Three types of skarn in the northern part of the Moldanubian Zone, Bohemian Massif – implications for their origin

Tři typy skarnů v severní části moldanubika a způsoby jejich vzniku

(15 figs, 7 tabs)

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The Holšice regionally metamorphosed Cpx-Grt skarn occurs in the north of the Moldanubian zone, Bohemian Massif. Several new skarn bodies were found by detailed mapping in the vicinity, and three different kinds of skarns were distinguished. The Holšice skarn consists of Cpx-Grt, and calc-silicate gneiss bands (cm). The garnet zoning reflects the post-peak metamorphic decompression after HP/HT regional metamorphism probably at approx. 800 °C and 12 kbars. The Zliv skarn is massive, and contains magnetite (high anomalies in magnetometry) without calc-silicate gneiss. Its Grt-Cpx, Cpx, Grt-Amp and Amp skarn types are poor in Al (hedenbergite, andradite, ferro-actinolite, cummingtonite). Grossular-almandine rich garnet from the Grt-Amp skarn equilibrated at 670 °C, 6–8 kbars (Grt-Amp geothermometry). The third type of skarn (Vápenka) occurs as a narrow contact zone (only 4–8 cm wide) between marble and orthogneiss and contains sulphides, scheelite and spessartine-rich garnet. The analysed minerals from the narrow skarn zone yielded high $\delta^{18}O$ values, which are compatible with the isotopic composition of the orthogneiss. On the other hand, the $\delta^{18}O$ values found in the Holšice and Zliv skarn bodies are not compatible with the hypothesis of originally contact metasomatic origin associated with metagranitoid rocks in the studied area, which have an isotopic composition of 6–10 ‰ $\delta^{18}O$. This fact also suggests that the hypothesis of skarn precursors as an integral part of the (volcano-) sedimentary series remains valid for these Moldanubian localities.

Key words: skarn; metamorphism; oxygen and carbon isotopes; Moldanubicum; Bohemian Massif

Introduction

Skarns of the Bohemian Massif occur in high-grade metamorphic units: in the Moldanubicum, the Kutná Hora-Svratka units, in the Saxothuringicum, and in the Lugicum. Majority of these skarns have been affected by high-grade Variscan regional metamorphism, which obscures their original pre-metamorphic nature. Their origin has been explained basically by two opposing hypotheses:

– contact metasomatic replacement of limestones associated with magmatic intrusions or migmatitization (*e. g.* Reh 1932, Koutek 1950, Zemánek 1959, Němec 1960, 1963, 1964, 1991, 1996, Lorenz – Hoth 1967, Žáček 1997, Šrein – Šreinová 2000), or by Ca metasomatism of basic rocks (rodingites) (Rötzler – Mingram 1998), followed by regional metamorphism, or
– sedimentation of Fe-Ca-rich units (Hinterlechner 1907, Zoubek 1946, Götzinger 1981), sedimentation combined with seafloor pseudohydrotermal alteration (Lange 1962, Klomínský – Sattran 1963), or sedimentation combined with exhalative activity (*e. g.* Pertold – Pouba 1982, Kotková 1991, Pertold *et al.* 1997, Pertoldová *et al.* 1998), followed by regional metamorphism.

The aim of this paper is to report on the presence, composition and metamorphic history of three skarn occurrences at Holšice and to contribute to the discussion of their pre-metamorphic precursors. On the basis of geological situation, bulk geochemistry, mineral composition, metamorphic history, and isotopic composition we are trying to contribute to the widely discussed problem of skarns in the Bohemian Massif.

Geology of the Holšice area

The skarns studied are located in the northern part of the Moldanubian Zone, in the Variegated Group (Drosendorf Unit) (according to Synek – Oliveriová 1993). Other authors assign the area to the Gföhl Unit (*e. g.* Matte *et al.* 1989, Neubauer – Handler 2000). For geological situation and localization of the Holšice area see Fig. 1.

The area studied in detail (see Koutek 1952, Drahota *et al.* 2000, Drahota 2001), is formed by biotite-sillimanite paragneiss and by an orthogneiss body accompanied by migmatites. The complex is intercalated with layers and bands of skarns, quartzite gneisses, and abundant calc-silicate rocks, which contain sporadic marbles. These rock bands strike predominantly in the east-west direction and their thickness varies from metres to tens of metres. Metabasite only occurs as small and rare intercalations in calc-silicate rocks. However, many larger amphibolite bodies and some serpentinized peridotite

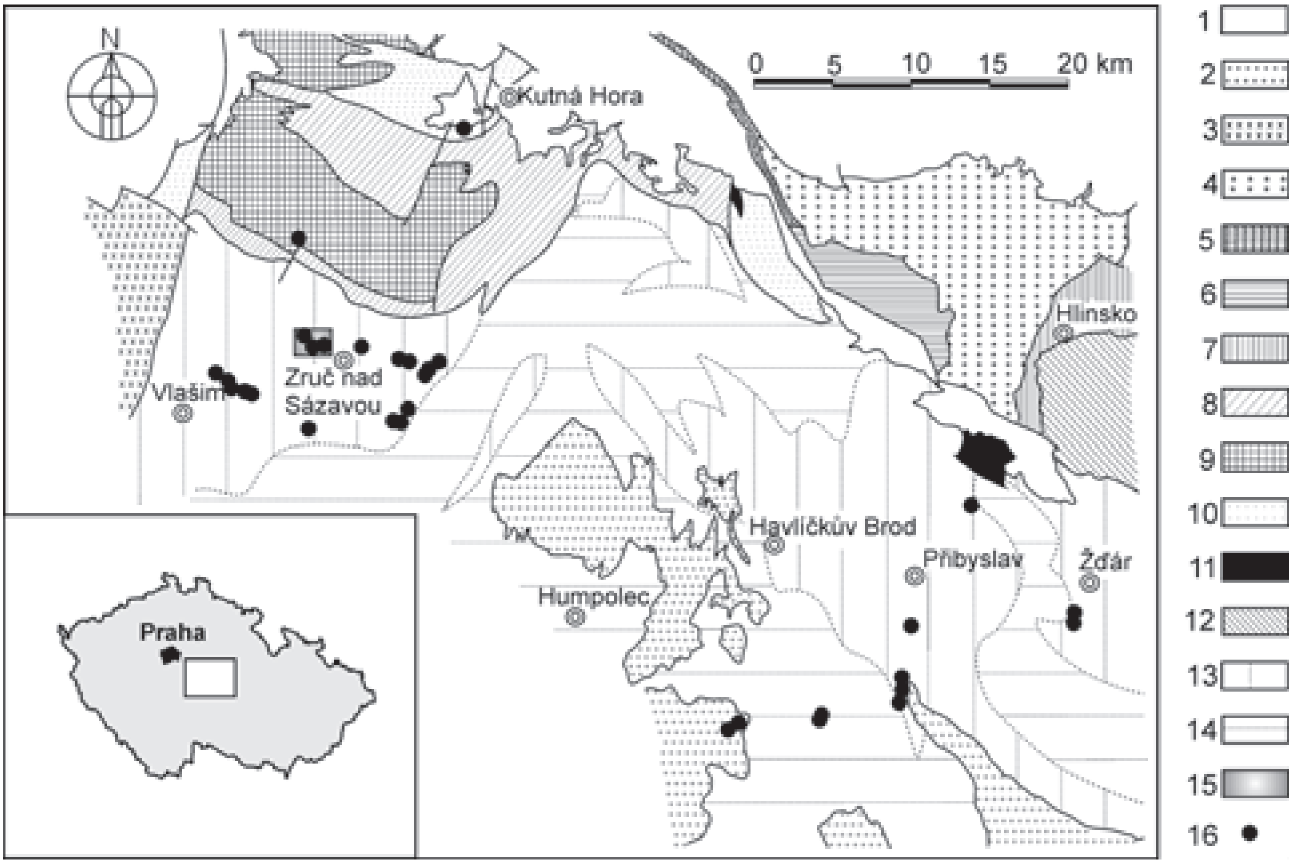


Fig. 1. The occurrence of regionally metamorphosed skarns in the northern part of Moldanubicum and neighbouring crystalline complexes. 1 – Permian-Cretaceous sedimentary cover; 2 – Moldanubian Pluton; 3 – Central Bohemian Pluton; 4 – Železné Hory Pluton; 5 – Podhořany crystalline complex; 6 – Oheb crystalline complex; 7 – Hlinsko zone; 8 – mica schist zone; 9 – Kouřim nappe; 10 – Gföhl nappe; 11 – large ultrabasic bodies; 12 – Svratka crystalline complex; 13 – Variegated Group of Moldanubicum; 14 – Monotonous Group of Moldanubicum; 15 – area studied; 16 – skarn bodies (after Synek – Oliveriová 1993).

bodies are exposed about 2 kilometres west, near the town of Kácov. A leucocratic two-mica Kácov orthogneiss (Němec – Páša 1986), probably of Variscan age, covers a large portion of the area. Its normative Q-Or-Ab composition is close to the low-pressure isobaric thermal minimum of the system; it is homogeneous, without evidence of magmatic differentiation and corresponds to S-type granites. Transition to rocks of paragneiss appearance, along with the presence of relics of para-material, suggests close relation of these gneisses with the orthogneiss. Some contacts could be intrusive or tectonic. Details of the orthogneiss chemistry are given in Table 1 and in the chapter on the relationship of igneous rocks to skarn types.

Skarn rocks

Three types of skarn occurrences were distinguished in the area of interest (Fig. 2), according to their geological position and petrological, mineralogical and isotopic compositions. The whole-rock chemistry is presented in Tables 1 and 2 and the isotope composition is given in Table 6. The first type of skarn, which was originally described by Koutek (1952), consists of several bodies located in a calc-silicate layer in the footwall of the Kácov orthogneiss body (Fig. 2). Skarn rocks form layers and lenses in calc-silicate gneiss and together with them they form the Holšice skarn body. The second type of skarn is represented by an isolated skarn body near Zliv, first described by Drahota *et al*. (2000). The third type represents a small skarn band at the Vápenka site.

