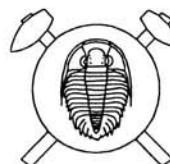


## Metamorphic Development of Skarns at Pernštejn, Svatka Crystalline Complex, Bohemian Massif

Metamorfí vývoj skarnů na lokalitě Pernštejn, svratecké krystalinikum,  
Český masiv (Czech summary)



(9 text-figs.)

JAROSLAVA PERTOLDOVÁ<sup>1</sup> – ZDENĚK PERTOLD<sup>2</sup> – MARTA PUDILOVÁ<sup>2</sup>

<sup>1</sup>Czech Geological Survey, Klárov 3, Prague 1, 118 21, Czech Republic

<sup>2</sup>Institute of Geochemistry, Mineralogy and Mineral Resources, Charles University, Albertov 6, Prague 2, 128 43, Czech Republic

A study was carried out at Pernštejn (Svatka Crystalline Complex, Bohemian Massif) of the geological and metamorphic development of skarns in relation to the surrounding parasesies, orthogneisses and migmatites, from the standpoint of the geological structure, mineral association, mineral chemism, geothermometry, REE and oxygen isotopes. From a lithological and mineralogical point of view, the skarns form nonhomogeneous lenses, whose deformation is more complex than in the surrounding parasesies. The temperatures of formation of garnet-clinopyroxene-magnetite paragenesis of the skarns, 620 °C (710 °C) or 670 °C (640 °C), determined on the basis of the distribution of the major elements and oxygen isotopes amongst the coexisting phases, correspond to the conditions of peak metamorphism in the amphibolite facies. The rocks of the parasesies were metamorphosed under the same conditions, while the migmatites and metagranitoids exhibit lower temperatures 550–600 °C. The isotopic composition of oxygen in the skarn silicates is contradictory to concepts of contact metasomatic formation of skarns, connected with metagranitoids and migmatites. Oxygen also probably did not originate from the metamorphic solutions, which were in equilibrium with the parasesies. The REE distribution indicates the presence of solutions of a reducing nature and/or of high temperatures. It is our opinion that the precursors of the skarns were present in the parasesies from the very beginning, were metamorphosed together with gneisses and were probably formed in a sedimentary exhalative environment.

**Key words:** skarn, metamorphism, geothermometry, oxygen and carbon isotopes, REE

### Introduction

Occurrences of skarns have been studied in the crystalline complex units of the Bohemian Massif by a great many authors, but opinions on their genesis continue to differ. Koutek (1950), Zemánek (1959), Němec (1973, 1979, etc.), Žáček (1997) describe the formation of skarn paragenesis by metasomatic replacement of limestones associated with intrusive rocks (orthogneisses, migmatites). Novotný (1954) explained the formation of skarns through the infiltration metasomatic effects of Fe and Ca enriched solutions on the surrounding parasesies. These opinions presuppose an open system with input of a number of components in hydrothermal solutions.

The formation of skarns in a closed system, i.e. regional metamorphism of rocks that were part of the parasesies (sedimentary or exhalative sedimentary horizons enriched in Fe, Ca and possibly further elements) has been favoured, e.g. by Zoubek (1946), Pertold – Pouba (1982), Pertold – Suk (1986), Suk (1974), Pertoldová (1986) and Pertoldová et al. (1987). The mineral composition of skarns would then correspond to the metamorphosed sediments or exhalatites (Kotková 1991 suggests volcano-sedimentary rocks). In addition, this possibility would presume the establishment of thermodynamic equilibrium amongst the minerals, and only limited movement of chemical components between the individual lithological layers.

The Pernštejn skarns provided suitable conditions for study of this subject through their lithological variability and easy access in two small quarries. Part of the data was taken from the works of Pertoldová (1986) and Per-

toldová et al. (1987), while part was obtained through the work financed by grants from the Grant Agency of the Czech Republic, No. 205/94/0925, and from the Grant Agency of Charles University, No. 274/97/B GEO.

### Geology of the area

The Pernštejn skarns are located in the south-western part of the Svatka Crystalline complex, in the Pernštejn mica schist zone (Mísař et al. 1983), in an area with very varied geological structure. It is characterized by alternation of parallel to subparallel bands of mica schists, mica-schist gneisses, banded biotite-muscovite gneisses to migmatites, orthogneisses, biotite gneisses ( $\pm$  garnet, muscovite) with intercalations of skarns, amphibolites, quartzites, tourmaline quartzites and crystalline limestones. The rock bands strike predominantly in the north-south direction and their thickness varies from tens of metres to 1 km. The thickness of the intercalations of skarns, amphibolites etc. is several metres to tens of metres. A simplified scheme of the geological situation is depicted in Fig. 1.

The detailed geological position of the skarn body was studied in a skarn quarry, which is located about 800 m to the west of Pernštejn castle (Fig. 2).

The varied association of skarn types in the hanging wall part of the quarry includes garnet-anthophyllite schist, garnet quartzite with amphibole, coarse-grained garnetite and quartz-garnet skarn. These rocks are rimmed by biotite gneisses and garnet-biotite schist.

The skarn lens is not a homogeneous body. A magnetite skarn layer occurs in the footwall of the quartz-gar-

