pyropic garnet compositions in similar rocks in other parts of the Variscan fold belt, such as in western Moravia in the Czech Republic (Medaris et al. 1990, Medaris et al. 2003). It also probably indicates a relatively confined source of pyrope in the Podsedice deposit.

No eclogitic garnets, characterized by elevated almandine and grossular components (Fig. 4), have been detected in the course of work on the Podsedice garnet samples. This may be due to the relatively small proportion of eclogites in comparison to that of the peridotites/lherzolites, and possibly also to the lesser resistance of these garnets to chemical weathering in detrital accumulations.

Diamond association with the Bohemian garnet

Two diamonds have been found in the waste of the garnet concentrates. The first one, from the area around Dlažkovice village, was found in 1869, and is 4.13 by 2.63 mm in size (0.2865 ct). A second diamond found near Chrášťany village is 3.00 by 2.60 mm. Both specimens are kept in the mineralogical collection of the National Museum in Prague. Ježek (1927) described the history of the study of these stones. Bouška et al. (1993) conducted an X-ray diffraction study, and described the details of their surface morphology and luminescence in ultraviolet light (366 nm). The two pieces, light lemon yellow and grey-yellow in incandescent daylight, show an anomalous grey-orange luminescence. This behaviour is different from that of ordinary diamonds from kimberlite-related deposits, which show luminescence at a higher wavelength in yellow and blue to violet colours. Bouška et al. (1993) noted that the luminescence properties are similar to impact-related diamonds, but the size of the stones, the absence of associated lonsdalite, and the absence of microcrystalline aggregate structure make an association with an impact improbable.

The compositional similarity between Bohemian garnet and pyrope from kimberlites, the textural similarity of basaltoid vent breccias in the České středohoří Mts. to

Table 2. Representative analyses of pargasite and Al-Cr spinel

Mineral	Pargasite		Spinel
Analysis No.	51	53	44
SiO_2	43.22	43.99	0.06
TiO_2	0.67	0.84	0.04
Al_2O_3	15.80	17.12	40.60
Cr_2O_3	1.73	0.97	28.19
V_2O_3	0.06	0.06	0.02
FeO*	2.07	1.98	10.45
MnO	0.08	0.02	0.07
NiO	0.02	0.04	0.00
ZnO	n.d.	n.d.	0.24
MgO	18.07	17.82	18.41
CaO	10.99	10.45	0.00
Na_2O	3.77	4.50	0.00
K_2O	0.55	0.56	0.00
H_2O**	2.11	2.15	–
Total	99.06	100.40	98.10
Number of ions	(16 cats.)		(6 cats.)
Si	6.138	6.139	0.003
Al	2.645	2.816	2.692
Ti	0.071	0.088	0.002
Cr	0.194	0.107	1.254
Fe^{3+}	0.000	0.000	0.043
Fe^{2+}	0.246	0.231	0.448
Mn	0.010	0.002	0.003
Zn	–	–	0.010
Mg	3.826	3.707	1.544
Ca	1.672	1.563	0.000
Na	1.038	1.218	0.000
K	0.099	0.099	–
OH**	2.000	2.000	0.000

* all iron given as FeO
** H_2O calculated from stoichiometry

breccia structures in kimberlite, plus the two diamond finds indicated to some geologists a significant similarity in the mode of geological occurrence (Ježek 1927, Kopecký 1961).

In early 1960s an intensive prospecting programme for diamonds was conducted in Tertiary volcanics and Quaternary sediments of the České středohoří Mts. in co-operation with specialists from VSEGEI-Russia (Kopecký et al. 1967). The results of that investigation, which included detailed geologic mapping, boring, and geophysical research, were interpreted as indicating some similarity between the pyrope-bearing diatremes of northern Bohemia and the diamond-bearing kimberlitic rocks of Yakutia in Siberia, but the final results were negative. Potužák and Novotný (1969) subsequently reprospected the České středohoří Mts. for diamondiferous gravels. Washing and screening to 0.5–1 mm, 1–2 mm, and 2–4 mm fractions, those authors processed two bulk samples of 200 and 250 tons from the Podsedice garnet deposit. The final concentrates were treated by an X-ray fluorescence separator and passed over a greased shaking table. However, no diamonds were found.

