The HT/LP metamorphism of dolomite marbles in the eastern part of the Moldanubicum; a manifestation of heat flow related to the Třebíč Durbachite Massif

HT/LP metamorfóza dolomitických mramorů ve východní části moldanubika; projev tepelného toku spojeného s třebíčským durbachitovým masivem (Czech summary)

(4 text-figs.)

MILAN NOVÁK - STANISLAV HOUZAR

Department of Mineralogy and Petrography, Moravian Museum, Zelný trh 6, 659 37 Brno, Czech Republic

Three independent metamorphic events are suggested in the dolomite marbles of the Strážek and Moravian Moldanubicum, western Moravia, Czech Republic: HT/HP-MP metamorphism M1, HT/LP metamorphism M2, and retrograde MT-LT/LP metamorphism M3. Since the studied region is tectonically heterogeneous and dolomite marbles are more sensitive than other rocks types to the changes in fluid composition (Ferry 1992), they may be affected in different stages of the metamorphic evolution. Consequently, the M2 metamorphism in dolomite marbles is not directly comparable to the M2 metamorphism in metapelites. The HT/LP metamorphism M2 produced a distinct mineralogical zoning around the Třebíč Durbachite Massif (TDM). Four metamorphic zones, formed by reactions involving the mineral assemblage tremolite + phlogopite + dolomite + calcite + forsterite + chlorite + spinel + clinohumite, were recognized. Two distinct paths of the metamorphism M2 were distinguished in the isobaric $T\text{-}X_{CO_2}$ diagram. The distribution of the metamorphic zones, course of the isograds and textural relations strongly indicate the heat flow related to the TDM. The cause of the heat flow, however, is not sufficiently understood. It seems to be very likely related to the emplacement and consolidation of the TDM amphibole-biotite melagranite, and the heat flow may have acted in early to near subsolidus stages of the intrusion emplacement. The age of the HT/LP metamorphism M2 in the range from 340 to 330 Ma is estimated from the radiometric ages of the durbachite intrusion (Pb-Pb, 343 Ma; Holub et al. 1996) and apparently postmetamorphic lepidolite pegmatites (Rb-Sr, 323-306 Ma; Černý et al. 1995), penetrating the studied metamorphic complex.

Key words: dolomite marble, HT/LP metamorphism, metamorphic zones, heat flow, Třebíč Durbachite Massif, Moldanubicum, western Moravia

Introduction

The regional HT/LP metamorphism and its position in the Variscan orogeny are commonly discussed in the Moldanubicum (e.g. Cháb - Suk 1977, Zaydan - Scharbert 1983, Petrakakis 1986, O'Brian - Carswell 1993, Büttner - Kruhl 1995, Babůrek 1995). Behrmann et al. (1994) formulated three hypothesis to explain HT/LP metamorphism in the Moldanubian of Bavaria: (i) vertical telescoping of thick crust by tectonically driven extension; (ii) fast adiabatic uplift; (iii) heat transfer from the deep crust or from mantle by fluids or by magmas on a regional scale. The latter hypothesis is considered the most probable by the authors. However, the position of the HT/LP metamorphism in a metamorphic evolution and the nature of the external heat sources in particular are still enigmatic in many cases.

The metamorphism of dolomite marbles studied within the Strážek and Moravian Moldanubicum, in the eastern part of the Moldanubian region (Fig. 1), displays HT/LP metamorphic conditions with high activity of H_2O and F in fluids (Novák 1988, 1989; Houzar - Novák 1991). New data given in this paper strongly indicate, that the HT/LP metamorphism is at least spatially related to the Třebíč Durbachite Massif (TDM) (Fig. 2).

Geological setting and metamorphic history

Dolomite marbles are a typical member of the metamorphosed volcano-sedimentary unit along with abundant amphibolites, however, relatively pure, coarse-grained calcite marbles exceptionally occur (Novák 1987, Houzar - Novák 1995). Dolomite marbles form lenticular bodies, about 20 m thick, mostly located in migmatized biotite gneiss. This dolomite-amphibolite-gneiss unit is widespread particularly in the Strážek Moldanubicum, NE of the TDM. A relatively narrow belt of similar dolomite marbles with rare associated amphibolites rims the Třebíč Durbachite Massif along its W and SE edge (Fig. 1). Dolomite marbles underlying durbachite were found in drill holes in the vicinity of Tasov and Jasenice (E border of TDM). The dolomite-amphibolite-gneiss unit is apparently different in its lithology and mineral assemblages from dolomite marbles of the Drosendorf Unit (Houzar - Novák 1995) and may correspond to the amphibolite-rich lower part of the Gföhl Unit (Fuchs 1991), and partly also to the Raabs Unit, in the sense of Steyrer - Finger (1994).

The TDM is a large intrusion of melagranites to melasyenites enriched in incompatible elements (e.g. Holub 1988). Geophysical data indicate a sheet-like shape of the body (Rejl - Sedlák 1987). It is mostly strongly foliated near the contact with host rocks (Bubeníček 1968), and locally rimmed by leucocratic granitic rocks (Němec 1982). The sheet-like body of durbachite rocks was significantly extended towards the NE, where small erosional relics locally occur (Novák 1989). A Pb-Pb age of 343 Ma interpreted as the time of intrusion was reported for the TDM (Holub et al. 1996). The effect of the contact metamorphism of the TDM on its mantle was not studied in detail.