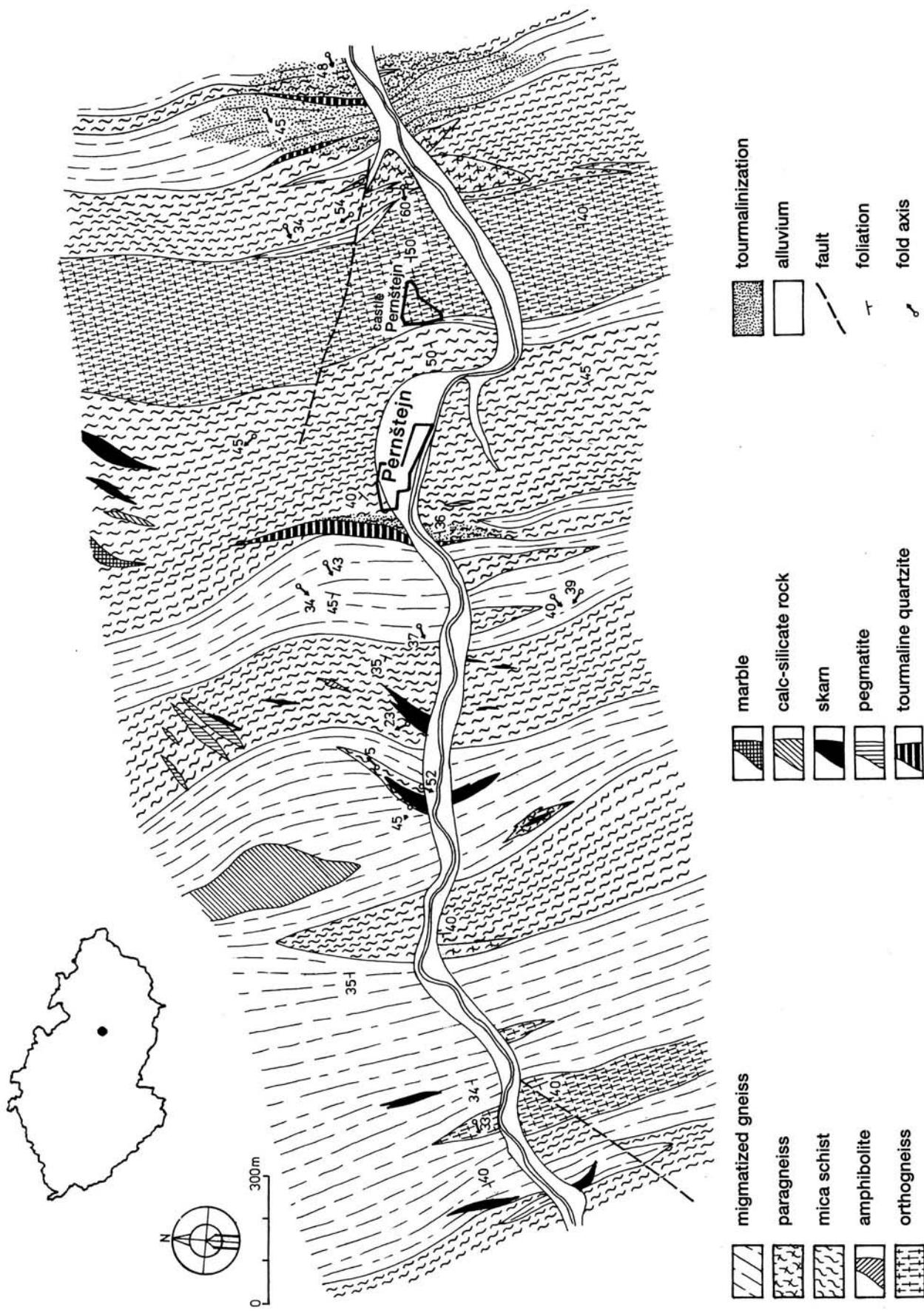


Fig. 1. Geological map of the Pernštejn area after Pertoldová (1986).

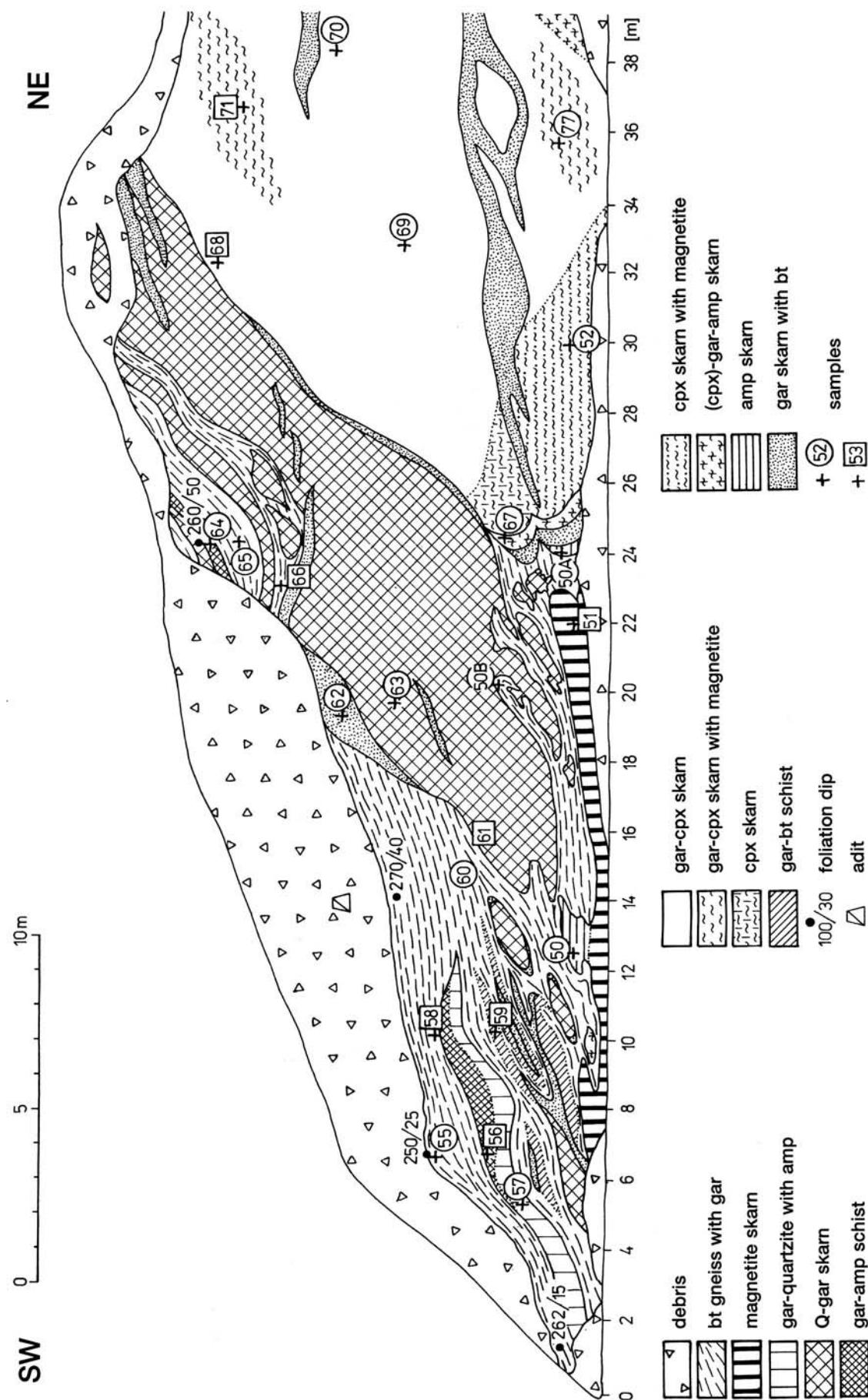


Fig. 2. Face of the Pernštejn open pit after Pertoldová (1986).