Detailed knowledge of the composition of several indicator minerals as diamond-prospecting tools has dramatically progressed during the past 40 years (Fipke et al. 1995). With the present level of knowledge, it is possible to say that the prospecting campaign of the 1960s in the České středohoří Mts. was directed toward an unpromising target. This follows from detailed differences in pyrope composition between those of the České středohoří Mts. and those in diamond-bearing kimberlites (Fig. 8). The most significant data set in this respect was published by Chopin and Sobolev (1995). It includes Cr_2O_3 and CaO contents in 170 garnet grains from Carboniferous sandstones, and a large number of grains from peridotite xenoliths in the Linhorka diatreme. The Cr_2O_3/CaO ratios all plot within the field of crustal garnet peridotites (Fig. 8).

Several studies during the previous century (Ježek 1927, Kopecký et al. 1967) repeatedly failed to appreciate the fact that garnet peridotite xenoliths in basaltoid breccias of the České středohoří Mts. are derived from peridotites located in a shallow subsurface position of the upper crust (Kopecký and Sattran 1966). In effect, the basaltoid breccias may be free (or nearly free) of garnet peridotite brought up directly from a deeper mantle lithosphere during the Neogene volcanism. It should be emphasized that the abundant pyropic garnet occurs in the České středohoří Mts. as a detrital mineral in certain horizons of Carboniferous-Permian and Upper Cretaceous sediments derived from the Variscan crystalline basement, i.e. in sediments older than the Tertiary basaltoid volcanism (Fig. 9). In contrast, in kimberlite provinces pyropic garnets (and diamonds) were brought to the surface from abyssal sources by kimberlite pipes.

The ultimate source and origin of the rare diamonds associated with the Bohemian garnet remain unknown. The manual processing of large volumes of detrital material during the nineteenth-century garnet mining was probably the decisive factor in finding the two specimens. Several

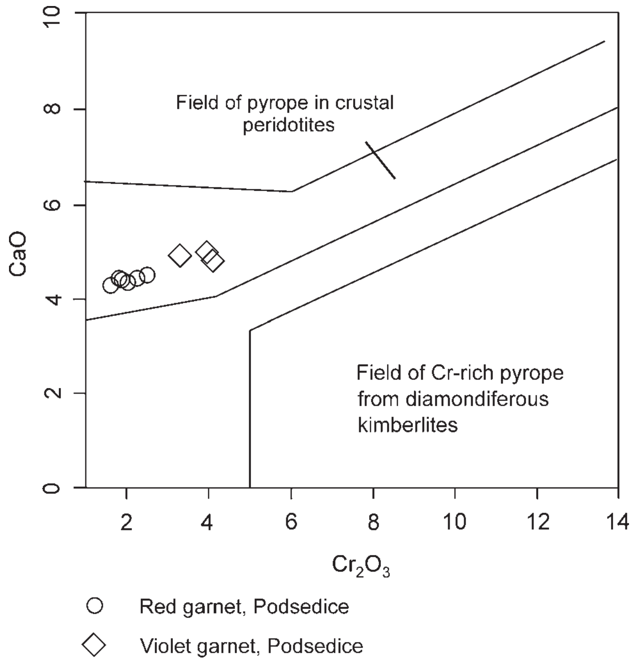

Figure 8. Plot of analysed pyrope garnets in Cr_2O_3 vs. CaO diagram. The upper field corresponds to pyrope from crustal ultramafic rocks (Chopin and Sobolev 1995). The lower field of high Cr/Ca ratio corresponds to pyrope from diamondiferous kimberlites.

potential sources of the rare diamonds can be considered: (a) some garnet peridotite slices in the Variscan crustal structure may have sampled a deeper domain of mantle lithosphere that contained rare diamonds; for instance, Massonne and Bautsch (2002) suggested the tectonic derivation of some ultramafics in Saxony from a mantle level ca 400 km deep; (b) microdiamonds occur as a relatively common accessory mineral in some ultrahigh-pressure garnet-quartz-feldspathic gneisses in Saxony (Nasdala and Massonne 2000); (c) it is difficult to exclude the possible presence of kimberlite or lamproite pipes of unknown age within the wider area, possibly hidden below the platform sedimentary cover. Finally, the uncertainty also includes possible fluvial transport, as a fraction of the Bohemian garnet did pass through Carboniferous and Upper Cretaceous redeposition cycles (Fig. 9).