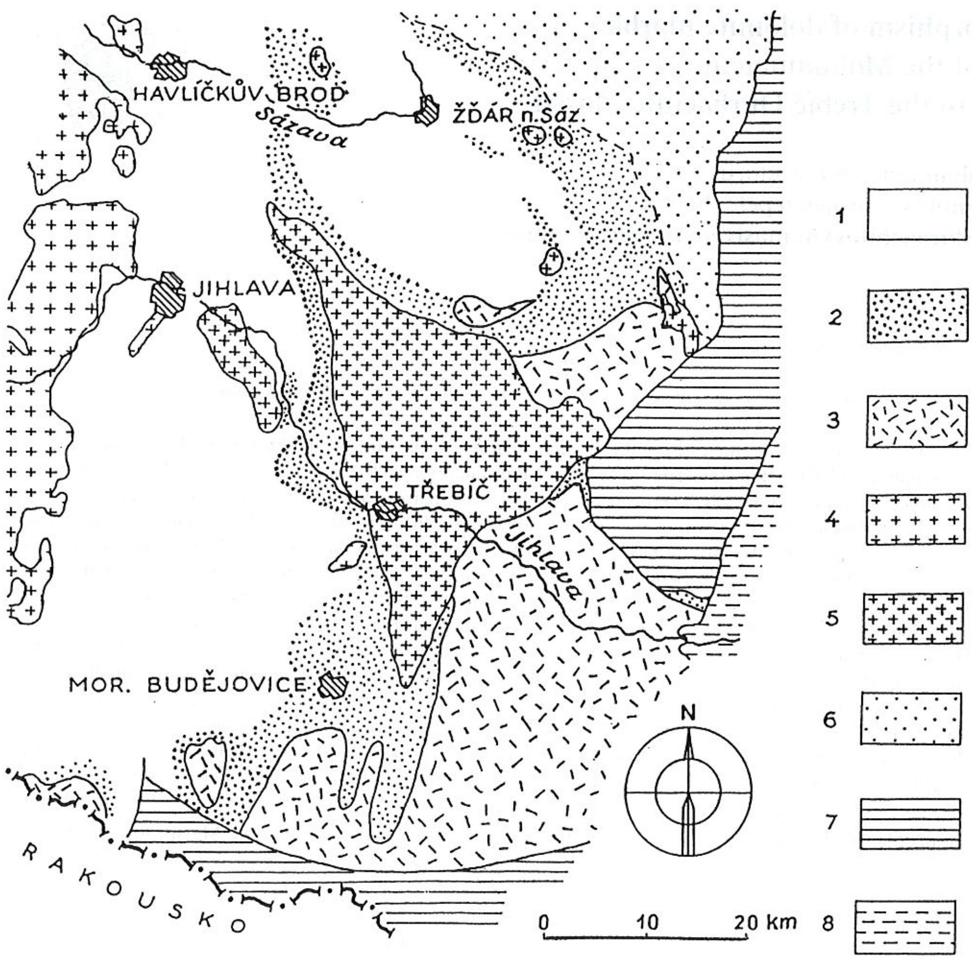

Fig. 1. Schematic geological map of the eastern part of the Moldanubicum showing the location of the Třebíč Durbachite Massif *1* - Monotonous and Varied Group; *2* - dolomite-amphibolite-gneiss unit; *3* - Gföhl gneiss and granulites; *4* - Central Moldanubian Pluton; *5* - durbachites; *6* - Svratka Unit; *7* - Moravicum (including the Olešnice, Vratěnín and Podhradí Units); *8* - sedimentary rocks (Carboniferous-Permian)

Novák (1988) hinted on a spatial and genetic relationship of chondrodite and clinohumite occurrences with respect to the TDM. Weiss (1977) and Houzar (1985) described the cordierite and wollastonite isograds spatially related to the TDM, but they did not discuss its genetic control in detail.

Three independent metamorphic events are suggested in the dolomite marbles, in part supported by mineral assemblages from associated gneisses: a HT/HP-MP metamorphism M1, a HT/LP metamorphism M2, and a retrograde MT-LT/LP metamorphism M3 (Novák 1989, Houzar - Novák 1991).

The early HT/HP-MP regional metamorphism M1 is characterized by the simple equilibrium mineral assemblage phlogopite + tremolite + calcite + dolomite, distributed through a part of the investigated area including the adjacent Svratka Unit. The mineral assemblages and their metamorphic textures indicate a maximum temperature of about 660 °C for estimated P_{fluid} = 600 MPa, syntectonic crystallization, and the PTX conditions of the metamorphism M1 similar in all marbles within the whole studied area (Novák 1989). Due to the absence of minerals or mineral assemblages indicating the pressure in the dolomite marbles, it was estimated based on the mineral assemblages of associated gneiss, the P-T conditions of metamorphism of marbles and calc-silicate rocks in the Varied Unit (Högelsberger 1989), and data from literature (Zaydan - Scharbert 1983, Petrakakis 1986, Vrána 1992).