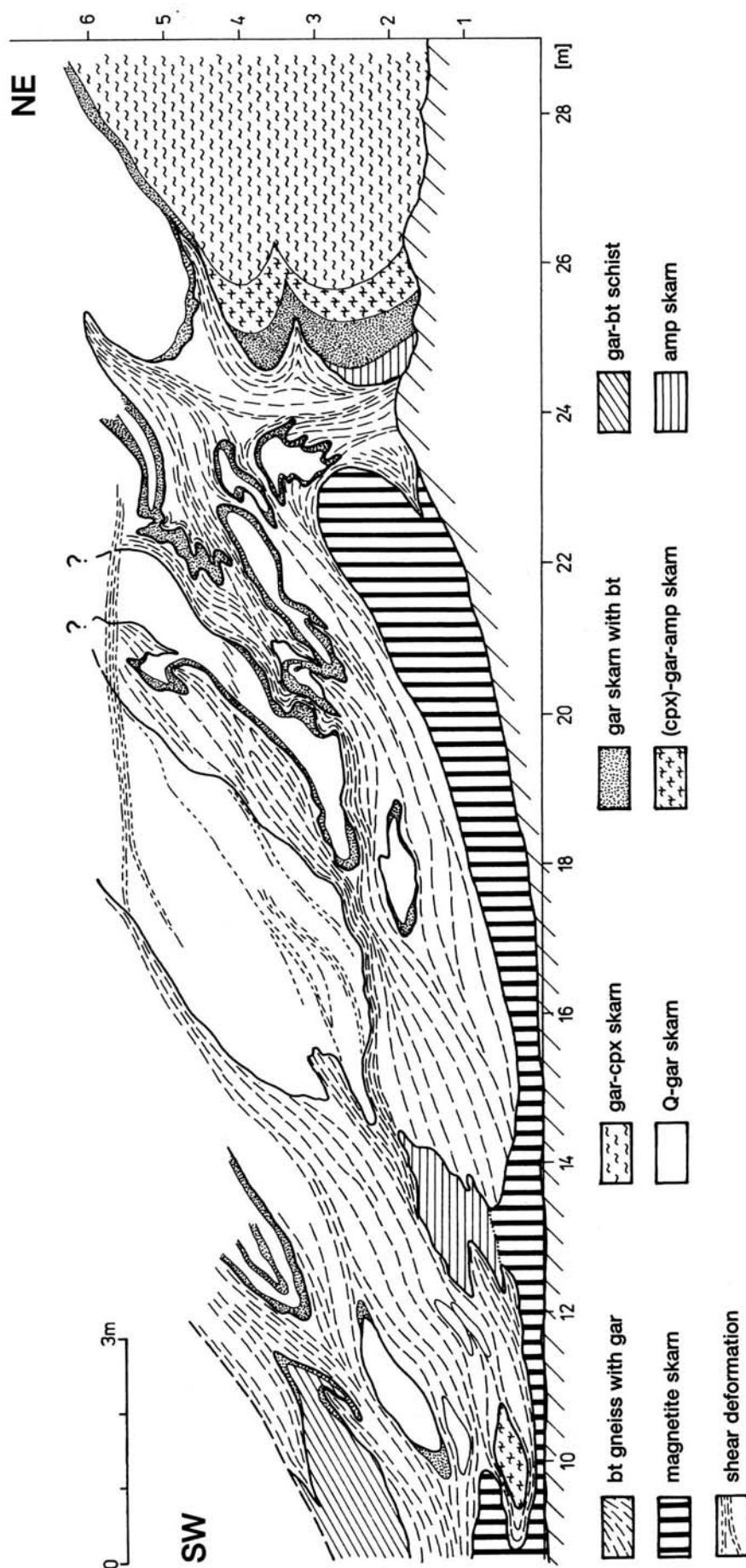


Fig. 3. Detail of the face of the Permštejn open pit after Pertoldová (1986).

net skarn with garnetite rims. The most frequent skarn type is garnet-pyroxene skarn ( $\pm$  magnetite), which passes into pyroxene skarns, pyroxene skarns with magnetite and garnet-amphibole skarns. Coarse-grained friable garnetite with biotite is a characteristic rock body crossing the skarn. This is a highly weathered rock that, in its geological position, probably follows a younger metamorphic structure within the framework of the skarn lens.

The simple monoclinal structure of the mica-schists and gneisses affected by shear deformation is different from the relatively complicated fold structure of more

competent skarns, in which the older fold structure was retained (Fig. 3).

### Mineral composition and metamorphic development of the skarns and the surrounding parasesries

Chemical analysis of the minerals was carried out in the laboratories of the Czech Geological Survey in Prague using a LINK eXL ED analyzer system and a CamScan 4 electron microscope, with an acceleration voltage of 15 kV and sample current of 3.5 nA. The data were recalculated using the MINPET (Richard 1997) and MINCALC (Melin and Kunst 1992) programs.

The determined metamorphic associations indicate complicated metamorphic development of the rocks and represent probably a consequence of two metamorphic phases. Disequilibrium mineral association was found in some cases.

### Skarns

The older metamorphic association in skarns consists of garnet, clinopyroxene, magnetite and, in the upper part of the skarn body, also quartz. The chemistry of the garnet corresponds to andradite-grossular-almandine composition, the pyrope component does not exceed 5 mol%. The relative contents of  $Fe^{2+}$ , Mn,  $Fe^{3+}$  and Ca differ in the individual lithological skarn layers, Fig. 4 and Tab. 1.

A younger garnet phase was found in sample 32/94, with a different chemical composition (the Gross component is in-

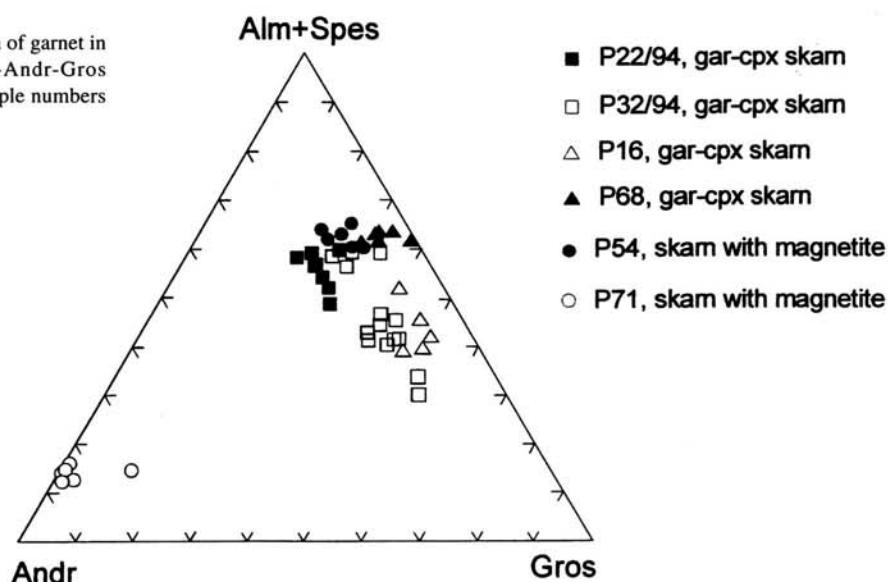
Table 1. Representative chemical composition of garnets

Sample Analysis	22/94 68s	32/94 55	P16 1 P16	P68 6 P68	P71 21 P71	P71 16 P71	P54 22 P54	P54 23 P54
Location Mineral	Pernštejn gar							
SiO <sub>2</sub>	36.58	37.89	37.76	37.51	34.45	33.09	37.60	38.28
TiO <sub>2</sub>	0.00	0.00	0.13	0.20	0.06	0.17	0.16	0.18
Al <sub>2</sub> O <sub>3</sub>	17.54	19.20	19.90	20.35	4.16	4.79	19.52	19.46
FeO calc	17.07	21.93	18.47	22.37	1.62	1.87	20.86	23.90
Fe <sub>2</sub> O <sub>3</sub> calc	6.66	2.72	2.02	1.30	29.04	29.38	1.91	1.20
MnO	8.33	3.42	5.13	5.21	2.16	2.83	5.69	4.13
MgO	0.41	1.97	0.37	1.16	0.09	0.11	1.39	1.65
CaO	13.71	12.85	16.41	11.99	29.11	27.17	12.56	11.70
Total	100.30	99.98	100.20	100.09	100.69	99.41	99.68	100.50
TSi	2.96	3.02	3.00	2.99	2.88	2.81	3.01	3.04
TAI	0.04	0.00	0.00	0.01	0.12	0.19	0.00	0.00
SumT	3.00	3.02	3.00	3.00	3.00	3.00	3.01	3.04
Al <sup>VI</sup>	1.63	1.80	1.86	1.90	0.29	0.29	1.84	1.82
Fe <sup>3</sup>	0.41	0.16	0.12	0.08	1.83	1.88	0.12	0.07
Ti	0.00	0.00	0.01	0.01	0.00	0.01	0.01	0.01
SumA	2.04	1.96	1.99	1.99	2.12	2.18	1.97	1.90
Fe <sup>2</sup>	1.16	1.46	1.23	1.49	0.11	0.13	1.40	1.59
Mg	0.05	0.23	0.04	0.14	0.01	0.01	0.17	0.20
Mn	0.57	0.23	0.35	0.35	0.15	0.20	0.39	0.28
Ca	1.19	1.10	1.40	1.02	2.61	2.47	1.08	1.00
SumB	2.96	3.02	3.01	3.01	2.88	2.82	3.03	3.06
Sum_cat	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
O	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00
Alm	39	48	41	50	4	5	46	52
And	20	8	6	4	86	86	6	4
Gross	20	28	40	30	4	1	30	29
Pyrone	2	8	1	5	0	0	5	6
Spess	19	8	11	12	5	7	13	9

22/94 gar-cpx skarn  
32/94 gar-cpx skarn  
P16 gar-cpx skarn

P68 gar-cpx skarn  
P71 gar-cpx skarn with magnetite  
P54 gar-cpx skarn with amphibole

Fig. 4. Chemical composition of garnet in ternary plot Alm+Spes-Andr-Gros (mol%) from Pernštejn. Sample numbers are indicated.



creased by 20 mol% at the expense of the Alm component) compared with the original garnet in the same rock. The composition of garnet in the anthophyllite schist corresponds to almandine-pyrope.