Holšice skarn body

The skarn rocks at Holšice form several bodies, elongated in the E-W direction to a distance of 700 m. Their width is very variable, with 30–36 m in the central part, which, with a medium dip of 30–55°, indicates a maximum true thickness of about 25–30 m. The skarns are completely surrounded by migmatized biotite paragneiss that forms a several-metre thick zone in their hanging wall, separating them from the Kácov orthogneiss. Typical characteristics of this skarn occurrence are its association with amphibole calc-silicate gneiss, banded structure, and uniform mineral composition.

The dominant rock of the Holšice body is banded calc-silicate gneiss (Fig. 3, Table 1), consisting particularly of feldspar, quartz, garnet, pyroxene and amphibole, with titanite, minerals of hisingerite-neotocite group, epidote, zircon and apatite as minor and accessory minerals (Fig. 4).

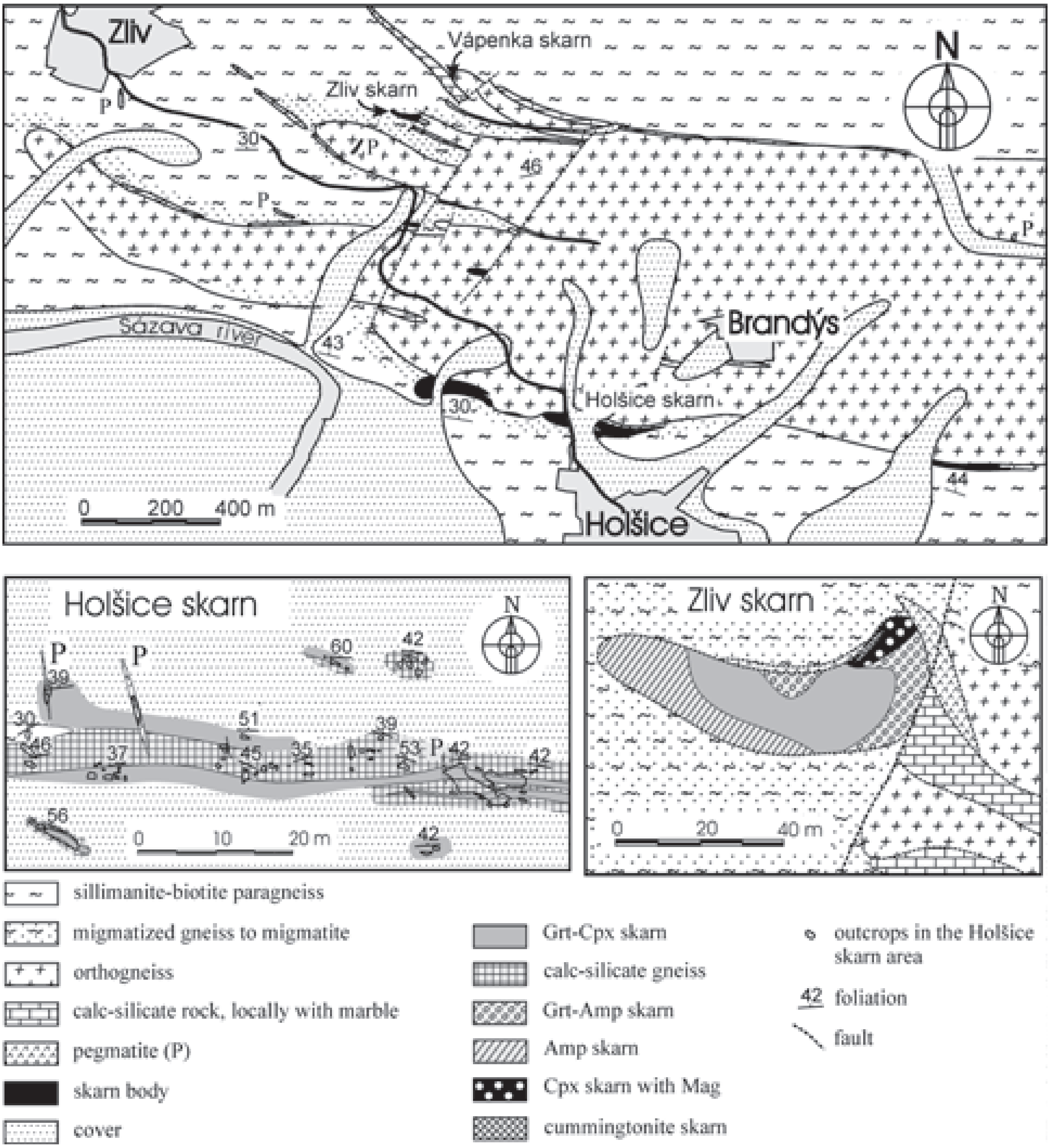


Fig. 2. Location and geologic setting of the Holšice, Zliv and Vápenka skarn occurrences (after Drahota 2001).

The Grt-Cpx skarn forms several-dm thick layers and lenses enclosed in the lighter-coloured calc-silicate gneiss. Their contacts are typically sharp (Figs 3, 4). Banded garnet-pyroxene skarn (Table 2) is locally penetrated by mm-cm wide quartz-plagioclase veins with pyroxene. Quartz, epidote and titanite occur as accessory minerals in Grt-Cpx skarn. Ore minerals have not been found and ground magnetometry excluded the presence of substantial quantities of magnetite or pyrrhotite inside the body.

Zliv skarn body

The Zliv body represents a typical Ca-Fe skarn with ore mineralization, which has also been confirmed by magnetometry. The skarn body is approximately 80 m long and 25 m wide, and occurs in migmatized paragneisses, close to one of the apophyses of the orthogneiss body (Fig. 2). It is also associated with calc-silicate rocks, but they have an entirely different chemical (more Ca, Mg, less SiO_2, alkalies – see Table 1), mineralogical and isotopic com-

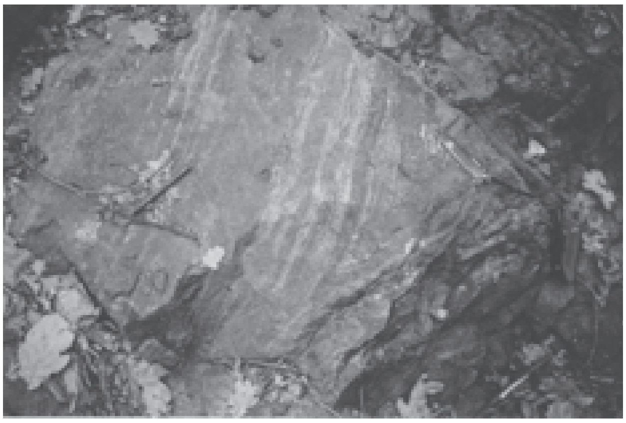


Fig. 3. Banded and folded skarn, Holšice (photo). Light and dark bands represent garnet-rich and clinopyroxene-rich skarn, respectively. Scale is indicated by knife.

Fig. 4. Contact between Grt-Cpx skarn (dark) and calc-silicate gneiss (light) from Holšice skarn body. The sample is 10 cm long.

Table 1. Major element composition of metamorphic rocks from the studied area. See Fig. 2 for sample location.

Rock Type	paragneiss with Grt	Bt-Ms orthogneiss	Bt orthogneiss	Ms-Bt orthogneiss	amphibolite	calc-silicate rock – Zliv	calc-silicate gneiss – Holšice skarn body	calc-silicate gneiss – Holšice skarn body
Sample	**31**	**48**	**56 (B6)**	**44**	**17**	**41**	**13c**	**6c**
SiO_2	68.00	76.96	75.48	74.98	48.72	48.80	67.52	61.00
TiO_2	0.57	0.11	0.13	0.20	1.25	0.64	0.55	0.67
Al_2O_3	12.74	12.42	12.41	12.26	15.27	11.46	9.18	7.78
Fe_2O_3	2.45	0.80	1.46	2.21	2.87	1.91	2.63	3.76
FeO	5.27	0.07	0.56	0.31	7.87	4.40	5.25	9.73
MnO	0.17	0.01	0.09	0.02	0.18	0.45	0.23	0.42
MgO	1.88	0.22	0.34	0.89	8.13	5.71	1.72	1.69
CaO	1.03	1.09	0.74	0.39	9.58	19.90	7.51	12.00
Na_2O	3.01	3.60	2.63	2.47	3.48	1.99	2.79	1.42
K_2O	3.20	3.31	5.42	3.96	0.46	0.63	1.57	0.32
P_2O_5	0.06	0.24	0.16	0.10	0.11	0.19	0.14	0.20
H_2O^+	1.08	0.77	0.52	1.67	1.77	1.29	0.66	0.89
H_2O^-	0.14	0.02	0.12	0.24	0.14	0.08	0.12	0.18
CO_2	0.00	0.05	0.13	0.00	0.03	2.16	0.01	0.03
Total	99.60	99.67	100.19	99.70	99.86	99.61	99.88	100.09

Table 2. Chemical composition of skarn rocks studied.