The low-pressure metamorphism M2, spatially related to the TDM is discussed in detail below. The retrograde metamorphism M3, characterized by replacement of forsterite by antigorite, is widespread irregularly through the whole studied area and within a single dolomite body. Very low $X_{CO_2} < 0.05$ and temperatures < 450 °C are suggested for this stage (Novák 1989).

Chemistry of rock-forming minerals in dolomite marbles

Representative chemical analyses of rock-forming minerals - phlogopite, tremolite, forsterite, clintonite, chlorite, spinel and humite minerals are given in Table 1; a complete list of analyses was published by Novák (1989). They were performed using electron microprobes ARL SEMQ (Geological Survey, Praha) and Jeol-50A (Geological Institute of Academy of Sciences, Praha). The fluorine contents were determined by a photometric method (analyst P. Povondra).

The analysed minerals are characterized by very low Fe and Mn concentrations, the X_{Mg} values vary from 0.96 to 0.99 in most minerals. Increased Fe contents were observed in spinel, and exceptionally in forsterite, tremolite and phlogopite. The order of Mg preference over Fe + Mn is as follows: chlorite > phlogopite > tremolite > clinohumite, forsterite >> spinel. Rare samples carrying forsterite, tremolite and phlogopite with X_{Mg} < 0.95 are not discussed here. This order is very similar to those from several metamorphic terrains (e.g. Rice 1977a, Bucher-Nurminen 1981, 1982a, Sauter 1983). Rare zincian spinels occur at Strážek and Lukov (Ulrych 1971, Němec 1973, Novák et al. 1997), but their position in the metamorphic evolution was not studied in detail.

Table 1. Representative electron microprobe analyses of minerals

	Phl	Tr	Fo	Chl	Spl	Chu	Cho	Cli
SiO_2	39.93	57.40	41.76	29.57	0.07	37.78	34.48	20.61
TiO_2	0.80	0.06	0.09	0.11	0.13	2.79	0.74	0.20
Al_2O_3	16.42	0.65	0.00	22.96	69.15	0.00	0.00	38.32
FeO	1.62	0.40	6.00	2.65	6.39	2.59	1.62	0.97
MgO	27.82	26.18	52.29	30.77	24.49	54.77	55.64	22.92
MnO	0.00	0.00	0.08	0.00	0.04	0.06	0.03	0.02
CaO	0.04	13.16	0.00	0.00	0.00	0.00	0.00	11.88
Na_2O	0.48	0.07	0.00	0.00	0.00	0.00	0.00	0.28
K_2O	8.73	0.07	0.00	0.00	0.00	0.00	0.00	0.00
F^*	1.05	n.d.	n.d.	n.d.	n.d.	1.80	4.42	n.d.
H_2O^+	3.84	2.21	n.d.	12.68	n.d.	2.61	5.34	4.29
F=O	-0.44	-	-	-	-	-0.77	-1.86	-
total	100.29	100.20	100.22	98.74	100.27	101.63	100.41	99.49
Si^{4+}	5.776	7.784	1.002	2.797	0.002	3.925	2.010	2.883
Ti^{4+}	0.087	0.006	0.002	0.008	0.002	0.218	0.032	0.021
Al^{3+}	2.799	0.104	-	2.560	1.982	-	-	6.318
Fe^{2+}	0.196	0.045	0.120	0.210	0.130	0.225	0.079	0.113
Mg^{2+}	6.000	5.292	1.871	4.340	0.888	8.483	4.834	4.780
Mn^{2+}	0.000	0.000	0.002	-	0.001	0.005	0.001	0.002
Ca^{2+}	0.006	1.912	-	-	-	-	-	1.781
Na^+	0.135	0.018	-	-	-	-	-	0.076
K^+	1.611	0.012	-	-	-	-	-	-
F^-	0.480	-	-	-	-	0.591	0.815	-
H^+	1.520	2.000	-	8.000	-	1.409	1.185	4.000
O_2^-	23.520	24.000	4.000	18.000	4.000	17.409	9.185	24.000
CATSUM	16.610	15.174	2.996	9.915	3.005	12.857	6.958	15.975

* fluorine determined photometrically, analyst Dr. P. Povondra.
\+ determined by stoichiometry. Individual minerals recalculated on a basis of 24 anions (phlogopite, tremolite, clintonite), 4 anions (forsterite, spinel), 18 anions (chlorite, clinohumite), 10 anions (chondrodite).

Metamorphism M2

Mineral reactions, zones and isograds

The metamorphism M2 produced a distinct mineralogical zoning in silica-undersaturated dolomite marbles (mostly less than 5 vol. % of silicates) around the TDM. A typical feature of the M2 metamorphism is a mosaic distribution of the newly-formed mineral assemblages in the matrix consisting of the relic mineral assemblages of the M1 metamorphism within a single thin section. Five metamorphic zones are defined by the following mineral assemblages:

A - tremolite + phlogopite + dolomite + calcite
B - forsterite + chlorite I + calcite + dolomite
C - forsterite + chlorite I + spinel + calcite + dolomite
D - forsterite + spinel + calcite + dolomite
K - clinohumite + spinel + calcite + dolomite ± forsterite ± chlorite I

The regional distribution of the zones is shown in Fig. 2. Mineral formulas and abbreviations used in mineral reactions given below are listed in Table 2.