On the basis of the Wo-En-Fs classification diagram, clinopyroxenes belong to the Fe-diopside and Mg-hedenbergite group, Fig. 5 and Tab. 2. They are frequently converted to secondary amphibole.

Table 2. Representative chemical composition of pyroxenes

Sample	22/94	32/94	P16	P68	P71	P19	P99	P25
Analysis	70s	50	361 P16	371 P68	379 P71	393 P19	394 P99	370 P25
Location	Pernštejn							
Mineral	cpx							
SiO <sub>2</sub>	50.01	52.10	52.02	50.78	50.52	51.65	53.77	51.97
TiO <sub>2</sub>	0.00	0.00	0.09	0.10	0.00	0.81	0.02	0.03
Al <sub>2</sub> O <sub>3</sub>	1.28	0.98	0.64	2.19	0.29	1.03	2.09	0.49
FeO tot	18.46	12.22	20.30	16.16	15.31	12.71	1.83	19.97
MnO	1.54	0.83	0.86	0.78	0.83	0.67	0.05	1.41
MgO	5.74	10.22	5.92	9.06	9.02	10.27	17.32	6.05
CaO	23.26	23.78	20.28	20.07	23.74	22.93	24.98	19.97
Na <sub>2</sub> O	0.48	0.35	0.09	0.86	0.27	0.19	0.26	0.21
Total	100.77	100.48	100.20	100.00	99.98	100.26	100.32	100.10
TSi	1.95	1.97	2.06	1.95	1.95	1.97	1.94	2.05
TAI	0.05	0.03	0.00	0.05	0.01	0.03	0.06	0.00
TFe <sub>3</sub>	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00
M1Al	0.01	0.02	0.03	0.05	0.00	0.02	0.03	0.02
M1Ti	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00
M1Fe <sub>3</sub>	0.08	0.03	0.00	0.06	0.07	0.00	0.05	0.00
M1Fe <sub>2</sub>	0.52	0.35	0.62	0.37	0.38	0.38	0.00	0.62
M1Mg	0.33	0.56	0.35	0.52	0.52	0.58	0.92	0.36
M2Mg	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00
M2Fe <sub>2</sub>	0.00	0.00	0.05	0.09	0.00	0.03	0.01	0.04
M2Mn	0.05	0.03	0.03	0.03	0.03	0.02	0.00	0.05
M2Ca	0.97	0.98	0.86	0.83	0.98	0.94	0.97	0.85
M2Na	0.04	0.03	0.01	0.06	0.02	0.01	0.02	0.02
Sum_cat	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
Q	1.83	1.90	1.88	1.80	1.88	1.93	1.90	1.86
J	0.07	0.05	0.01	0.13	0.04	0.03	0.04	0.03
WO	49.62	49.34	45.03	43.72	48.55	48.10	49.42	44.29
EN	17.04	29.51	18.29	27.46	25.67	29.98	47.68	18.67
FS	33.34	21.15	36.69	28.82	25.78	21.92	2.90	37.04
WEF	96.27	97.42	99.28	93.44	97.93	98.58	98.13	98.34
JD	0.29	0.90	0.72	2.77	0.00	1.42	0.68	1.66
AE	3.44	1.68	0.00	3.78	2.07	0.00	1.20	0.00

22/94 gar-cpx skarn

32/94 gar-cpx-skarn

P16 gar-cpx skarn

P25 cpx skarn with magnetite

P68 gar-cpx skarn

P71 gar-cpx skarn with magnetite

P19 gar-amp skarn

P99 marble

Of all the skarn samples studied (a total of 6), only sample 32/94 (gar-cpx, skarn from the Eastern part of the quarry) corresponds to the chemical conditions recommended by Ai (1994) for temperature calculation. The temperatures calculated according to Ai (1994) were compared with the temperatures estimated on the basis of the gar-cpx geothermometer of Ellis – Green (1979), Tab. 5.

The chemical composition of the skarn paragenesis and temperature of 620 °C or 710 °C calculated on the basis of the garnet-pyroxene geothermometer correspond to equilibration of the skarn paragenesis under the conditions of the amphibolite facies, moderate oxygen fugacity and not extremely low X<sub>CO<sub>2</sub></sub>.

The younger metamorphic association is formed by amphiboles (Fe-pargasite, Fe-pargasitic amphibole, ferro-edentic amphibole, Fe-amphibole, tschermakite), biotite, epidote, cummingtonite and possibly also chlorite. Conversion of pyroxenes to younger amphibole occurs especially in skarns with calcareous character.

### Rocks of the paraseries

The gneisses of the surrounding paraseries were found to contain the mineral association: plagioclase (An<sub>23–34</sub>), quartz, muscovite, garnet of almandine chemistry – Fig. 6, Tab. 3, biotite – Tab. 4 and kyanite. The minerals formed under younger metamorphic conditions include sillimanite, muscovite and chlorite.

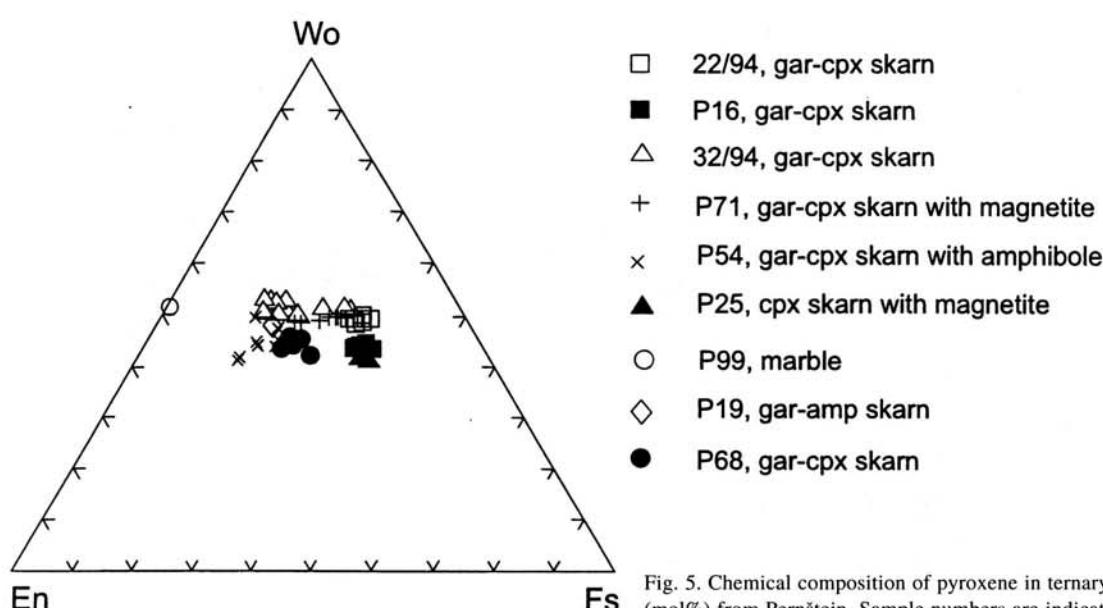


Fig. 5. Chemical composition of pyroxene in ternary plot Wo-En-Fs (mol%) from Pernštejn. Sample numbers are indicated.