Rock Type	Grt-Cpx skarn	Grt-Cpx skarn with Mag	Grt-Amp skarn	Amp skarn with Cpx	Cum skarn	Grt-Amp skarn
Locality	**Holšice**	**Zliv**	**Zliv**	**Zliv**	**Zliv**	**Vápenka**
Sample	**6a**	**27 (B8)**	**68 (B7)**	**66 (B5)**	**21.00**	**57.00**
SiO_2	49.22	37.38	38.06	44.98	50.50	43.86
TiO_2	0.43	0.13	0.96	0.32	0.24	1.41
Al_2O_3	8.09	0.33	17.69	3.52	1.07	18.01
Fe_2O_3	6.07	27.84	5.54	11.28	4.42	4.35
FeO	12.86	3.59	19.76	19.24	31.38	7.95
MnO	0.99	0.45	0.64	1.24	0.94	0.64
MgO	1.66	0.51	2.46	4.86	8.46	3.75
CaO	19.23	28.83	9.87	11.12	1.07	10.04
Na_2O	0.45	0.17	0.77	0.54	0.20	0.20
K_2O	0.09	0.03	0.58	0.22	0.06	3.55
P_2O_5	0.13	0.12	0.82	0.19	0.09	0.30
H_2O^+	0.69	0.49	2.25	1.51	1.36	3.31
H_2O^-	0.28	0.20	0.26	0.56	0.16	0.32
CO_2	0.00	0.19	0.17	0.40	0.08	1.89
Total	100.19	100.26	99.83	99.98	100.03	99.58

position (Table 7). In addition, they are probably separated from the skarn body by faults (Fig. 2) (based on Very Low Frequency method). The skarn is characterised by the occurrence of markedly Al-poor and Fe^{3+}-rich rocks (Table 2) and a considerable petrographic heterogeneity.

Similarly to other skarn localities of the Bohemian Massif (Němec 1991), the oldest metamorphic association at Zliv consists of andradite and hedenbergite with minor magnetite in the massive garnet-pyroxene skarn, which occurs particularly in the central part of the skarn body (Fig. 2). This rock gradually passes into granoblastic garnet-amphibole skarn or amphibole skarn towards the margins of the skarn body. Along with garnet of almandine-grossular composition and amphibole replacing pyroxene, this mineral association is enriched in small amounts of quartz, ilmenite and plagioclase. Magnetite mineralization is bound mainly to the massive pyroxene skarn and partly to local cummingtonite skarn. These two types of rocks are simple in mineral composition with only scattered grains of magnetite. These rocks have been found in the area of the magnetometric maximum in the eastern part of the body, where cummingtonite skarn is probably present in the form of layers or veins in association with pyroxene skarn. In very rare cases, garnet-amphibole gneiss was found as a several cm thick reaction rim between the garnet-amphibole skarn and the surrounding migmatites. Small size of the reaction rim indicates that the effect of the metamorphic fluid (probably connected with migmatization of surrounding gneisses) on the rocks of the Zliv skarn body was very limited, in contrast to other skarn bodies of the Bohemian Massif (*e. g.* formation of the Vlastějovice hybrid rocks – "pseudodiorites", Koutek 1959).

Several pegmatite dykes are located in the immediate vicinity of the Zliv skarn body. They apparently penetrated along faults and lithologic boundaries. No contamination processes, such as those described by Koutek (1959) and Drahota *et al.* (2000) at Holšice, were observed at the pegmatite-skarn contacts.

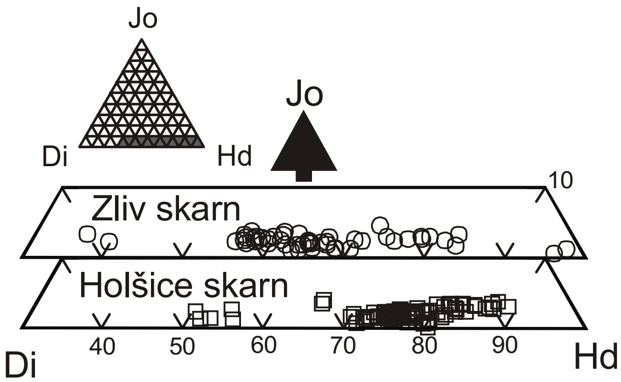
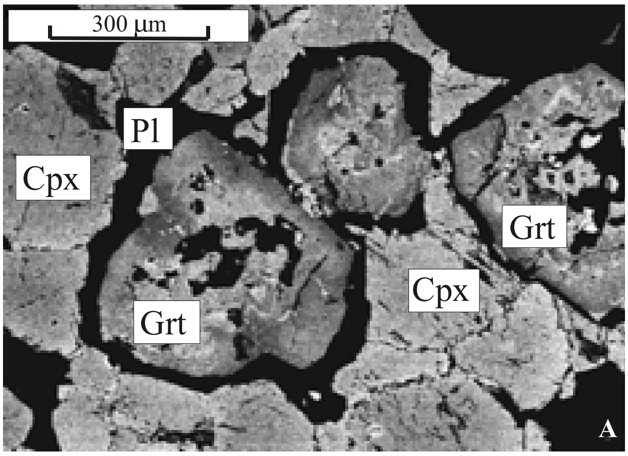


Fig. 5. Composition of pyroxene from Zliv and Holšice skarns in the ternary plot johannsenite-diopside-hedenbergite.

Table 3. Representative chemical analyses of pyroxenes.

	calc-silicate gneiss		Grt-Cpx skarn						Cpx skarn with Mag		Amp skarn with Cpx
Location	**Holšice**	**Holšice**	**Holšice**	**Holšice**	**Holšice**	**Zliv**	**Zliv**	**Zliv**	**Zliv**	**Zliv**	**Zliv**
Sample	**1/5**	**2/9**	**14/72**	**24/149**	**25/155**	**4bc261**	**B1-8**	**E1-25**	**26a321**	**26a326**	**5bc342**
SiO_2	48.58	48.27	47.43	48.90	51.75	50.85	51.75	51.43	51.22	51.55	51.66
TiO_2	0.11	0.13	0.21	0.18	0.15	0.35	0.00	0.10	0.00	0.00	0.15
Al_2O_3	1.73	1.68	2.08	1.97	0.79	0.11	0.25	1.49	0.00	0.00	0.37
FeO_{total}	24.15	23.72	24.42	21.86	16.73	24.18	18.80	13.75	20.43	20.46	19.49
MnO	0.46	0.54	0.17	1.16	0.41	0.70	0.61	0.86	0.86	0.53	0.88
MgO	3.36	3.55	2.90	5.05	8.21	2.61	6.04	8.75	4.97	4.44	7.04
CaO	21.15	21.52	22.70	21.01	22.16	21.34	21.89	22.33	20.99	21.63	19.56
Na_2O	0.35	0.44	0.21	0.48	0.55	1.08	1.44	1.51	1.77	1.94	1.07
Total	100.01	99.97	100.12	100.61	100.75	101.31	101.78	100.22	100.24	100.55	100.31
Si	1.950	1.930	1.900	1.930	1.990	2.010	2.000	1.950	2.000	2.010	2.010
Ti	0.000	0.000	0.010	0.010	0.000	0.010	0.000	0.000	0.000	0.000	0.000
Al	0.080	0.080	0.100	0.100	0.030	0.010	0.010	0.070	0.000	0.000	0.020
Fe^{2+}	0.810	0.800	0.820	0.720	0.530	0.810	0.610	0.430	0.670	0.670	0.630
Fe^{3+}	0.040	0.080	0.100	0.080	0.020	0.030	0.100	0.130	0.130	0.130	0.030
Mn	0.020	0.020	0.010	0.040	0.010	0.020	0.020	0.030	0.030	0.020	0.030
Mg	0.200	0.210	0.170	0.300	0.470	0.150	0.350	0.500	0.290	0.260	0.410
Ca	0.910	0.920	0.980	0.890	0.910	0.910	0.910	0.910	0.880	0.900	0.820
Na	0.030	0.030	0.020	0.040	0.040	0.080	0.110	0.110	0.130	0.150	0.080
Total	4.000	3.990	4.010	4.030	3.980	4.000	4.010	4.000	4.000	4.010	4.000
Q	1.9	1.9	1.9	1.8	1.9	1.8	1.8	1.7	1.7	1.7	1.8
J	0.1	0.1	0.0	0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.2
WO	47.0	47.4	49.4	45.7	47.2	48.1	48.2	48.6	47.1	48.9	43.2
EN	10.4	10.9	8.8	15.3	24.3	8.2	18.5	26.5	15.5	14.0	21.6
FS	42.7	41.7	41.8	39.1	28.5	43.8	33.4	24.9	37.3	37.1	35.2
WEF	97.2	96.5	98.3	96.2	95.9	91.8	89.2	88.6	86.6	85.4	92.0
JD	1.2	0.4	0.0	0.6	2.1	1.4	1.1	1.4	0.0	0.0	2.7
AE	1.6	3.1	1.7	3.2	2.1	6.8	9.7	10.0	13.4	14.6	5.3



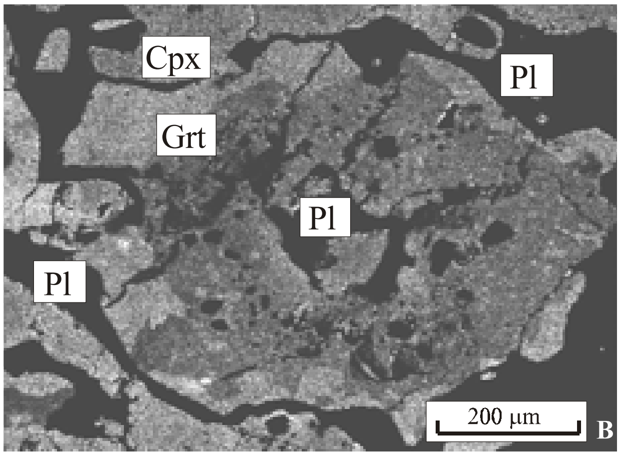


Fig. 6A, B. BSE images of calc-silicate gneiss with garnet and clinopyroxene from the Holšice skarn. A – Zoned garnets with plagioclase (Pl) in the core, fissures and along the rims; B – A younger Fe-rich garnet (light-coloured) along contact with plagioclase filling extension fractures.