Table 2. Abbreviations and composition of minerals

calcite	Cal	$CaCO_3$
chlorite	Chl	$Mg_5Al_2Si_3O_{10}(OH)_8$
chondrodite	Cho	$Mg_5Si_2O_8(OH,F)_2$
clinohumite	Chu	$Mg_9Si_4O_{16}(OH,F)_2$
clintonite	Cli	$Ca(Mg,Al)_3(Al_3Si)O_{10}(OH)_2$
diopside	Di	$CaMgSi_2O_6$
dolomite	Dol	$CaMg(CO_3)_2$
forsterite	Fo	Mg_2SiO_4
phlogopite	Phl	$KMg_3AlSi_3O_{10}(OH,F)_2$
quartz	Qtz	SiO_2
spinel	Spl	$MgAl_2O_4$
tremolite	Tr	$Ca_2Mg_5Si_8O_{22}(OH,F)_2$

Except clintonite all abbreviations according to Kretz (1983)

The equilibrium mineral assemblage of Zone A - phlogopite + tremolite + calcite + dolomite, produced during the HT/HP-MP M1 metamorphism, occurs particularly within the Svratka Unit, and as a relic of the metamorphism M1 locally also in Zone B. The boundary between Zone A and Zone B, defined by the first appearance of forsterite and chlorite I, represents the first recognizable manifestation of the metamorphism M2. Reaction textures demonstrate that the replacement of tremolite by forsterite may go via the reaction:

$$\text{Tr} + 11\ \text{Dol} = 8\ \text{Fo} + 13\ \text{Cal} + 9\ CO_2 + H_2O \quad (1)$$

However, the replacement of the assemblage phlogopite + tremolite + dolomite by forsterite + chlorite I may be expressed by the complex reaction:

$$2\ \text{Phl} + 2\ \text{Tr} + 27\ \text{Dol} = 19\ \text{Fo} + \text{Chl} + 31\ \text{Cal} + 23\ CO_2 + K_2O \quad (2)$$

Tremolite was mostly consumed by the reactions (1) and (2), and its relics occur only very exceptionally within the zones C and D.

Zone C is characterized by the first occurrence of spinel in an equilibrium with chlorite I. The diagnostic equilibrium assemblages of this zone, forsterite + chlorite I + spinel + calcite ± clinohumite ± dolomite, may correspond to the isobaric univariant mineral reaction:

$$\text{Chl} + 2\ \text{Dol} = 3\ \text{Fo} + \text{Spl} + 2\ \text{Cal} + 2\ CO_2 + 4\ H_2O \quad (3)$$

or to an invariant point, if clinohumite + dolomite occur in an equilibrium with the other minerals. Textural relations indicate that the mineral assemblages were formed at the expense of phlogopite and dolomite by the reactions:

$$4\ \text{Phl} + 12\ \text{Dol} = 9\ \text{Fo} + \text{Chl} + \text{Spl} + 12\ \text{Cal} + 12\ CO_2 + 2\ K_2O \quad (4)$$

$$4\ \text{Phl} + 13\ \text{Dol} + H_2O = 5\ \text{Fo} + \text{Chl} + \text{Spl} + \text{Chu} + 13\ \text{Cal} + 13\ CO_2 + 2\ K_2O \quad (5)$$

The disappearance of chlorite I beside common spinel defines the Zone D with the equilibrium assemblages forsterite + spinel + calcite ± clinohumite ± dolomite. Replacement of phlogopite and dolomite could be expressed by the reactions:

$$2\ \text{Phl} + 7\ \text{Dol} = 6\ \text{Fo} + \text{Spl} + 7\ \text{Cal} + 7\ CO_2 + 2\ H_2O + K_2O \quad (6)$$