Fig. 6. Chemical composition of garnet in ternary plot Alm+Spes-Pyr-Gros (mol%) from Pernštejn. Sample numbers are indicated.

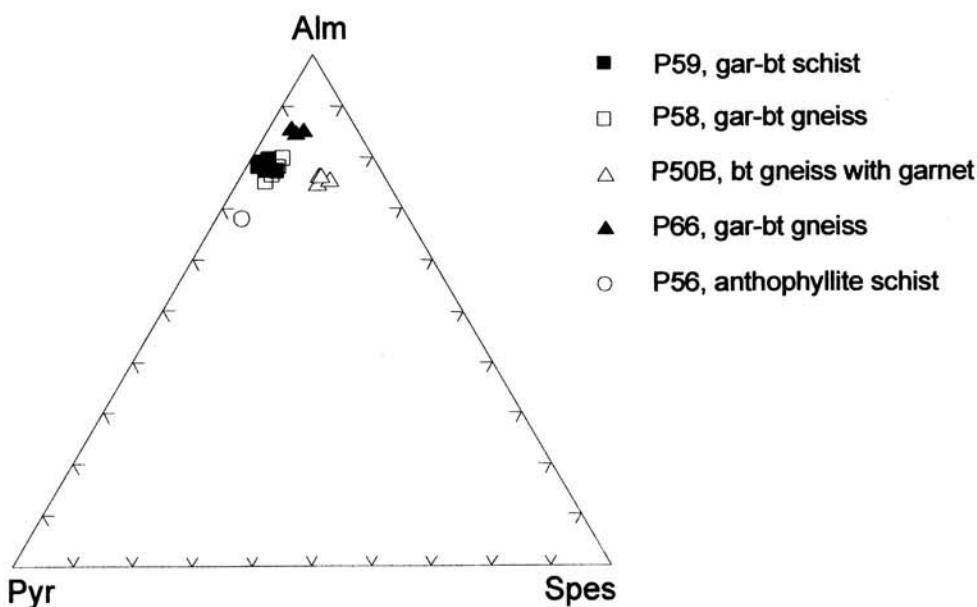


Table 3. Representative chemical composition of garnets

Sample Analysis	P59 43 P59	P59 44 P59	P58 38 P58	P50B 55 P50B	P66 60 P66	P56 84 P56	DB20A 76 DB20A	DB20A 77 DB20A
Location Mineral	Pernštejn gar	Pernštejn gar						
SiO <sub>2</sub>	38.42	38.18	37.64	36.45	35.61	38.23	35.63	36.57
TiO <sub>2</sub>	0.06	0.13	0.09	0.04	0.00	0.00	0.06	0.05
Al <sub>2</sub> O <sub>3</sub>	21.08	21.24	21.43	22.00	20.77	21.67	21.82	20.41
FeO calc	34.89	34.82	33.88	31.39	33.42	31.10	31.93	33.27
Fe <sub>2</sub> O <sub>3</sub> calc	0.00	0.00	0.00	0.00	3.18	0.00	0.82	0.09
MnO	1.29	1.26	1.94	5.44	2.15	1.61	7.80	7.81
MgO	4.49	4.44	4.60	2.54	2.37	6.67	1.12	0.95
CaO	0.32	0.28	0.36	0.63	2.22	0.72	0.72	0.77
Total	100.55	100.35	99.94	98.49	99.42	100.00	99.90	99.92
TSi	3.06	3.04	3.01	2.98	2.90	3.00	2.92	3.00
TAI	0.00	0.00	0.00	0.02	0.10	0.00	0.08	0.00
SumT	3.06	3.04	3.01	3.00	3.00	3.00	3.00	3.00
Al <sup>VI</sup>	1.97	1.99	2.02	2.10	1.90	2.01	2.02	1.97
Fe <sub>3</sub>	0.00	0.00	0.00	0.00	0.20	0.00	0.05	0.01
Ti	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00
SumA	1.98	2.00	2.02	2.11	2.09	2.01	2.07	1.98
Fe <sub>2</sub>	2.32	2.32	2.26	2.15	2.28	2.04	2.19	2.29
Mg	0.53	0.53	0.55	0.31	0.29	0.78	0.14	0.12
Mn	0.09	0.09	0.13	0.38	0.15	0.11	0.54	0.54
Ca	0.03	0.02	0.03	0.06	0.19	0.06	0.06	0.07
SumB	2.97	2.96	2.98	2.89	2.91	2.99	2.93	3.01
Sum_cat	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
O	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00
Alm	78	78	76	74	78	68	75	76
And	0	0	0	0	1	0	0	0
Gross	1	1	1	2	6	2	2	2
Pyrone	18	18	18	11	10	26	5	4
Spess	3	3	4	13	5	4	18	18

P59 gar-bt schist  
P58 gar-bt schist  
P50B bt gneiss with garnet

P66 gar-bt gneiss  
P56 anthophyllite schist  
DB 20A migmatized gneiss

is supposed to decrease the granite melting point (Pichavant 1981).

The pressure of equilibration of the mica schist gneisses was calculated using the plagioclase-garnet-Al<sub>2</sub>SiO<sub>5</sub>-quartz geobarometer of Ghent (1976). The presence of sillimanite and kyanite in the rock indicates disequilibrium relations. The lack of equilibrium is also reflected in the calculation of the value of the distribution coefficient K<sub>D</sub> and pressures, which exhibit scattering ( $\log K_D = -1.6$  to  $-2.7$ ,  $P = 5$  to  $7.9$  kbar) (Pertoldová 1986).

The younger metamorphism of the paraseries rocks is of retrograde nature, which is apparent from the presence of transverse growth of muscovite, formation of chlorite and sillimanite at the expense of biotite, and chlorite at the expense of garnet.

#### Oxygen and carbon isotopes

The oxygen and carbon isotope study of the minerals from the skarn paragenesis, metasediments and marble was carried out, Tab. 6.

In the skarns, the  $\delta^{18}\text{O}$  values varied in the range 0.2 to 2.4 ‰ for garnets and a value of  $-3.3$  was obtained for magnetites from two different samples. Equilibration temperatures of  $670$  °C ( $\pm 50$  °C) and  $640$  °C ( $\pm 50$  °C) were calculated for the garnet-magnetite and clinopyroxene-magnetite pairs respectively for sample 22/94; these values are in agreement with the temperatures of  $620$  °C or

The temperature and pressure conditions of equilibration of rocks surrounding the skarn mineralization were derived using the garnet-biotite geothermometer (Ferry – Spear 1978), garnet-phengite (Green – Hellman 1982) and plagioclase-microcline (Whitney – Stormer 1977) geothermometers. The temperatures determined are given in Tab. 5. It is apparent that the rocks of the paraseries equilibrated at higher temperatures,  $613$ – $730$  °C, than the temperature values corresponding to orthogneisses and migmatites,  $550$ – $600$  °C (Pertoldová 1986), where B<sub>2</sub>O<sub>3</sub>