Pyrope in diamond exploration

The application of modern exploration techniques reflects the success of increasing diamond production over the last 20 years. However, the appropriate laboratory equipment has not been available to us. The most widely used technique is the monitoring of trace elements contained in indicator heavy minerals, which permit an assessment of the diamond potential of the source. The Cr-pyrope garnet is one of the most common minor minerals in ultramafic rocks, and is regarded as a key indicator mineral in exploring and assessing diamond potential (Fipke et al. 1995).

The newly developed Ni-thermometer (Griffin et al. 1989) is based on the partitioning of Ni between chromium pyrope garnet and olivine in garnet peridotite xenoliths from kimberlites, while the "Cr barometer" is based on the

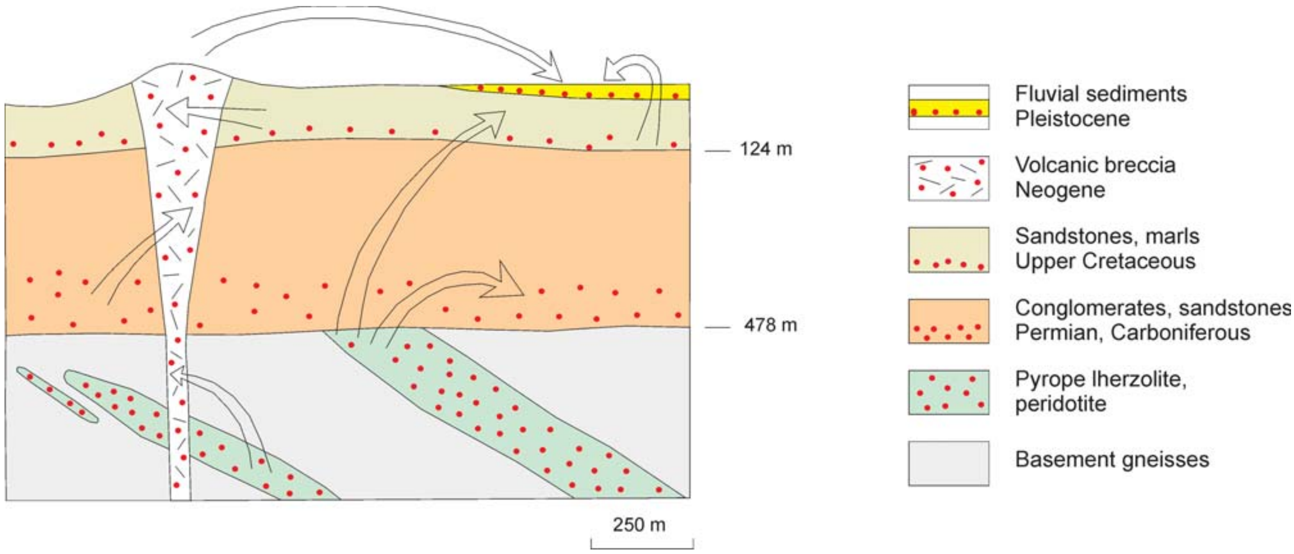

Figure 9. A schematic section showing redeposition of pyrope derived primarily from pyrope lherzolite and peridotite in a shallow crustal position. The geological situation is based on drill hole data (Kopecký and Sattran 1966). The routes of pyrope (red dots) redeposition, indicated by arrows, are schematic and condensed from information compiled throughout a wider area.

partitioning of Cr between garnet and orthopyroxene in equilibrium with chromite (Griffin and Ryan 1995; Ryan et al. 1996). Both methods give estimates of the local paleogeothermal and thermobarometric conditions at the depth of origin of single pyrope grains. They are currently widely used for obtaining information about the economic potential of diamond-bearing source rocks.