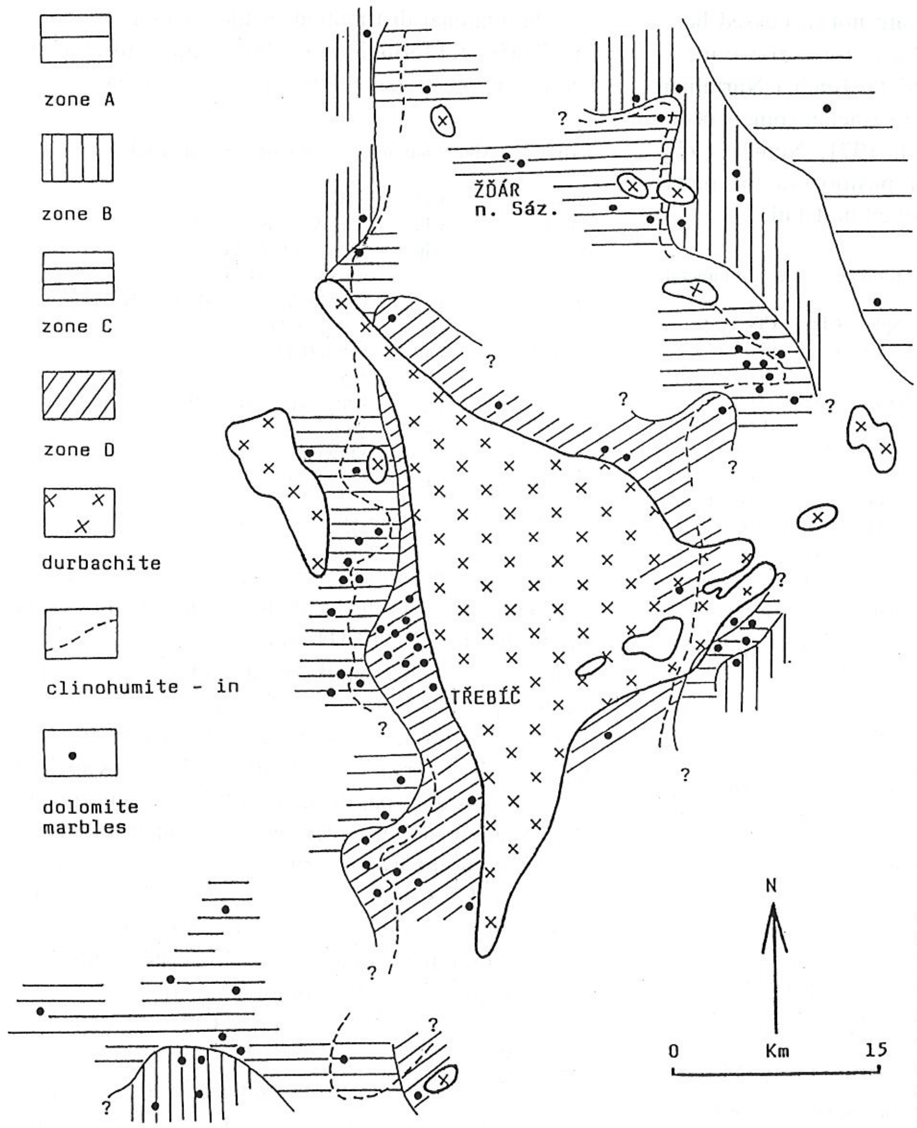

Fig. 2. Distribution of mineral assemblages in dolomite marbles
Diagnostic mineral assemblages: Zone A - tremolite + phlogopite + dolomite + calcite; Zone B - forsterite + chlorite I + calcite + dolomite; Zone C - forsterite + chlorite I + spinel + calcite + dolomite; Zone D - forsterite + spinel + calcite + dolomite; Zone K - clinohumite + spinel + calcite + dolomite ± forsterite ± chlorite I. Mineral assemblages from all dolomite marble bodies in Fig. 2 were studied in thin sections

2 Phl + 8 Dol = 2 Fo + Spl + Chu + 8 Cal + 8 CO_2 + H_2O + K_2O (7)

Tremolite is usually absent and phlogopite is apparently less abundant within this zone relative to Zone C. Diopside in coexistence with forsterite and spinel, as an indication of a higher-grade zone, was observed only in one thin section within the Zone D. It would be defined by the reaction:

3 Tr + 5 Cal = 11 Di + 2 Fo + 5 CO_2 + 3 H_2O (8)

known from terraines metamorphosed under conditions of upper amphibolite to granulite facies (Glassley 1975, Sauter 1983). Almost all tremolite was consumed by the reactions (1) and (2), and the assemblage diopside + forsterite + spinel possibly formed by the reaction:

3 Chl + 2 Cal = 5 Fo + 2 Di + 3 Spl + 5 CO_2 + 12 H_2O (9)

The presence of clinohumite or exceptionally chondrodite in the equilibrium mineral assemblages within Zone C and Zone D defines the metamorphic Zone K. Clinohumite is formed in equilibrium with forsterite by reactions (5) and (7). The typical reaction producing clinohumite:

4 Fo + Dol + H_2O = Chu + Cal + CO_2 (10)

seems to be less important in this area. Forsterite only scarcely is absent in the mineral assemblages of Zone K. Rare chondrodite is known only from marbles close to the contact with durbachite or leucogranitic rocks but their mineral reactions were not studied in detail.

Rare clintonite associated with chondrodite and spinel was found in the drill hole near Tasov, situated several hundred m below the contact with durbachite. The reaction producing this mineral is not known due to complicated textural relationships and scarcity of the mineral.

Late chlorite II commonly appears on the boundary between spinel and forsterite or clinohumite within the zones C and D. This chlorite represents a retrograde phase of the metamorphism M2, distributed through almost the whole studied area, and closely following the prograde phase. Its formation could be explained by a decreasing temperature and expressed by the hydration and carbonation reactions:

3 Fo + Spl + 2 Cal + 2 CO_2 + 4 H_2O = Chl + 2 Dol (11)

3 Chu + 4 Spl + 11 Cal 11 CO_2 + 13 H_2O = 4 Chl + 11 Dol (12)

Locally, a direct replacement of chlorite I by very fine-grained chlorite II is recorded.

The mineral reactions involving phlogopite, forsterite, chlorite, spinel, clinohumite, calcite and dolomite, discussed above, correspond to the KCMAS + (H_2O-CO_2-F) system, and they are commonly described from dolomite marbles (Tracy - Frost 1991). However, most of them, particularly those involving phlogopite, have not been experimentally studied yet and their positions in isobaric T-X_{CO2} diagrams are not known. Due to these reasons, the K-free mineral assemblages involving forsterite, chlorite, spinel, clinohumite, calcite and dolomite in the CMAS + (H_2O-CO_2-F) system, were used for a detailed discussion of the T-X_{CO2} conditions in the studied area.