Table 4. Representative chemical composition of biotites

Sample Analysis	P59 188 P59	P59 189 P59	P58 174 P58	P58 175 P58	P50B 200 P50B	P66 205 P66	P66 206 P66	DB20A 223DB20A
Location Mineral	Pernštejn biotite							
SiO <sub>2</sub>	36.69	36.23	34.69	34.81	35.82	33.32	31.58	36.39
TiO <sub>2</sub>	2.51	2.46	2.63	2.65	2.30	1.96	1.68	3.17
Al <sub>2</sub> O <sub>3</sub>	19.36	19.75	20.09	19.71	26.40	20.41	19.87	19.51
FeO	18.33	18.92	19.08	18.94	15.63	23.82	25.33	25.03
MnO	0.00	0.00	0.09	0.06	0.20	0.06	0.10	0.32
MgO	11.22	11.33	11.78	11.71	7.80	8.45	8.50	4.65
CaO	0.00	0.05	0.05	0.00	0.10	0.06	0.00	0.00
Na <sub>2</sub> O	0.61	0.63	0.45	0.35	0.18	0.24	0.25	0.10
K <sub>2</sub> O	7.28	6.65	8.06	7.84	7.57	7.68	7.83	7.68
H <sub>2</sub> O	4.05	4.05	4.00	3.92	4.13	3.91	3.86	3.93
Total	100.05	100.07	100.92	99.99	100.13	99.91	99.00	100.78
Si <sup>IV</sup>	5.43	5.36	5.15	5.20	5.19	5.11	4.96	5.51
Al <sup>IV</sup>	2.57	2.64	2.85	2.80	2.81	2.89	3.04	2.49
T site	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
Al <sup>VI</sup>	0.81	0.80	0.67	0.68	1.70	0.80	0.64	1.00
Ti <sup>VI</sup>	0.28	0.27	0.29	0.30	0.25	0.23	0.20	0.36
Fe <sup>+2</sup>	2.27	2.34	2.37	2.37	1.90	3.06	3.33	3.17
Mn <sup>+2</sup>	0.00	0.00	0.01	0.01	0.03	0.01	0.01	0.04
Mg	2.48	2.50	2.61	2.61	1.69	1.93	1.99	1.05
O site	5.83	5.92	5.96	5.96	5.56	6.02	6.18	5.62
Ca	0.00	0.01	0.01	0.00	0.02	0.01	0.00	0.00
Na	0.18	0.18	0.13	0.10	0.05	0.07	0.08	0.03
K	1.37	1.26	1.53	1.50	1.40	1.50	1.57	1.49
A site	1.55	1.44	1.67	1.60	1.47	1.58	1.65	1.52
O	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00
OH	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
mg <sub>SL</sub>	0.52	0.52	0.52	0.52	0.47	0.39	0.37	0.25

P59 gar-bt schist  
P58 gar-bt gneiss  
P50B bt gneiss with garnet

P66 gar-bt gneiss  
DB20A migmatized gneiss

710 °C derived for skarn paragenesis by the element distribution method gar-cpx geothermometer of Ai (1994), Ellis – Green (1979). In magnetite skarn P51, amphibole is apparently in disequilibrium with magnetite, which confirms the results of petrological study (amphibole is formed secondarily at the expense of clinopyroxene).

For the rocks of the surrounding parasesries, the following temperatures were calculated on the basis of the measured δ<sup>18</sup>O values: for garnet-biotite schist P59 610±50 °C (the quartz-garnet pair) and for biotite gneiss with garnet (P50B) 710±70 °C (the quartz-biotite pair). These values are not in contradiction with the temperatures derived on the basis of distribution of the elements between garnet and biotite and garnet and phengite.

For marble from the broader surroundings of the skarn rocks (sample 100, sample 101), δ<sup>18</sup>O values of 14.0 and 18.4 and δ<sup>13</sup>C values of – 0.6 and 1.9 ‰ were measured,

corresponding to regionally metamorphosed marbles (Shieh – Taylor 1969, Hudson 1977).

The δ<sup>18</sup>O values in the skarn minerals differ from the δ<sup>18</sup>O values for minerals of the surrounding rocks of the parasesries – they are systematically lower. Similarly, the measured δ<sup>18</sup>O and δ<sup>13</sup>C values of calcite in marble P99 (marble forms a 20 cm thick lens in the garnet-amphibole skarn) are low and differ from the marble in the broad surroundings, whose δ<sup>13</sup>C values correspond to the values for oceanic carbonates. The decrease in the δ<sup>18</sup>O for these marbles from the broad surroundings compared to the values for the oceanic carbonates could be partly caused by decarbonization during metamorphism and exchange with metamorphic solutions. The δ<sup>18</sup>O and δ<sup>13</sup>C values for calcite marble P99 are very low. In the case of oxygen, it is possible to consider either primarily low values, produced by hydrothermal activity during sedimentation, or secondarily decreased values caused

by the effects of the metamorphic fluids. At high metamorphic temperatures and low δ<sup>18</sup>O values of the metamorphic fluids (~ 3 ‰), the δ<sup>18</sup>O value for calcite was shifted to the values for the metamorphic fluids and attained a value of ~ 7 ‰. The low δ<sup>13</sup>C value of this calcite apparently indicates that, in addition to decarbonization reactions, it could be affected by the presence of organic matter in the protolite and/or enrichment from an external source.

The δ<sup>18</sup>O values are lowest in skarns and in the marble intercalation (P99) and increase in the surrounding metasediments. Metamorphic isotope homogenization of the skarns with their surroundings did not occur.

The δ<sup>18</sup>O values in the garnet-pyroxene skarns, varying between –0.3 and 2.5 ‰, are not in agreement with the concept of formation of these skarns from high-temperature metasomatic solutions derived from granitoid rocks.

Table 5. Calculated temperatures at the Pernštejn locality (at 5kbar)

Sample	$\bar{x}$ T°C (FS)	$\sigma$	$\bar{x}$ T°C (GH)	$\sigma$	$\bar{x}$ T°C (WS)	$\sigma$	$\bar{x}$ T°C (A)	$\sigma$	$\bar{x}$ T°C (E-G)	$\sigma$
P 58 gar-biot gneiss	613	21								
P 21 gar-biot gneiss	642	25								
P 59 gar-biot schist	653	21								
P 66 gar-biot gneiss	653	32								
D.b.28 biot gneiss with gar	729	10	665	32						
D.b.36A biot gneiss with gar	677	5	646	47						
D.b.25A mica-schist gneiss			666	20						
32/94 gar-cpx skarn							624	5	707	10
D.b.20A migmatized gneiss	562	28	600	24	554	22				
D.b.22 orthogneiss					584	10				

(FS) - Ferry, Spear 1978

(GH) - Green, Hellman 1982

(WS) - Whitney, Stormer 1977

(A) - Ai 1994

(E-G) - Ellis, Green 1979

Table 6. Stable isotope analysis  $\delta^{18}\text{O}$  (SLOW) and  $\delta^{13}\text{C}$  (PDB) of minerals from skarns and surrounding rocks

Location	Sample	Rock type	Quartz	Pyroxene	Garnet	Amphibole	Biotite	Magnetite	Calcite	Calcite $\delta^{13}\text{C}$ ‰ PDB
Pernštejn	22/94	gar-cpx skarn		0.2	-0.3				-3.3	
Pernštejn	32/94	gar-cpx skarn		2.4	1.2					
Pernštejn	32/94	garnet in band			2.5					
Pernštejn	P 51	magnetite skarn				2.8		-3.3		
Pernštejn	P 54	gar-cpx skarn		1.4	1.5					
Pernštejn	P 61	gar skarn	3.8		1.7					
Pernštejn	P 59	gar-biot schist	4.7		1.0			3.7		
Pernštejn	P 56	anthophyllite schist	12.9		6.8	a) 4.7	a) 4.7			
Pernštejn	P 50B	gar-biot gneiss	8.9					5.4		
Pernštejn	P 99	marble		b) 1.6		b) 1.6			7.1	-9.9
Nedvědice	100	marble							14.0	-0.6
Smrk	101	marble							18.4	1.9

a) mixture of amphibole and biotite

b) mixture of pyroxene and amphibole

The  $\delta^{18}\text{O}$  values of granitoids generally vary between 6 and 10 ‰ and high-temperature solutions that would be in equilibrium with such rocks would have similar isotopic composition at the probable low water-rock ratio.