Griffin et al. (1999) examined the major- and trace-element composition of more than 12,600 Cr-pyrope xenocrysts (Cr_2O_3 > 1 wt%) in volcanic rocks to evaluate their compositional ranges and elemental relations. They found that the Cr content of garnet is a primary indicator of the degree of depletion of the host rock, that the prominent Ca-Cr correlation ("lherzolite trend") seen in garnets from clinopyroxene-bearing rocks is controlled primarily by the Cr/Al of the host rock, and that Ca shows a strong negative association with Mg. The ion mass spectrometry method has been applied to the study of mantle-derived xenoliths and xenocrysts from the intruding mid-Tertiary hypabyssal minettes and ultramafic breccias of Proterozoic crust in the Colorado Plateau (Roden and Shimizu 2000). This method has shown that typical garnet xenocrysts derived from shallow, low temperature peridotites are light REE depleted, have relatively high Y abundances and low Zr and Ti abundances, and are characterized by relatively low Zr/Y and high Al/Cr ratios, consistent with the lherzolitic source, while garnets from the higher temperature garnet peridotites tend to have lower Al/Cr and higher Zr/Y ratios indicating their derivation from relatively fertile source rock.

The significance of the Bohemian garnet data for the petrology and geotectonics of peridotites in the Bohemian Massif

Pyrope crystallization in ultramafic rocks of the Bohemian Massif has been interpreted either as occurring from a melt under upper mantle conditions, or as a consequence of high-pressure reactions that consume spinel in cases such as when tectonic processes bring a hot peridotite slab into contact with cooler rock masses, e.g. granulites (Medaris et al. 1990). Neither of these scenarios, nor a third model presented by Schmädicke and Evans (1997), involves a stage of hydrous amphibole crystallization predating the growth of pyropic garnet. Our data seem to be the first record of amphibole inclusions in pyrope in the Bohemian Massif. These data probably indicate a stage of low to moderate temperature metamorphic reactions in the host-rock peridotite prior to pyrope crystallization, and probably the prior involvement of peridotite in crustal tectonic processes. Such ultramafic rocks may be comparable to the class of IIAi prograde peridotites of Brueckner and Medaris (2000) or to type B garnet peridotites with a previous crustal history (Zhang and Liou 1998). The pargasite inclusions may thus provide important petrological and geotectonic information on the metamorphic state of the ultramafic host-rock prior to garnet crystallization. In a strict sense, such a scenario is applicable only to the pyrope grains with pargasite inclusions. A next step should be a search for primary occurrences of garnet peridotites with this type of pargasite-bearing pyrope.

The Al-Cr spinel identified as a minute inclusion associated with pargasite (Fig. 6a) has $Mg/(Mg+Fe^{2+}) = 0.775$ and $Cr/(Cr+Al) = 0.318$. These values correspond closely to those of typical spinel inclusions in the pyrope of garnet peridotites (Medaris and Jelínek 2004). This relation may suggest that the spinel probably does not reflect processes responsible for the crystallization of the associated pargasite.

The iron-nickel sulphide with Fe/Ni ratios near unity, probably pentlandite, forms a small cluster of inclusions positioned directly in the garnet (Fig. 6b).

Bauer and Králová (1960) studied zircon inclusions in one of the largest pyrope stones (12.3 × 8.6 mm;

2.64 grams) from this locality. They classified zircon inclusions into three groups according to their habit, which suggest the complicated evolution of zircon in the parent peridotite. Bauer (1966) described three morphologic types of zircon inclusions (up to 0.57 mm) and Cr-diopside inclusions in pyrope. However, no zircon has been detected among the inclusions in our material.

The fact that pargasitic amphibole, chromium-aluminium spinel, and iron-nickel sulphide are identified for the first time as minor inclusions in the Bohemian garnet indicates a rich potential for the further study of these inclusions.

Outlook for Bohemian garnet mining at other localities in the Czech Republic

Another location at which Bohemian garnet is presently mined is the village of Vestřev, near Trutnov in northeastern Bohemia (Řídkošil et al. 1997). Pyrope is extracted from Quaternary alluvial gravels at this locality. The local pyrope source is comprised of Carboniferous sandstones, from which garnet was released by weathering. One important aspect indicated by the Vestřev deposit is that the particular geological setting with Tertiary volcanics in the České středohoří Mts. (i.e., the Podsedice deposit) is in no way a unique condition for significant accumulations of detrital pyrope. Additional occurrences of pyrope in alluvial sediments, probably not always economic, have long been known, including locations near Kolín and Jičín towns in central and northeastern Bohemia. This situation indicates that there are additional sources of this mineral. Future exploitation may largely depend on factors such as labour cost, landscape and environmental protection interests in addition to the commercial aspects concerning the Bohemian garnet jewellery.