A typical feature of the mineral reactions involving phlogopite is dealkalization (K-depletion). No other K-bearing phases such as K-feldspar and muscovite, known from some dolomite marbles (Rice 1977b, Bucher-Nurminen 1982b), were observed. Potassium seems to be removed from the dolomite marble bodies via metamorphic pore fluids. The small amount of K added can be hardly recorded in the mineral assemblages of the host gneisses. The apparent width of metamorphic zones of up to 10 km on the present surface (Fig. 2) indicates a regional-scale contact metamorphism. However, shallow to subhorizontal dips of the TDM contacts, observed particularly in the eastern part of the intrusion (Rejl - Sedlák 1987, Bouček et al. 1988), and the presence of erosional relics of durbachite rock NE of the TDM, imply the true thickness of the individual zones to be much smaller, about 1 km or less.

Fluid activity

The activity of CO_2 and H_2O in pore fluids and their importance for metamorphism of carbonate rocks are discussed in many papers (see Tracy - Frost 1991, Ferry 1991). Both high X_{CO_2} from 0.5 to 0.9 (e.g. Moore - Kerrick 1976, Rice 1977a,b, Bucher-Nurminen 1981), and low X_{CO_2} (below 0.4) (e.g. Moore - Kerrick 1976, Rice 1979, Bowman - Essene 1982) were described. Increased activity of F in fluids, inferred particularly from the presence of humite minerals in mineral assemblages, is also known from contact aureoles of granite plutons (Rice 1977a, 1980a,b).

Based on the chemical composition of minerals, textural relations, metamorphic assemblages and sequence of metamorphic isograds, low X_{CO_2} in metamorphic fluids is inferred in the studied region. (i) The observed prograde sequence: tremolite - forsterite - spinel, and the absence of the mineral assemblage tremolite + forsterite + chlorite I + spinel + calcite + dolomite corresponding to the invariant point V (Fig. 3), indicate X_{CO2} < 0.55. (ii) Forsterite, rimmed by calcite in a matrix of dolomite + rare tremolite, as well as a direct replacement of tremolite by forsterite + calcite indicate water-rich fluids with X_{CO_2} < 0.4

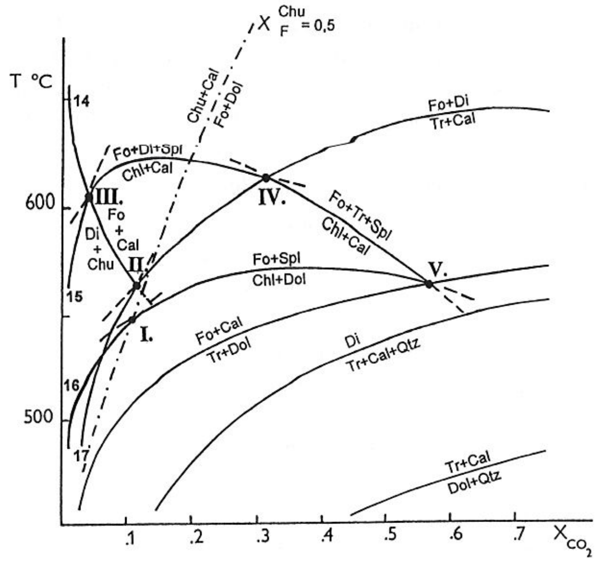

Fig. 3. Isobaric T-X_{CO2} diagram at 200 MPa showing important mineral reactions in dolomitic marbles (J. M. Rice 1980a, modified) Stoichiometry of the mineral reactions given in Table 4

(Heinrich et al. 1986) within the Zone B. (iii) Clinohumite compositions with X_F = 0.38-0.49 (Novák 1989) imply a low X_{CO_2} below 0.2 and very likely also increased activity of F (Rice 1980a) within the Zone K. (iv) Low X_{CO_2} values below 0.2 are indicated by the presence of clintonite (Rice 1979). (v) The isobaric invariant mineral assemblage forsterite + clinohumite + spinel + chlorite I + dolomite + calcite corresponding to the invariant point I (Fig. 3), found at some localities within the Zone C (K), indicates X_{CO_2} about 0.1.

Variations in X_{CO_2} in the studied area are documented through the sequence of metamorphic isograds, mineral reactions, widespread divariant, rare univariant and invariant mineral assemblages, and composition of mineral phases (Ferry 1991). They indicate a decrease of X_{CO_2} from the outer Zone B towards the TDM contact; from X_{CO_2} about 0.4 or less in the Zone B to about 0.1 near the contact with durbachite within zones D and K. The invariant mineral assemblage forsterite + clinohumite + spinel + chlorite I + dolomite + calcite indicates X_{CO_2} about 0.1 within the zones C and K (see Fig. 3).