The  $\delta^{18}\text{O}$  values obtained for comparison from the contact scheelite skarn from Vrbík near Horažďovice, formed by replacement of Moldanubian limestones at the contact with the Červenský granodiorite, are much higher and correspond to the concept of high-temperature solutions derived from granitoid rocks. In two samples from Vrbík,  $\delta^{18}\text{O}$  values 7.8 and 8.5 ‰ for cpx, 9.2 and 8.8 ‰ for garnet, and 7.2 and 6.4 ‰ for scheelite were found.

## Distribution of REE

The REE contents were measured in skarns from the Pernštejn locality, in the rocks of the surrounding paragneisses, and also in the separated phases (garnets, pyroxenes, magnetites) of the skarn paragenesis.

The REE contents of the metasediments in the vicinity of the skarns correspond to the values for post-Archaic sediments with typical ratios of LREE and HREE of  $\approx 10$  and with a negative europium anomaly, Fig. 7. The REE contents of skarns are lower, Fig. 8. The ratio of light and heavy REE is  $\approx 1$  and a positive Eu anomaly is apparent for some samples.

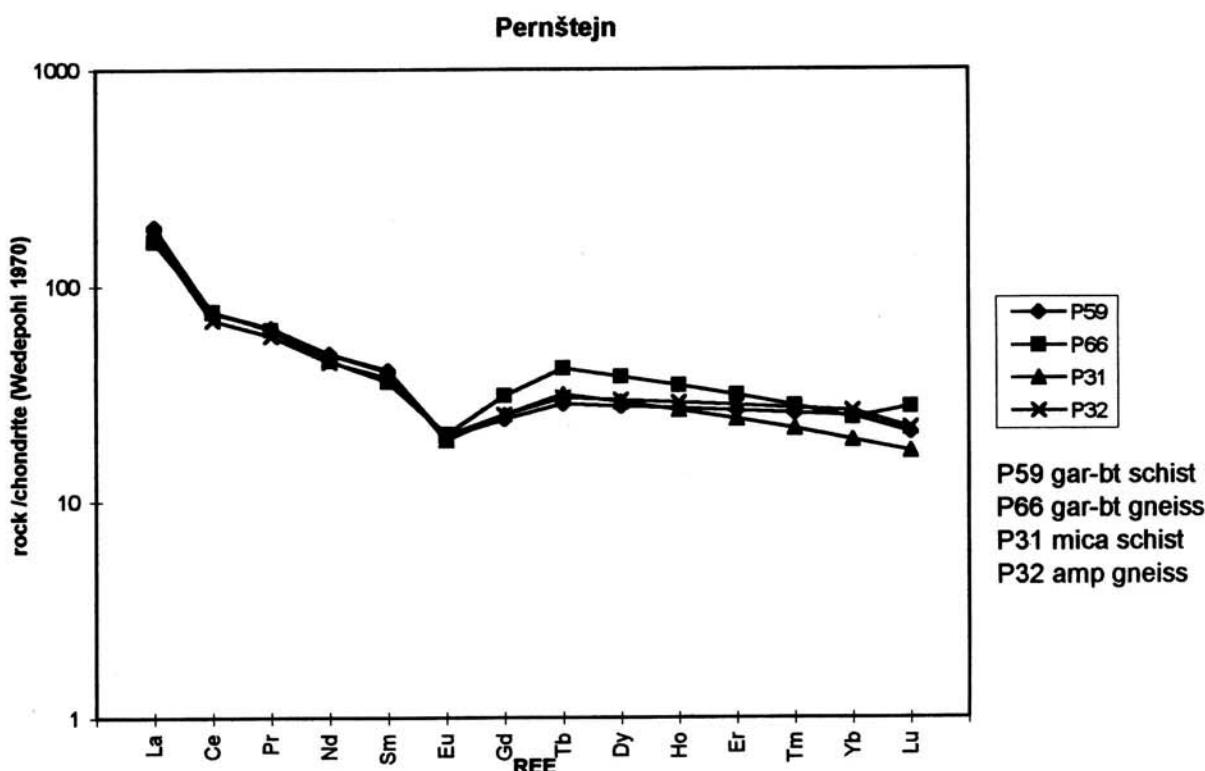


Fig. 7. Chondrite-normalized REE plot of Pernštejn gneiss. Sample numbers are indicated.

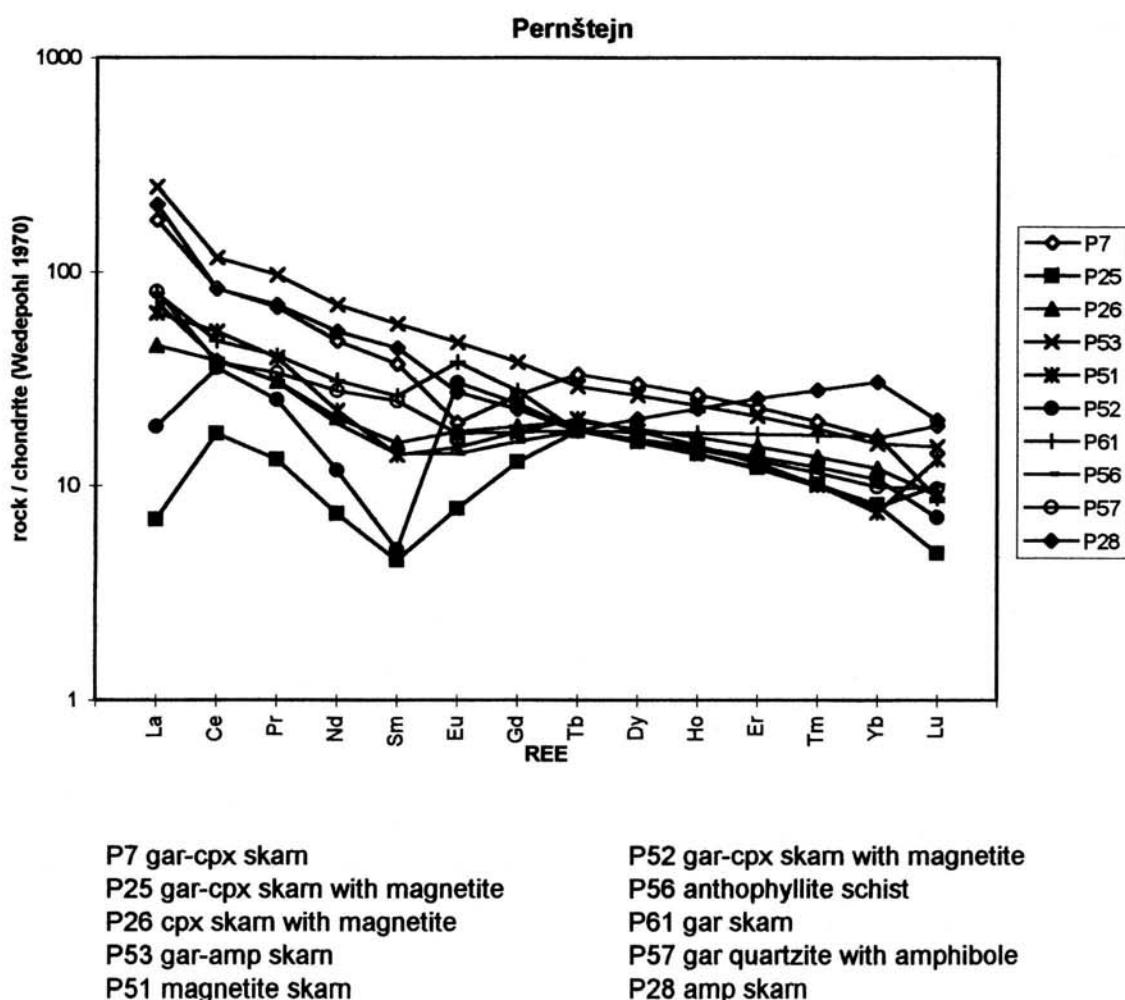


Fig. 8. Chondrite-normalized REE plot of Pernštejn skarns. Sample numbers are indicated.