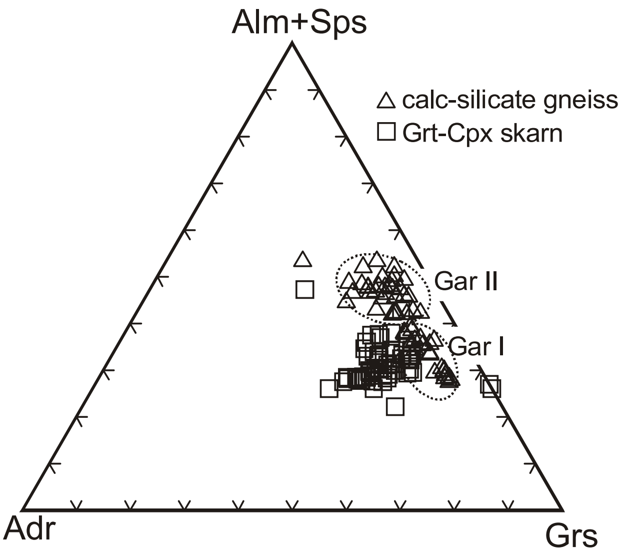


Fig. 7. Chemical composition of garnet from Grt-Cpx skarn and garnet I and II from calc-silicate gneiss at Holšice.

Vápenka skarn band

A small calc-silicate band (4–8 cm wide), which locally contains rock with mineral composition corresponding to amphibole or garnet-amphibole skarn, is formed at the contact of crystalline limestone with the Kácov orthogneiss. The main minerals are quartz, feldspar, amphibole (magnesiohornblende, ferrohornblende) and garnet of spessartine-almandine composition. Titanite, scheelite, sulphides (pyrrhotite enclosing minor chalcopyrite, pyrite, sphalerite) and Fe-chlorites are minor minerals.

Mineral composition and metamorphic development of skarns and of their host rocks

Chemical analyses of minerals were carried out in the laboratories of the Czech Geological Survey in Prague and of the Faculty of Science, Charles University in Prague using the LINK eXL ED analyser system and a Cam Scan 4 electron microscope (acceleration voltage of 15 kV, sample current of 3.5 nA). The data, including calculation of Fe^{2+} and Fe^{3+} ratio, was recalculated using Mincalc (Melín – Kunst 1992) and Minpet (Richard 1997) software.

Holšice skarn locality

Using the classification of Morimoto (1988), analysed clinopyroxene belongs to the diopside-hedenbergite series (Fig. 5, Table 3). Pyroxene associated with hornblende in calc-silicate gneiss is usually more magnesium-rich than pyroxene of the Grt-Cpx skarn. Evidently, iron prefers amphibole (Perčuk 1970) leaving more magnesium for pyroxene. Both Al and Na contents in clinopyroxene are low, but they exhibit slight zoning in a few samples of calc-silicate gneiss (especially with association of plagioclase and garnet), with Al and Na depleted towards the rims.

Garnet of almandine-grossular composition (Fig. 7, Table 4) from the Grt-Cpx skarn is unzoned in contrast to garnet from calc-silicate gneiss. Although Ca contents are high in the red interior cores in garnets of calc-silicate gneiss, X-ray maps (Fig. 6a, b) indicate a distinct drop in Ca content adjacent to large plagioclase inclusions. The loss of Ca from garnet core is probably a function of plagioclase inclusions and adjacent garnet acted as a reaction domain during post-peak metamorphic decompression (represented by decompression arrow in Fig. 12).

The analysed plagioclase matrix has a broad range of compositions of $An_{20–41}$ (Table 5). Inclusions in garnet and in the intergranular aggregate between garnet and clinopyroxene show a slightly more calcic composition ($An_{32–44}$) (Table 5). Plagioclase inclusions and intergranular aggregates with slightly higher anorthite contents occur in heavily fractured areas, where the Ca content in adjacent garnet is depleted.

Using the classification scheme of Leake *et al.* (1997), all the analysed amphibole of Holšice calc-silicate gneiss belongs to hastingsite and ferro-edenite (Table 6). The comparison of the contents of alkalis in amphiboles from

Table 4. Representative chemical analyses of garnets.

	calc-silicate gneiss		Grt-Cpx skarn					Grt-Amp skarn	Grt-Amp gneiss	Grt-Amp skarn	
Location	**Holšice**	**Holšice**	**Holšice**	**Holšice**	**Holšice**	**Zliv**	**Zliv**	**Zliv**	**Zliv**	**Vápenka**	**Vápenka**
Sample	5c/20	8a/219	8a/21	18b/168	6a/120	4bc262	4bd271	7b157	D-34	57a224	57a242
SiO_2	37.49	37.67	38.22	37.63	37.40	36.61	36.78	37.15	37.87	38.66	37.99
TiO_2	0.12	0.28	0.00	0.32	0.35	0.00	0.00	0.06	0.00	0.30	0.00
Al_2O_3	20.22	19.91	20.46	17.24	16.15	0.90	1.10	21.10	21.13	22.23	21.28
Cr_2O_3	0.10	0.00	0.00	0.00	0.10	0.00	0.12	0.20	0.00	0.17	0.00
FeO_{calc}	20.99	21.49	13.83	10.91	11.30	0.00	0.00	28.73	26.94	23.35	22.04
$Fe_2O_{3\ calc}$	1.62	1.61	1.82	6.02	7.76	31.51	28.99	0.00	0.00	0.00	0.00
MnO	2.06	1.23	1.78	1.66	1.27	0.19	0.31	1.29	0.93	5.33	3.30
MgO	0.38	0.19	0.10	0.00	0.17	0.20	0.25	1.51	1.27	1.56	1.49
CaO	16.60	17.41	22.89	25.15	25.01	32.12	33.79	8.74	11.48	10.30	13.43
Total	99.58	99.79	99.10	98.93	99.51	101.53	101.34	98.78	99.62	101.90	99.53
Si	2.990	3.000	3.020	3.010	2.990	3.020	3.000	3.000	3.021	3.010	3.012
Ti	0.010	0.020	0.020	0.020	0.020	0.000	0.000	0.000	0.000	0.020	0.000
Al	1.900	1.870	1.900	1.620	1.510	0.090	0.100	2.010	1.985	2.040	1.987
Fe^{2+}	1.400	1.430	0.910	0.730	0.750	0.000	0.000	1.940	1.800	1.520	1.460
Fe^{3+}	0.100	0.100	0.110	0.360	0.470	1.950	1.780	0.000	0.000	0.000	0.000
Mn	0.140	0.080	0.120	0.110	0.090	0.010	0.020	0.090	0.063	0.350	0.222
Mg	0.050	0.020	0.010	0.000	0.020	0.030	0.030	0.180	0.152	0.180	0.176
Ca	1.420	1.490	1.930	2.150	2.140	2.830	2.950	0.760	0.981	0.860	1.141
Total cat	8.010	8.010	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
Alm	46.6	47.4	30.6	24.3	25.1	0.0	0.0	65.4	60.0	52.2	48.7
Adr	4.9	4.9	5.4	18.1	23.3	98.7	94.0	0.0	0.0	0.0	0.0
Grs	42.1	44.3	59.6	53.9	47.7	0.0	3.8	24.9	32.8	29.0	38.0
Prp	1.5	0.8	0.4	0.0	0.7	0.9	1.1	6.1	5.1	6.2	5.9
Sps	4.6	2.8	4.0	3.8	2.9	0.5	0.8	3.0	2.1	12.1	7.4
Alm+Sps	51.3	50.1	34.6	28.1	28.0	0.5	0.8	68.4	62.1	64.3	56.1

the calc-silicate gneiss (Fig. 10) reflects in particular a broad range of potassium contents and a restricted range of sodium contents.

Epidote, albite and hisingerite (Drahota *et al.* 2000) represent the youngest minerals. Epidote occurs in the form of veinlets penetrating garnets, and is associated with young albite. Both of them originated during the closing stages of regional metamorphism (the end of skarn evolution path arrow in Fig. 12). Hisingerite often replaces pyroxene in the calc-silicate gneiss (Fig. 11) and its formation represents the youngest hydrothermal alteration of the rock.

Of all the Grt-Cpx skarn and calc-silicate gneiss studied, only a few gneiss samples correspond to the chemical conditions recommended for geothermobarometers by Ravna (2000) and Kohn – Spear (1990), because of a very low-Mg and high-Ca garnet composition, and the possibility of net transfer and/or later cation exchange reactions. Garnet compositions used for thermometer calculations are $X^{Grt}_{Mg\#}$=0.06–0.013; X^{Grt}_{Ca}=0.47–0.53. The temperature and pressure ranges of 760–810 °C and 11.5–13.4 kbars calculated on the basis of garnet-pyroxene geothermometer (Ravna 2000) and garnet-plagioclase-amphibole-quartz geobarometer (Kohn – Spear 1990) correspond to high-grade conditions of metamorphic equilibration. The temperatures estimated using Ravna (2000) calibration do not show large deviations from previous calibrations (*e. g.* Ellis – Green 1979, Powell 1985, Ai 1992, Berman *et al.* 1995) and are regarded as more accurate for a large compositional range of rocks (Ravna 2000). Only ten percent of analyzed garnet-clinopyroxene pairs (only from the rims of grains) were found suitable for this geothermometer and results in the above mentioned relatively broad range of calculated temperatures.

Zliv skarn locality

Clinopyroxene corresponds to diopside-hedenbergite (Fig. 5, Table 3) with a small amount of Mn (1.5–3.0 mol % of johannsenite component), but compared to Holšice skarn pyroxenes, it is poorer in aluminium (0.2 wt % Al_2O_3 on average). In contrast, the Na content is much higher (up to 1.9 wt % Na_2O). The increase of hedenbergite component in narrow rim of pyroxene is typical for many regionally metamorphosed skarn bodies in the Bohemian Massif (*e. g.* Šrein – Řídkošil 1983, Potužák 1996).