P-T conditions and T-X_{CO_2} paths of the metamorphism M2

Based on the phase equilibria and fluid composition discussed above, T-X_{CO_2} conditions of the metamorphism M2 were estimated from the isobaric T-X_{CO_2} diagram (Fig. 3 and 4). This figure was constructed from the experimental data of Skippen (1974), Walther - Helgeson (1980), Rice (1980a), and a list of mineral reactions is given in Table 4. The assummed pressure P_{fluid} = 200 MPa is inferred from: (i) the presence of clintonite in dolomite marbles, because all of its known occurrences are limited to a HT/LP contact metamorphism, although the experimentally determined stability field of clintonite is large (Olesch - Seifert 1976, Bucher-Nurminen 1976, Rice 1979); (ii) the presence of cordierite-bearing rocks along the western and north-eastern border of the TDM (Weiss 1977, Veselá et al. 1988). However, the increased pressure up to P_{fluid} = 400 MPa is also possible.

The following temperatures are postulated for the individual metamorphic zones (Table 3). The maximum temperature of about 620 °C for the Zone D could be slightly higher up to 640 °C, where the equilibium mineral assemblage diopside + forsterite was exceptionally found. However, the absence of either periclase or brucite pseudomorphs after periclase may imply temperature below 650 °C, if the pressure P_{fluid} was about 200 MPa or less (Greenwood 1975). Increase of the pressure up to P_{fluid} = 400 MPa would correspond to increase of temperatures in Table 3 by about 50 to 70 °C, and these values are still consistent with the mineral assemblages in the studied dolomite marbles. Generally, the postulated temperatures (Table 3) are similar to those given for the Variscan HT/LP metamorphism (Blümel - Schreyer 1976, Urban 1990, Babůrek 1995). Higher pressure of up to 600 and 800 MPa requires maximum temperature for the metamorphism of dolomite marbles about 750 to 800 °C. Such values seem to be unrealistic, because comparable temperatures were inferred in dolomite marbles from the granulite facies (Glassley 1975, Sauter 1983). The isobaric T-X_{CO_2} diagram (Fig. 4) illustrates the T-X_{CO_2} paths of the prograde stage of the metamorphism M2. Two distinct paths are suggested for the sequence of the observed metamorphic zones distinguished in the studied region: (i) involving clinohumite in the Zone C and Zone D, and (ii) clinohumite-free sequence of metamorphic zones.

Table 3. Postulated temperatures of the M2 metamorphism inferred from the T-X_{co2} diagrams for P_{fluid} = 200 MPa

Zone	T (°C)	Diagnostic mineral assemblage
A	< 500-570	Tr + Do
B	540-570	Fo + ChlI
C	550-580	Fo + Spl + ChlI ± Chu
D	560-620	Fo + Spl ± Chu
K	540-620	Chu (Chu + Fo)

Table 4. Stoichiometry of mineral reactions shown in Figures 3 and 4

Reaction	
1.	Tr + 11 Dol = 8 Fo + 13 Cal + 9 CO_2 + H_2O
3.	Chl + 2 Dol = 3 Fo + Spl + 2 Cal + 2 CO_2 + 4 H_2O
8.	3 Tr + 5 Cal = 11 Di + 2 Fo + 5 CO_2 + 3 H_2O
9.	3 Chl + 2 Cal = 5 Fo + 2 Di + 3 Spl + 12 H_2O
10.	4 Fo + Dol + H_2O = Chu + Cal + CO_2
13.	11 Chl + 4 Cal = 17 Fo + 2 Tr + 11 Spl + 4CO_2 + 42 H_2O
14.	Di + 3 Chu + CO_2 = 14 Fo + Cal + 3 H_2O
15.	14 Chl + 11 Cal = 11 Di + 5 Chu + 14 Spl + 11 CO_2 + 51 H_2O
16.	4 Chl + 11 Dol = 3 Chu + 4 Spl + 11 Cal + 11 CO_2 + 13 H_2O
17.	7 Tr + 12 Cal = 26 Di + Chu + 12 CO_2 + 6 H_2O
18.	Tr + 3 Cal + 2 Qtz = 5 Di + 3 CO_2 + H_2O
19.	Dol + 8 Qtz + H_2O = Tr + 3 Cal + 7 CO_2

The first (i) path, characterized by the absence of clinohumite in Zone B, and only locally in Zone C, implies that the mineral reactions were driven by an increase of temperature combined with decreasing X_{CO_2} up to 0.1 in the Zone C. The path follows univariant assemblage forsterite + spinel + chlorite + calcite + dolomite and appearance of clinohumite in this mineral assemblage indicates that T-X_{CO_2} conditions reached the invariant point I (Zone K). Zone D (Zone K) is characterized by the presence of clinohumite and indicates the activity of H_2O- and F-rich fluids at X_{CO_2} about 0.1, and the mineral reaction is driven particularly by increase of temperature.

The second path (Fig. 4), representing the clinohumite-free sequence of metamorphic zones, is characterized by the absence of invariant mineral assemblages. The path reached univariant mineral assemblage - forsterite + diopside + spinel + calcite + dolomite of the reaction (9), at the area left of the invariant point IV., where X_{CO_2} < 0.3. The mineral reactions are driven by increase of temperature, decreasing of X_{CO_2} seems to be less important.