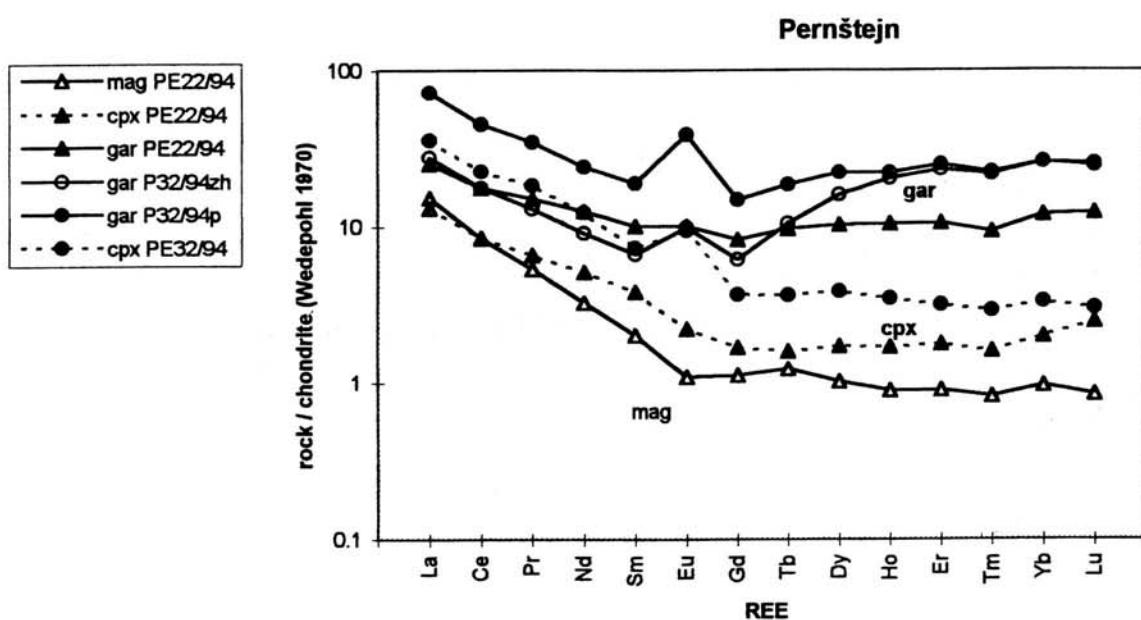


Fig. 9. Chondrite-normalized REE plot of Pernštejn skarn minerals. magPE22/94 – mag from the 22/94 gar-cpx skarn; cpxPE22/94 – cpx from the 22/94 gar-cpx skarn; garPE22/94 – gar from the 22/94 gar-cpx skarn; garP32/94zh – gar from the 32/94 gar-cpx skarn; garP32/94p – gar from the band 32/94 gar-cpx skarn; cpxPE32/94 – cpx from the 32/94 gar-cpx skarn.

The REE curves in the separated minerals from two skarn samples (analyzed by the ICP methods in the laboratories of Analytika Co. Ltd.) reveal identical characteristics and also differences, Fig. 9. The overall slope of the curves is slight. Fractionation of the HREE into the garnets is apparent. Sample P32/94 is overall richer in REE and both its main minerals exhibit a clear positive Eu anomaly. In this sample garnet was analyzed from a band crossing the skarn body (P32/94p). This garnet was apparently formed as a relatively younger member in the metamorphic paragenesis. It differs from the garnet of the main skarn paragenesis in a higher content of LREE.

Analyses of the REE in whole rock samples and the separated minerals indicate that the individual lithological skarn layers have somewhat variable characteristics, indicating different compositions of the skarn layers, which were not eliminated even by intense regional metamorphism at a temperature of about 660 °C. This indicates limited or no metamorphic mobility of these elements between the rock types. On the other hand, REE moved on a small scale in the rock (rock type, position), as is indicated by the fractionation of REE between garnet, pyroxene and magnetite.

## Conclusions

Skarns at Pernštejn constitute a lithologically inhomogeneous body in which the older fold structures were retained and that is folded in its hanging wall part together with the surrounding paraseses. The derived temperatures of skarn association of 620 °C (710 °C) or 670 °C (640 °C) are close to the temperatures of the regional metamorphism of the surrounding metasediments, i.e. ≈ 660 °C. Migmatites and metagranitoids exhibit lower temperatures, 550–600 °C. In some rock types of the surrounding paraseses, mineral paragenesis indicating disequilibrium relations was found.

The intensity of the younger metamorphic event is variable, depending on the rock type and geological position. For example, the effects of younger metamorphism do not attain an intensity in the skarns such as can be observed for the metasediments of the broader surroundings. This is probably caused by low water fugacity in the original skarn mineral association.

In the light of the derived metamorphic temperatures, it cannot readily be imagined that the skarn was formed by the action of orthogneiss or migmatite, because these two rocks were formed after the peak of the metamorphism, which the skarns underwent together with the metasediments. The isotopic composition of oxygen also do not permit the concept of formation of the skarns from high temperature solutions derived from granitoid rocks. The oxygen of the skarns could also not have been derived from a sedimentary carbonate environment. It was most probably derived from hydrothermal solutions. The REE distribution indicates the presence of high-temperature and (or) reducing solutions, which are common in hydrothermal systems at the ocean floor (Lottermoser 1992).

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## Metamorfní vývoj skarnů na lokalitě Pernštejn, svratecké krystalinikum, Český masiv

Na lokalitě Pernštejn (svratecké krystalinikum, Český masiv) byl studován geologický a metamorfní vývoj skarnů ve vztahu k okolní parasérii, ortorulám a migmatitům z hlediska geologické stavby, minerálních asociací, chemismu minerálů, geotermometrie, izotopů kyslíku a vzácných zemin. Skarny jsou z litologického i mineralogického hlediska nehomogenní čočky, jejichž deformace je komplikovanější než v okolní parasérii. Teploty vzniku granát-klinopyroxen-magnetitové parageneze skarnů, 620 °C (710 °C), resp. 670 °C (640 °C) (odvozené na základě distribuce hlavních prvků a izotopů kyslíku mezi koexistující fáze) odpovídají podmírkám hlavní metamorfózy v amfibolitové facii. Za stejných podmínek byly metamorfovány i horniny parasérie, kdežto migmatity a metagranitoidy vykazují teploty nižší (550–600 °C). Izotopické složení kyslíku v silikátech skarnových paragenezí není ve shodě s představou o kontaktně metasomatickém vzniku skarnů, spojeném s metagranitoidy a migmatity. Kyslík pravděpodobně nepochází z metamorfních roztoků, které byly v rovnováze s parasérií. Distribuce vzácných zemin ukazuje na působení roztoků redukční povahy nebo na vysoké teploty. Domníváme se, že prekurzory skarnů byly přítomny v parasérii již od počátku, byly s ní metamorfovány, a pravděpodobně vznikly v sedimentárně-exhalacním prostředí.