Nearly pure andradite garnets occur in the Grt-Cpx skarn (Fig. 8, Table 4). Their composition is comparable to andradite garnets at Kottaun in Austria (Götzinger 1981). The origin of the andradite-rich garnets reflects the original whole rock composition (high Fe, Ca and extremely low Al – Table 2) and high O_2 activity (Gustafson 1973, Vrána 1987). Grossular component of the garnet increases toward the margin of the skarn body (Fig. 8). The average of porphyroblastic garnet from Grt-Amp skarn and Grt-Amp gneiss in the marginal parts of the skarn body corresponds to Alm_{63} Grs_{25} Adr_5 Sps_2 Prp_6.

Younger and accessory garnet (Alm_{21} Grs_{78} $Sps_{0.7}$ $Prp_{1.4}$) of these rocks forms small intergranular grains in older garnet and amphibole.

Amphibole composition also reveals continuous change from the central part of the Zliv skarn body to its margins (from Cpx skarn with Amp → Grt-Amp skarn → to Grt-Amp gneiss). Titanium, potassium, and iron contents increase in amphiboles slightly toward the margin of the skarn body, whereas sodium and magnesium contents decrease rapidly. The equilibration temperature of Ca-rich ferro-actinolite with abundant cummingtonite exsolution-lamellae in Amp skarn depends on its composition (Cameron 1975). The lower limit of metamorphic conditions has been estimated at 600±35 °C. This is in reasonable agreement with the restricted temperature range of 670–690 °C calculated for the Grt-Amp skarn using the Graham – Powell (1984) thermometer. Also the pressures of 6.0–6.5 kbars estimated by the garnet-plagioclase-amphibole-quartz geobarometer (Kohn – Spear 1990) describe well the metamorphic mineral association of the Zliv marginal skarn rocks (Fig. 12).

Vápenka skarn band

An elevated spessartine content of garnet (average Alm_{46} Grs_{31} Adr_3 Sps_{15} Prp_6) in the Vápenka skarn band is often characteristic for fluids from a magmatic source (*e. g.* Einaudi – Burt 1982, Němec 1991). Representative chemical compositions of garnet and amphibole are listed in Tables 4 and 6, respectively.

Rocks of the paragneiss unit

Paragneiss and the Kácov orthogneiss body were found to contain the following mineral association: plagioclase ($An_{12–28}$), K-feldspar, quartz, garnet of almandine composition, biotite I. The younger metamorphic association includes: biotite II, sillimanite, muscovite, chlorite, and spessartine-rich narrow rims of older garnet. The temperature and pressure conditions of equilibration were calculated using the garnet-biotite thermometer (Williams – Grambling 1990), plagioclase-amphibole thermometer (Blundy – Holland 1990), and garnet-plagioclase-quartz-Al_2SiO_5 geobarometer (Koziol – Newton 1988). The temperatures and pressures (610–640 °C, 6.8–8.0 kbars) correspond to the PT conditions of the marginal parts of the Zliv skarn body (Amp skarn and Grt-Amp skarn). The retrograde metamorphism is apparent from the biotite II growth, formation of chlorite at the expense of biotite, and garnet zoning similar to the youngest zoning in garnets of Holšice calc-silicate gneiss. Metamorphic conditions of the retrogression were estimated at 510–580 °C and 5.3–6.3 kbars (Fig. 12) on the basis of Grt-Bt thermometer (Williams – Grambling 1990) and garnet-plagioclase-quartz-Al_2SiO_5 geobarometer (Koziol – Newton 1988).

Table 5. Representative chemical analyses of plagioclase from calc-silicate gneiss from Holšice. Numbers of atoms are calculated on the basis of 32 oxygen atoms.

Sample	5c/34	5c/3	5c/167
SiO_2	61.71	62.43	57.20
Al_2O_3	23.26	22.49	26.56
FeO_{total}	0.37	0.22	0.18
CaO	5.12	3.95	8.87
Na_2O	7.72	8.37	6.18
K_2O	0.38	0.37	0.19
Total	98.56	97.83	99.18
Si	11.090	11.252	10.325
Al	4.930	4.777	5.650
Fe^{2+}	0.056	0.033	0.027
Ca	0.986	0.763	1.715
Na	2.690	2.925	2.163
K	0.087	0.085	0.044
O	32.000	32.000	32.000
An	26.000	20.000	44.000
Ab	71.000	78.000	55.000
Or	2.000	2.000	1.000

Numbers of atoms are calculated on the basis of 32 oxygen atoms.

Chemical evidence for potential genetic connection between igneous rocks and associated skarn occurrences

Broad correlations between igneous rock compositions and skarn types have been described by several authors (*e.g.* Shimazaki 1980, Kwak – White 1982, Newberry – Svanson 1986, Ray *et al.* 1996, Meinert 1993, 1995). Using these correlations, we examined the major-element chemistry of the Kácov orthogneiss body situated next to all three skarn occurrences (Fig. 13). The Kácov orthogneiss body is probably of S-type, a peraluminous granodiorite to granite with high silica, aluminium and total alkali content (Fig. 13a, b and d, Table 1). It contains low quantities of Ca (average of 0.74 wt % CaO) and has a K_2O/Na_2O ratio averaging 1.53. Major oxides tend to vary sympathetically such that smooth trends are apparent on Harker-type comparison plots. In Figures 13c and d, the orthogneiss contains significantly more K_2O or SiO_2 and less MgO than could be expected for an intrusion associated with Fe-skarn mineralization.

Oxygen and carbon isotopes

Oxygen for the mass isotope determination was released from separated minerals or "whole-rock" samples in a special apparatus, constructed for this purpose in the laboratories of the Faculty of Science of Charles University (M. Pudilová). Mass spectroscopic determination of the oxygen and carbon isotopes was later carried out by K. Žák in the Stable Isotope Laboratory of the Czech Geological Service, Prague, on a Finnigan MAT 251 instrument.

The values of the isotopic compositions of oxygen and carbon of the separated rock-forming minerals, together with the estimated values of isotopic composition of the whole rock from their modal contents, are given in Table 7 and in Figures 14 and 15.

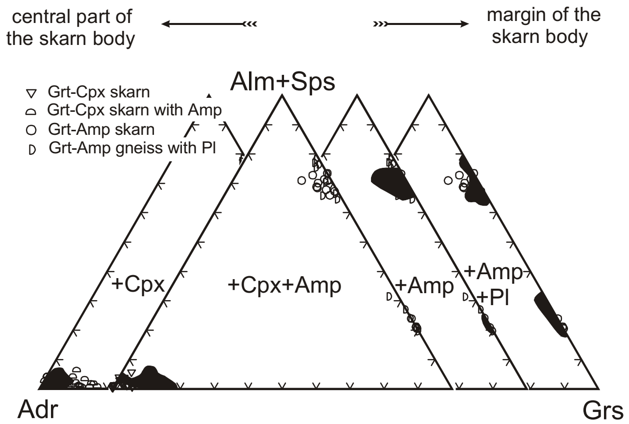


Fig. 8. The Alm+Sps-Adr-Grs plots of garnets from Zliv skarn rocks with associated main rock-forming minerals. Black fields represent compositional range of garnets from the given mineral assemblage.

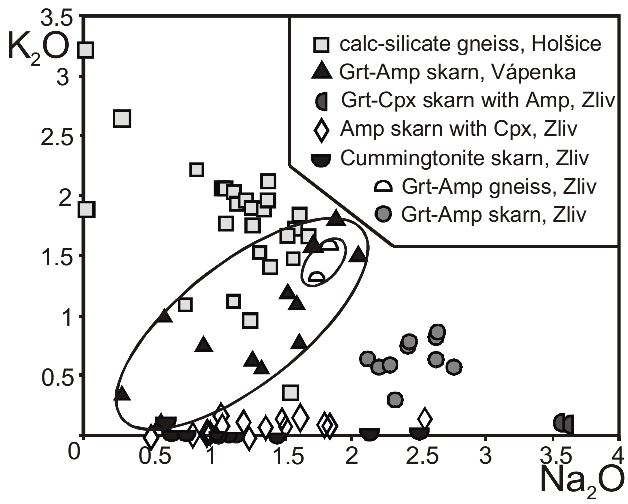


Fig. 10. Na_2O and K_2O contents (wt. %) of amphiboles from the Holšice, Zliv, and Vápenka skarns.

The $\delta^{18}O$ values for the skarn minerals differ from the $\delta^{18}O$ values for minerals of the surrounding rocks – they are systematically lower (Fig. 14). They are lowest at Zliv, where magnetite in Grt-Cpx skarn exhibits a negative value of –0.9 ‰, garnet (andradite) 0.0 ‰ and clinopyroxene (hedenbergite) +1.2 ‰ $\delta^{18}O$. Thus, the isotopic composition of the whole rock $\delta^{18}O_{WR}$ equals approximately +0.3 ‰. In Grt-Amp skarn (rims of the Zliv skarn body), the $\delta^{18}O$ value for garnet is +3.2 ‰ and, for amphibole, +4.0 ‰. Grt-Cpx skarn at the Holšice has a low $\delta^{18}O$ content of +2.2 ‰ in garnets, and +2.6 ‰ in pyroxenes, the $\delta^{18}O_{WR}$ value was estimated at about +2.7 ‰. Calc-silicate gneiss has a $\delta^{18}O_{WR}$ value elevated to +4.5 ‰.

The determined $\delta^{18}O$ values of minerals from the band of the Vápenka skarn actually exhibit higher heavy oxygen content (+6.0 for garnets, +6.8 for feldspar and +7.1 ‰ for amphiboles), which is fully in accord with the isotopic composition of the orthogneiss (Fig. 14).