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References

Agricola G. (1546): De Natura Fossilium. Froben, Basel.

Bauer J. (1966): Inclusions in garnets of ultrabasic and granulitic rocks in the Northern tract of the Bohemian Massif. Krystalinikum 4, 11–18.

Bauer J., Králová M. (1960): Zircon inclusions in pyrope – contribution to study of genesis of the Bohemian pyrope. Sborník VŠCHT, Fac. of Inorganic and Organic Technology 4, Part 1, 319–324 (in Czech).

Bouška V., Skála R., Frýda J. (1993): Czech diamonds. Geol. Průzk. 35, 6–10 (in Czech).

Brueckner H. K., Medaris L. G. (2000): A general model for the intrusion and evolution of mantle garnet peridotites in high-pressure and ultra-high-pressure metamorphic terranes. J. Metamorph. Geol. 18, 123–133.

Chopin C., Sobolev N. V. (1995): Principle mineralogic indicators of UHP in crustal rocks. In: Coleman R. G., Wang X. (eds) Ultra-high-pressure metamorphism. Cambridge University Press, Cambridge, 1–32.

De Boot A. B. (1609): Gemmarum et lapidum Historia. Prague.

Fiala J. (1965): Pyrope of some garnet peridotites of the Czech Massif. Krystalinikum 3, 55–74.

Fiala J., Kopecký L. (1964): A genetic study of pyrope and other garnets in the Tertiary volcanic breccia at the Velký vrch and Malý vrch hills near Třtěno. Věst. Ústř. Úst. geol. 39, 267–272 (in Czech).

Fiala J., Paděra K. (1984): Eclogitic rocks from the basement of the České středohoří Mts. Krystalinikum 17, 33–45.

Fipke C. E., Gurney J. J., Moore R. O. (1995): Diamond exploration techniques emphasizing indicator mineral geochemistry and Canadian examples. Geological Survey of Canada, Bulletin 423, 1–86.

Götz B., Turnovec I. (1975): Perspectives of the Bohemian garnet occurrence of the southwestern part of the České Středohoří Mts. Sbor. Hornická Příbram, G-16, 285–306 (in Czech).

Götz B., Turnovec I., Urbanec J. (1979): Garnets of the České Středohoří Mts. A monographic study of the Regional Museum in Teplice 17, Teplice (in Czech).

Griffin W. L., Cousens D. R., Ryan C. G., Sie S. H., Suter G. F. (1989): Ni in chrome pyrope garnets: a new geothermobarometer. Contr. Mineral. Petrology 103, 199–202.

Griffin W. L., Ryan C. G. (1995): Trace Elements in Indicator Minerals: Area Selection and Target Evaluation in Diamond Exploration. J. geochem. Explor. 53, 311–337.

Griffin W. L., Fisher N. I., Friedman J., Ryan C. G., O'Reilly S. Y. (1999): Cr-pyrope garnets in the lithospheric mantle. I. Compositional systematics and relations to tectonic setting. J. Petrology 40, 679–704.

Hibsch J. E. (1920): Geologische Karte des Böhmischen Mittelgebirges, Blatt 14 (Meronitz-Trebnitz). Wien.

Ježek B. (1912): Olivine and pyrope from the environs of Jičín. Příroda 11, 32 (in Czech).

Ježek B. (1927): On diamond finds in Bohemia. Horn. Věst. 9, 433–437, 461–466 (in Czech).

Kopecký L. (1961): Study of kimberlites and intrusive pyrope-bearing ultramafic rocks in the Bohemian Massif and its perspectives. Geol. Průzk. 3, 33–37 (in Czech).

Kopecký L., Paděra K. (1974): Bänderung der ultramafitischen Gesteine in der Bohrung T-7 Staré bei Třebenice (Nordböhmen). Minerogenesis. Bulgarian Academy of Sciences (Geological Institute), Sofia, 161–169.