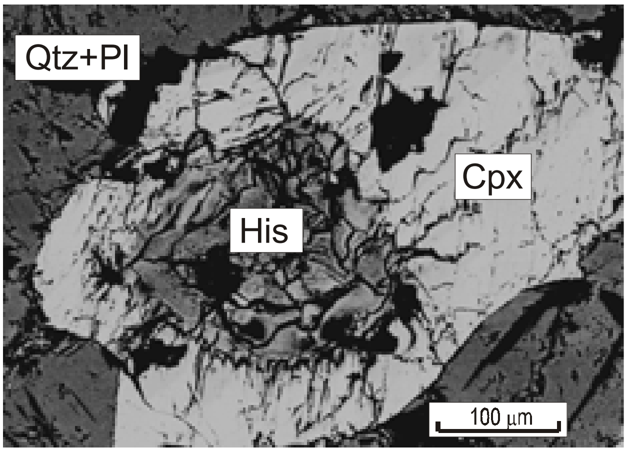


Fig. 11. BSE image showing hisingerite (His) replacement of clinopyroxene (Cpx) in the quartz and plagioclase matrix (Qtz+Pl). Calc-silicate gneiss from the Holšice skarn.

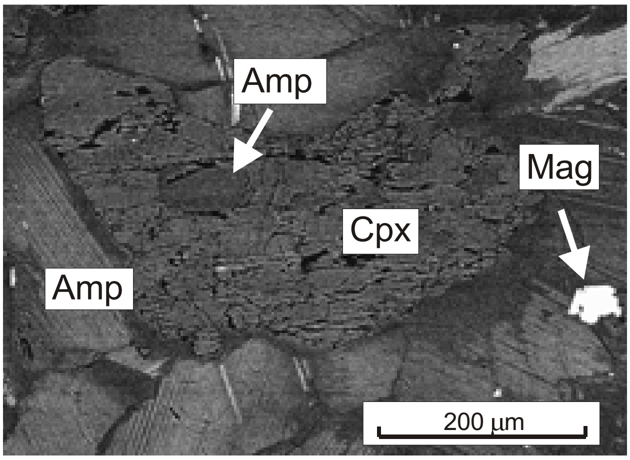


Fig. 9. BSE image showing lamellar and zonal amphibole (Amp) replacement of clinopyroxene (Cpx). Amphibole skarn with clinopyroxene from the Zliv skarn.

At the Vápenka site, the $\delta^{18}O$ and $\delta^{13}C$ isotopic compositions were also analysed on a short profile of the crystalline limestone from the contact with the garnet-amphibole skarn band (Fig 1b). The limiting values [$\delta^{18}O$ +14.8 ‰ (SMOW) and $\delta^{13}C$ –2.9 ‰ (PDB)] inside the crystalline limestone have compositions corresponding to regionally metamorphosed limestones of Upper Proterozoic to Palaeozoic age (Veizer – Hoefs 1979, Hudson 1977).

Disscussion

From the standpoint of their geological positions, the Holšice and partly also the Zliv skarn bodies seem to be an integral part of more extensive calc-silicate layers in the paragneiss unit. Structurally, these skarn rocks exhibit brittle structures, which facilitated penetration of numer-

Table 6. Representative chemical analyses of amphiboles. Numbers of atoms are calculated on the basis of (24 O, OH).

	calc-silicate gneiss			Grt-Amp skarn		Amp skarn with Cpx			Cummingtonite skarn		Grt-Cpx skarn with Amp	Grt-Amp gneiss	Grt-Amp skarn	
Location	**Holšice**	**Holšice**	**Holšice**	**Zliv**	**Zliv**	**Zliv**	**Zliv**	**Zliv**	**Zliv**	**Zliv**	**Zliv**	**Zliv**	**Vápenka**	**Vápenka**
Sample	**13c144**	**13c153**	**17c253**	**B7-a139**	**B7-b161**	**B5c344**	**B5f356**	**B5c346**	**60ac72**	**60ba305**	**E1-28**	**D2-44**	**57aa210**	**57ab217**
Mineral	**hastingsite**			**Fe-pargasite**		**ferro-actinolite**		**cummingtonite**	**cummingtonite**		**Fe-pargasite**	**ferropargasite**	**Fe-pargasite**	**ferro-edenite**
SiO_2	40.20	41.60	37.67	41.50	42.46	50.41	49.49	51.73	49.89	51.15	38.61	40.65	42.66	44.72
TiO_2	1.32	1.64	0.56	1.15	0.97	0.00	0.13	0.12	0.00	0.00	0.68	1.18	0.93	0.80
Al_2O_3	10.99	11.05	13.60	13.65	14.25	2.09	3.33	0.44	0.00	0.00	14.30	14.34	13.05	10.83
FeO_{total}	28.40	24.13	29.97	21.63	22.92	27.82	24.60	33.19	34.77	40.07	20.80	22.44	19.44	17.79
MnO	0.56	0.22	0.28	0.10	0.21	0.82	0.65	1.94	0.72	0.80	0.60	0.38	0.58	0.80
MgO	3.15	5.55	1.61	5.23	4.30	8.57	7.92	8.27	8.83	4.55	5.79	4.37	7.30	8.31
CaO	11.29	11.20	11.43	10.63	10.60	6.16	10.14	1.69	1.07	0.36	11.40	11.33	11.54	11.65
Na_2O	1.32	1.48	1.10	2.61	2.30	1.78	1.80	0.86	2.12	1.10	3.60	1.82	1.96	1.56
K_2O	1.55	1.69	2.03	0.82	0.59	0.08	0.09	0.00	0.00	0.00	0.10	1.56	1.21	1.12
H_2O_{calc}	1.89	1.93	1.86	1.95	1.90	1.95	1.96	1.94	1.90	1.84	1.90	1.94	1.99	1.99
Total	100.79	100.49	100.11	99.27	100.50	99.68	100.11	100.41	99.30	99.87	97.94	100.01	100.66	99.57
Si	6.370	6.450	6.080	6.390	6.390	7.750	7.560	7.980	7.870	8.170	6.080	6.280	6.440	6.750
Ti	0.160	0.190	0.070	0.130	0.120	0.000	0.020	0.010	0.000	0.000	0.080	0.140	0.110	0.090
Al	2.050	2.020	2.590	2.480	2.650	0.380	0.600	0.080	0.000	0.000	2.660	2.610	2.320	1.920
Fe	3.760	3.130	4.050	2.790	2.760	3.580	3.140	4.280	4.580	5.460	2.740	2.900	2.450	2.250
Mn	0.080	0.030	0.040	0.020	0.030	0.110	0.080	0.250	0.100	0.110	0.080	0.050	0.070	0.100
Mg	0.740	1.280	0.390	1.200	1.010	1.960	1.800	1.900	2.080	0.860	1.360	1.010	1.640	1.870
Ca	1.920	1.860	1.980	1.760	1.800	1.020	1.660	0.280	0.180	0.060	1.920	1.870	1.870	1.880
Na	0.410	0.450	0.340	0.780	0.700	0.530	0.540	0.320	0.550	0.350	1.100	0.550	0.580	0.440
K	0.310	0.330	0.420	0.160	0.120	0.020	0.020	0.000	0.000	0.000	0.020	0.310	0.230	0.220

Numbers of atoms are calculated on the basis of 24 (O, OH).

ous postmetamorphic pegmatites. The less frequent isoclinal folds of dm dimensions (Fig. 3) in banded skarn of the Holšice body have different morphology and orientation than the ductile deformations in surrounding paragneisses. Direct contact of granitoid rocks with a lens of crystalline limestone was found at the Vápenka locality. Only a narrow, maximally 8 cm thick band of calc-silicate rock, which occasionally passes into similarly thick skarn, was found at their contact. Mineral composition of this skarn band differs substantially from the other two studied Fe-rich skarn bodies (*e.g.* in the content of sulphides, scheelite, high content of spessartine component in garnets), and there is also an important difference in the isotopic composition of oxygen. The formation of Vápenka skarn band is interpreted as a contact metasomatic or metamorphic product, or can be connected with migmatization of the surrounding gneisses. The skarn forming fluid was derived from orthogneisses and limestones (based on oxygen isotopes).

The Holšice and Zliv skarn bodies underwent HT/HP metamorphism. This is indicated by the chemical composition and zonality of garnets, clinopyroxenes and plagioclases in the calc-silicate gneisses of the Holšice skarn body, which are characterized by post-peak decompression conditions. There is an apparent similarity with the high-pressure granulites of the Bohemian Massif (Whitney 1991, Cooke *et al.* 2000) or Ca-rich granulites (calc-silicate granulites) of eastern Greenland (Stephenson – Cook 1997). Numerous large fractures in the analysed garnets, close to the plagioclase inclusions, interconnected the inclusions with matrix, and allowed participitation of matrix phases (clinopyroxene + quartz) in decompression-driven reactions. Additionally, the role of a fluid phase, present during retrogression, could be also considered important in enhancing net-transfer reaction. Low and flat Mn and Mg distribution pattern in skarn and gneiss garnets from the Holšice body is typical for the

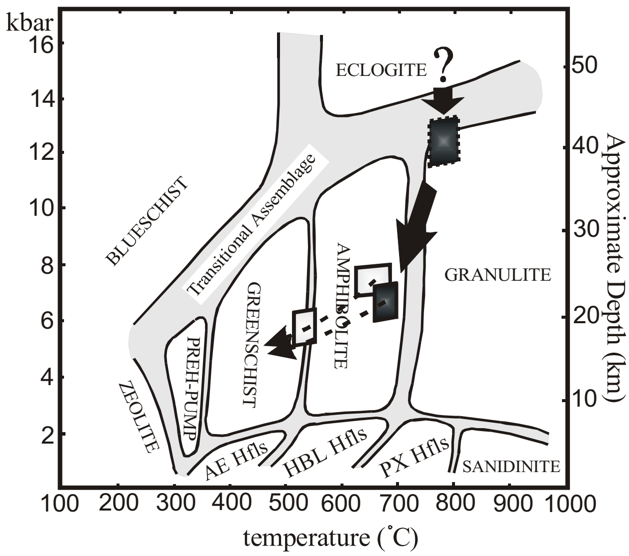


Fig. 12. P-T diagram illustrating the retrograde PT path of skarns (dark grey) and surrounding gneisses (light grey) from the Holšice and Zliv localities. Fields of metamorphic facies were modified after Yardley (1989).

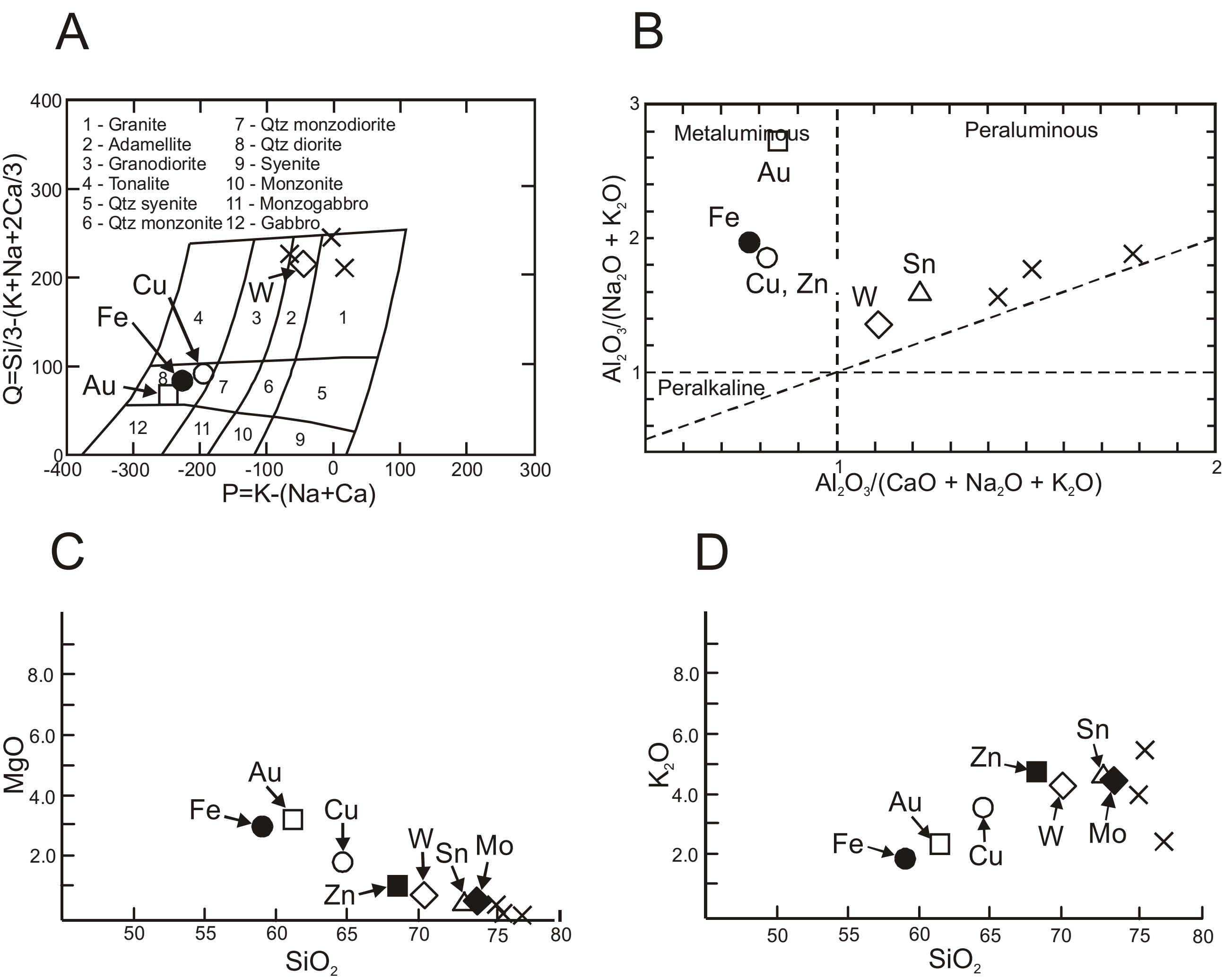


Fig. 13A, B, C, D. Plot comparing the major element geochemistry of Kácov orthogneiss (crosses) to intrusions related to Au, Fe, Cu, Zn, W, Mo, and Sn metasomatic skarns. Data from Ray *et al.* 1996 and Meinert (1995). A – Q–P plot (after Debon – Le Fort 1983); B – Aluminium saturation plot (after Maniar – Piccoli 1989); C, D – Harker variation diagrams for MgO and K_2O versus SiO_2.

Table 7. Stable isotope compositions $\delta^{18}O$ (SMOW) and $\delta^{13}C$ (PDB) of minerals and the calc-silicate whole rock.

rock	sample	locality	Cal	Qtz	Fs	Pl	Ms	Cpx	Amp	Grt	Bt	Mag	$\delta^{18}O_{WR}$; (calculated [c])	Cal $\delta^{13}C$
Grt-Cpx skarn	6a	Holšice	–	6.4	–	–	–	2.6	–	2.2	–	–	2.7 [c]	–
calc-sicilicate gneiss	5c	Holšice	–	5.3	–	3.7 [1]	–	–	3.6	–	–	–	4.5 [c]	–
Grt-Cpx skarn	B8	Zliv	–	–	–	–	–	1.2	–	0.0 [3]	–	–0.9	0.3 [c]	–
Grt-Amp skarn	B7	Zliv	–	–	–	–	–	–	4.0	3.2	–	–	3.5 [c]	–
cummingtonite skarn	21	Zliv	–	–	–	–	–	–	3.7	–	–	–	3.7 [c]	–
calc-sicilicate rock	41	Zliv	–	–	–	–	–	–	–	–	–	–	6.0	–
Grt-Amp skarn	57	Vápenka	–	–	–	6.8 [2]	–	–	7.1	6.0	–	–	6.8 [c]	–
calcitic marble	53	Vápenka	10.5–16.3	–	–	–	–	–	–	–	–	–	–	(–2.9)–(–8.2)
MsBt orthogneiss	44	Vápenka	–	10.0	7.9	–	–	–	–	–	5.8	–	8.3 [c]	–
Bt-Ms orthogneiss	48	–	–	8.1	7.6	–	7.8	–	–	–	–	–	7.8 [c]	–
paragneiss with Grt	31	–	–	14.0	–	–	–	–	–	10.6	7.7	–	11.4 [c]	–

[c] – whole-rock $\delta^{18}O$ values calculated from modal mineral composition

[1] – An 25–35

[2] – An 50–90

[3] – pure andradite

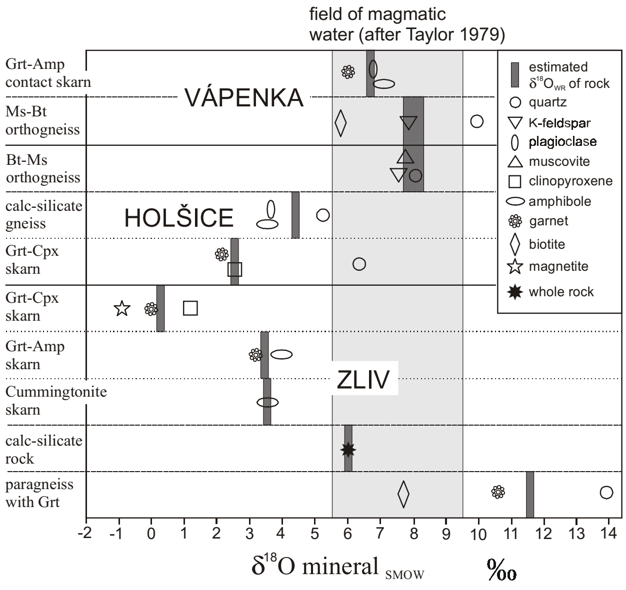


Fig. 14. δ^{18}O values for minerals and rocks from skarns, orthogneisses, and surrounding paragneiss of the studied area.

regionally metamorphosed skarns of the Bohemian Massif (Němec 1991). However, the spessartine component shows slight zoning towards narrow Mn-rich rims, indicative of the youngest record of metamorphic retrogression (Spears 1993, Žáček – Povondra 1991). The prograde growth zonation in garnet grains is not preserved, because increased diffusion rates during the assumed HT/HP metamorphism led either to growth of chemically homogeneous garnet or to elimination of previously developed zoning. In addition, the evidence of post-peak decompression conditions of HP/HT metamorphism from grain rims was supported by geothermobarometric calculation (760–810 °C, 11.5–13.4 kbars) (Fig. 12), which, however, need not yield accurate temperature-pressure conditions for metamorphic peak that is represented by question mark in the Fig. 12. The low-Mg and high-Ca content in the garnets limited the number of mineral pairs suitable for temperature calculation (Drahota 2001). There is also a possibility of younger ion exchange and/or participation of both minerals in net-transfer reactions. The subsequent metamorphism in the amphibolite facies at 620–690 °C and 6–8 kbar fully affected the metasediments of the paragneiss unit, but affected the skarn bodies only in their border zone. This metamorphic event was accompanied by intrusion of the Kácov orthogneiss body, the related migmatization of the surrounding gneisses and the invasion of younger fluids into the border zone of the skarn bodies. During this metamorphic retrogression, external fluids were the main source of Na, K and volatiles (H_2O, F) for amphiboles, however pyroxene decomposition also supplied some Na to the system. Grt-Amp gneiss at the Zliv skarn originated by relatively younger contamination of the garnet-amphibole skarn by felsic minerals (especially plagioclase, less frequently quartz and K-feldspar), as the garnet and amphibole relics in this gneiss fully correspond to mineral association in the Grt-Amp skarn from a structural and chemical standpoint. In addition, the real variations in the distribution of felsic minerals in gneiss are clearly visible on a scale of several centimetres. A further decrease in temperature and pressure (to approx. 540 °C, 5–6 kbar) is reflected in the spessartine component enrichment in rim zones of garnets in skarns and gneisses, the formation of biotite II in the gneisses of the paragneiss unit, and epidote with albite in the skarn. Analysed mineral associations in all studied rocks (Table 6) are not generally in isotopic equilibrium (Drahota 2001) and could thus not be used for calculation of the temperatures of their mutual isotopic equilibration. This fact is contradictory to conditions at some skarn localities in the eastern part of the Moldanubicum of the Bohemian Massif (Slatina, Rešice and Pernštejn), where Pertold *et al*. (1997) and Pertoldová *et al.* (1998) found selected mineral association in isotopic equilibrium.