Kopecký L., Píšová J., Pokorný L. (1967): Pyrope-bearing diatremes of the České středohoří Mountains. Sbor. Geol. Věd, geol., 12, 81–130.

Kopecký L., Sattran V. (1962): On the genesis of pyrope in the České středohoří Mts. Věst. Ústř. Úst. geol. 37, 4, 269–283 (in Czech).

Kopecký L., Sattran V. (1966): Buried occurrences of pyrope-peridote and the structure of the crystalline basement in the extreme SW of the České středohoří Mountains. Krystalinikum 4, 65–86.

Králová M., Bauer J. (1960): Light-coloured garnets from pyrope-bearing gravels in the České středohoří Mts. Sbor. VŠCHT, Faculty of Inorganic and Organic Technology 4, Part 1, 285–294 (in Czech).

Leake B. E. et al. (1997): Nomenclature of amphiboles: Report of the Subcommittee on Amphiboles of the International Mineralogical Association Commission on New Minerals and Mineral Names. Mineral. Mag. 61, 295–321.

Massonne H.-J., Bautsch H.-J. (2002): An unusual garnet pyroxenite from the Granulitgebirge, Germany: Origin in the transition zone (> 400 km depth) or in a shallow Upper Mantle region? Int. Geol. Rev. 44, 779–796.

Medaris L. G., Jelínek E. (2004): The Mohelno peridotite: a fragment of suboceanic mantle in the Náměšť granulite. Int. workshop on petrogenesis of granulites and related rocks, Náměšť nad Oslavou, Czech Republic, 13–16.

Medaris L. G. Jr., Wang H. F., Jelínek E., Jakeš P. (2003): Garnet peridotite in the Moldanubian Zone in the Czech Republic – a heat source for the Variscan metamorphism? J. Czech Geol. Soc. 48, 92–93.

Medaris L. G. Jr., Wang H. F., Mísař Z., Jelínek E. (1990): Thermobarometry, diffusion modelling and cooling rates of crustal peridotites: two examples from the Moldanubian zone of the Bohemian Massif. Lithos 25, 189–202.

Nasdala L., Massonne H.-J. (2000): Microdiamonds from the Saxonian Erzgebirge, Germany: in situ micro-Raman characterization. Eur. J. Mineral. 12, 495–498.

Potužák V., Novotný J. (1969): Verification of diamond presence in pyrope bearing gravels of the České středohoří Mts. Sbor. geol. Věd, Technolog. Geochem. 9, 59–80 (in Czech).

Reuss A. E. (1838): Über das Vorkommen des Pyrops in Böhmen. Karstens Archiv für Mineralogie, Geognosie, usw., 298–314.

Roden M. F., Shimizu N. (2000): Trace element abundances in mantle-derived minerals which bear on compositional complexities in the lithosphere of the Colorado Plateau. Chem. Geol. 165, 283–305.

Rost R. (1962): Supplements to the mineralogy of pyrope-bearing gravels in the České středohoří. Čas. Mineral. Geol. 7, 4, 407–417 (in Czech).

Ryan C. G., Griffin W. L., Pearson N. J. (1996): Garnet geotherms: Pressure-temperature data from Cr-pyrope garnet xenocrysts in volcanic rocks. J. geophys. Res. – Solid Earth 101 (B3), 5611–5625.

Řídkošil T., Langrová A., Kašpar P. (1997): A gemmological study of pyrope from Podsedice and Vestřev. Sbor. OMČR Turnov, 47–51 (in Czech).

Schlüter J., Weitschat W. (1991): Bohemian Garnet – Today. Gems and Gemology, 168–173.

Schmädicke E., Evans B.W. (1997): Garnet-bearing ultramafic rocks from the Erzgebirge, and their relation to other settings in the Bohemian Massif. Contrib. Mineral. Petrology 127, 57–74.

Winter Z. (1893): The history of Bohemia, Moravia and Silesia regions. Vol. 2. Praha (in Czech).

Zahálka Č. (1884): Nerosty z pyropových ložisek v Českém středohoří. Vesmír 13, 172.

Zhang Ru. Y., Liou J. G. (1998): Dual origin of garnet peridotites of Dabie-Sulu UHP terrane, east-central China. Episodes 21, 229–234.