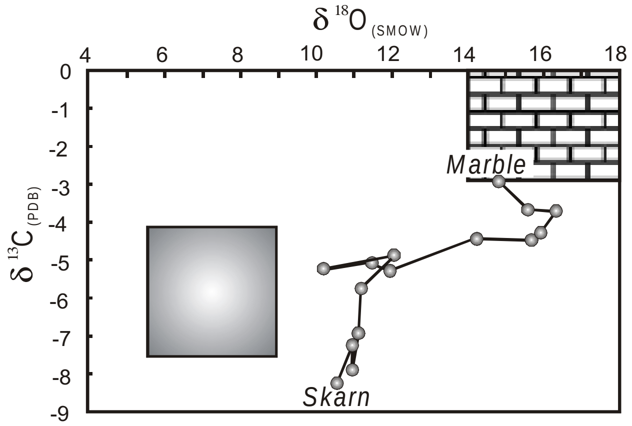


Fig. 15. δ^{13}C (PDB) versus δ^{18}O (SMOW) variation in a short profile (step of 1–5 cm) across marble contact zone from the Vápenka skarn locality. Brickfield covers the range shown by Palaeozoic limestones (Veizer – Hoefs 1976) and grey field the typical range shown by magmatic fluids (Ohmoto – Rye 1979, Taylor 1979).

All the determined temperature and pressure conditions correspond to metamorphic events, which were not the primary events for the Holšice and Zliv skarns, whatever hypothesis we prefer for the formation of these skarns. However, because of the derived metamorphic temperatures, it is especially difficult to imagine the formation of skarns through the action of fluids derived from the adjacent metagranitoid body or migmatites, as these rocks were formed after the peak of the metamorphism, which the skarns underwent, apparently together with metasediments. There is no direct proof for the hypothesis of a joint HP/HT metamorphism of the rocks of the paragneiss unit together with skarns, because in contrast to the skarns, no relics of HP/HT metamorphism have been found in the gneisses. The only proof is the assumption of an integral connection of skarns with the calc-silicate horizons, as this appears especially at the Holšice skarn locality. A similar genetic connection of the skarn body with calc-silicate rocks at Zliv is less certain. Another possibility is a tectonic uplift of these rocks from the area close to the lower crust corresponding to the HT/HP metamorphism, as could be indicated by the occurrence of ultrabasic bodies (2 km to the W).

The general experience in genetic connection of certain types of skarn ore mineralization with various types of granitoid rocks (Ray *et al.* 2000, Meinert 1993) does not indicate that the magnetite skarn at Zliv and the Fe-rich skarn at Holšice would be genetically connected with the neighbouring orthogneiss of the Kácov body. However, the orthogneiss chemistry suggests good agreement with the scheelite-containing Vápenka skarn band because, chemically, the Kácov orthogneiss body resembles many of the plutonic rocks associated with W, Sn, and Mo skarns elsewhere in the world and also in the Moldanubicum (Fišera *et al.* 1986, Němec – Páša 1986).

The relationship between skarns and granitoid rocks in the studied area was also investigated on the basis of the oxygen isotopic composition. The $\delta^{18}O_{WR}$ values of the garnet-pyroxene skarn rocks at Holšice and Zliv, in the range of +0.3 to +2.7 ‰, cannot be explained by the action of high-temperature metasomatic solutions derived from surrounding granitoid rocks. These values of the Grt-Cpx skarn are lower than those at the Kordula and Slatina localities and are very similar to the $\delta^{18}O_{WR}$ composition of Grt-Cpx skarns in the vicinity of Pernštejn in the Svratka crystalline complex (Pertold *et al.* 1997, Pertoldová *et al.* 1998). The Kácov orthogneiss minerals from the close vicinity of the studied skarns have $d^{18}O$ (SMOW) values of +5.8 to +10.0 ‰ and, according to Taylor (1979), can be assigned to isotopically normal granitic rocks with a range of +6 to +10 ‰ $\delta^{18}O$. If the skarn rocks of the Holšice and Zliv bodies were formed from high-temperature metasomatic solutions derived from this orthogneiss, they would have very similar isotope compositions to the values of the Kácov orthogneiss. An elevated content of heavier oxygen in the marginal skarn rocks at Zliv and in the calc-silicate gneiss at Holšice probably indicates a primarily higher isotopic composition of the protolith. A certain effect of younger metamorphic solutions, which somewhat influenced the peripheral parts of the skarn body during the retrograde phase of the regional metamorphism, is also probable because of the younger paragenetic position of amphibole in relation to the Grt-Cpx association at Zliv. The skarn band at Vápenka has an overall isotopic composition of 6.8 ‰ $\delta^{18}O$. This is in agreement with the composition of the neighbouring orthogneisses, whose whole-rock composition corresponds to 7.5 and 8.3 ‰ $\delta^{18}O$. It is thus possible to adopt the hypothesis that this band of skarn and calc-silicate rock was formed at high temperature in isotopic equilibrium with the orthogneiss.

The general variation of the $\delta^{18}O$ and $\delta^{13}C$ ratios in calcite in the profile of the Vápenka locality indicates that their exchange was affected especially by devolatilization during the regional metamorphism (Fig. 15). Greater changes in the isotopic compositions of $\delta^{18}O$ and $\delta^{13}C$ in calcite are limited only to the peripheral contact zones (about 20 cm) of the limestone, as the ratio of metamorphic fluids to the rock inside the massive lenses of pure crystalline limestone is usually very low and the effect of decarbonization and isotope exchange with the circulating fluid is thus also minimal. The determined irregularities (especially in the $\delta^{18}O$ values) nonetheless indicate that the system was also partly infiltrated by fluids from external sources, which preferentially circulated in the zones connected with decarbonization reactions (Žák – Sztacho 1993).

Consequently, we interpret the precursors of the Holšice and Zliv skarn bodies as a probable integral part of the paragneiss unit prior to the HP/HT metamorphism. Because of their abnormal chemical and mineral compositions, geological positions and oxygen isotope composition, they may indicate a submarine exhalative origin.

Conclusions

Three different types of skarn occurr in an area of approximately 4 km^2 in the Varied unit of the Moldanubicum of the Bohemian Massif: Holšice skarn body, Zliv skarn body with magnetite and Vápenka skarn band with sulphides and scheelite. They differ in their size, geological position, mineral composition, mineral chemistry and $\delta^{18}O$ isotopic composition. On the basis of metamorphic mineral association, application of geothermobarometers and mineral zonality, metamorphic temperature and pressure of the host-rock gneisses and especially of the skarns have been determined. The data indicate several metamorphic events, including postmetamorphic decompression under the condition close to the granulite facies at 760–810 °C, 11–13 kbar, regional metamorphism close to the upper amphibolite facies at 620–690 °C, 6–8 kbar, and a younger retrograde regional metamorphism at 520–560 °C, 5.3–6.3 kbar. The isotopic composition of oxygen of skarns and orthogneiss, PT history of the skarns and surrounding rocks and the composition of the orthogneiss do not indicate a metasomatic formation of the skarn bodies associated with orthogneiss and migmatites. All the evidence, including the PT history of skarns, chemistry of the minerals and rocks, and the mineralogical composition indicate that the precursors of Holšice and Zliv skarns were already present in the paragneiss unit prior to its metamorphism. On the other hand, the Vápenka contact skarn corresponds well to the isotopic composition of the neighbouring orthogneiss and thus its formation can be connected with fluids derived from this granite.

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Tři typy skarnů v severní části moldanubika a způsoby jejich vzniku

Regionálně metamorfované skarny u Holšic se nacházejí západně od Vlastějovic, v severní části moldanubika. Při mapování bylo nalezeno několik nových skarnových těles, které náležejí třem geologickým typům. Holšický skarn je tvořen Grt–Cpx a erlánovými pásky cm mocností. Zonálnost granátových zrn odráží dekompresi po HT/HP maximu regionální metamorfózy při přibližně 800 °C a 12 kb. Skarn u Zlivy je masivní bez erlánových pásků a obsahuje magnetit (potvrzeno magnetometricky). Jeho jednotlivé typy, tvořené asociacemi Grt-Cpx, Cpx, Grt-Amp a Amp, jsou chudé Al (hedenbergit, andradit, ferro-aktinolit, cummingtonit). Grosular-almandinový granát v Grt-Amp skarnu ekvilibroval při 670 °C a 6–8 kb (Grt-Amp geotermometrie). Třetí typ skarnu (Vápenka) tvoří jen 4–8 cm mocnou kontaktní zónu mezi mramorem a ortorulou. Obsahuje sulfidy, scheelit a Grt bohatý spessartinovou složkou. Minerály tohoto skarnového typu mají vysoké hodnoty $\delta^{18}O$, které odpovídají izotopovému složení ortoruly. Naopak, hodnoty $\delta^{18}O$ holšického a zlivského skarnu jsou nízké a nelze je vysvětlit kontaktně metasomatickým působením metagranitů studované oblasti (pro které jsou charakteristické hodnoty 6–10 $\delta^{18}O$). Všechny tyto skutečnosti ukazují, že hypotéza o skarnových prekurzorech jako integrální součásti (vulkano-) sedimentární série zůstává v platnosti pro moldanubické lokality Holšice a Zliv.