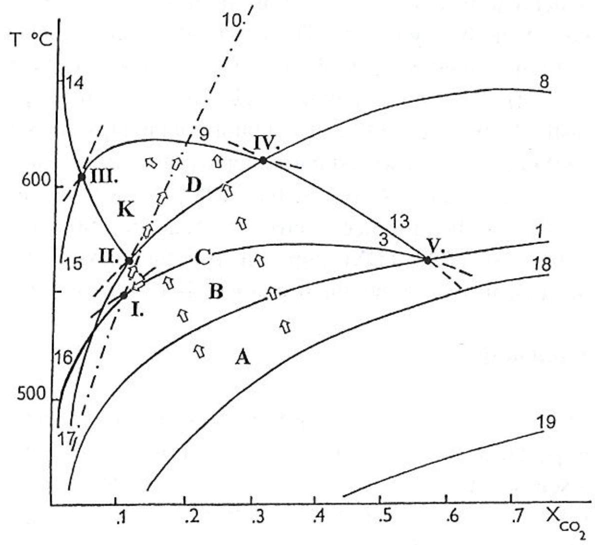

Fig. 4. T-X_{co2} diagram at 200 MPa showing possible T-X_{co2} paths for the metamorphism M2 of dolomite marbles in the Třebíč Durbachite Massif

Two possible paths of progressive metamorphism for the clinohumite-bearing and clinohumite-free sequences of metamorphic zones are given schematically by the arrowed lines. Stoichiometry of the mineral reactions given in Table 4

Discussion

The distribution of the metamorphic zones and the course of the isograds strongly indicate that the heat flow is related to the TDM. Such consideration is also supported by the course of metamorphic isograds, related to the erosional relics of durbachites within the Strážek Moldanubicum (Fig. 2), and distribution of mineral assemblages in the drill cores, which cut rock sequences with durbachites underlying dolomite marbles in the eastern part of the TDM. In spite of the apparent spatial relationship of durbachite rocks and the increased grade of metamorphism (Fig. 2), the cause of the heat flow is not sufficiently understood (compare Behrmann et al. 1994), as discussed below.

(i) The metamorphism M2 seems to be very likely related to the emplacement and crystallization of the durbachite rocks. Whether the heat flow acted in relatively early stages of the intrusion emplacement or was somehow connected with near subsolidus processes in the TDM remains unclear.

(ii) Mostly leucocratic granitic rocks, situated commonly along the contact with durbachites and later than the durbachite intrusion (Němec 1982), may participate in the metamorphism M2. However, their spatial distribution is not consistent with distribution of metamorphic zones, particularly in the eastern part of the studied region. Consequently, a control of metamorphism M2 by leucocratic granitic rocks seems to be limited, if any. Perhaps, these rocks serve as a source of F, and control the chondrodite formation, related locally to their contact.

(iii) Another heat source (magmatic ?) beneath the area, derived from a deep-seated (crustal or mantle) source (Behrmann et al. 1994), also seems possible. The absence of a negative gravimetric anomaly which would indicate the existence of granite pluton beneath the area, and the distribution of mineral assemblages in the drill holes near Tasov (authors' unpubl. data), which does not indicate increasing metamorphism with depth, make the last option least probable.

The age of the metamorphism M2 is not well understood. Postmetamorphic complex pegmatites with the radiometric age of lepidolite (Rb-Sr, 323-306 Ma), penetrating metamorphic rocks of the Strážek Moldanubicum, are apparently later than the HP/LP metamorphism M2 (Černý et al. 1995) and may serve as a limit. The Pb-Pb age of 343 Ma, interpreted as the time of intrusion for the TDM (Holub et al. 1996), may represent the other limit. The age of the metamorphism M2 from 340 to 330 Ma is similar to the age suggested for HT/LP metamorphism in the Moldanubian region by O'Brian - Carswell (1993).

The relationship of the HT/LP metamorphism M2 of dolomite marbles to other Variscan metamorphic events in the Moldanubian region is unclear. Metamorphism was mostly studied in a variety of different rocks particularly in metapelites and in other regions (e.g. Blümel - Schreyer 1976, Zaydan - Scharbert 1983, Petrakakis 1986, Babůrek 1995). Furthermore, rocks with composition and rheology different from those of dolomites, such as metapelites, may be affected in distinct stages of the Variscan metamorphic cycle, based particularly on the kinetics of individual metamorphic reactions in these rocks (e.g. Kerrick et al. 1991). Considering the above discussion, a comparative study of the metamorphic evolution combined with a detailed structural study in distinct rock types in the eastern part of the Moldanubian region, is required to find and compare mutual relationships among individual metamorphic events in the Variscan cycle.

Acknowledgements. The authors are indebted to three anonymous reviewers, whose constructive suggestions improved significantly the paper. We would also like to thank to H. Houzarová for drawing the figures.

References

Babůrek, J. (1995): High, medium and low pressure assemblages from the Czech part of the Královský Hvozd Unit (KHU) in the Moldanubian Zone of SW Bohemia. - J. Czech Geol. Soc., 40, 1-2, 115-126. Praha.

Behrmann, J. H. - O'Brien, P. - Tanner, D. C. - Schuster, J. (1994): Heat and motion during late Variscan mountain building in the Moldanubian of Bavaria. - J. Czech Geol. Soc., 39, 1, 8-9. Praha.

Blümel, P. - Schreyer, W. (1976): Progressive regional low-pressure metamorphism in Moldanubian metapelites of the Northern Bavarian Forest, Germany. - Krystalinikum, 12, 7-30. Praha.

Bouček, Z. - Chmelař, J. - Plhal, J. (1988): Geologická stavba a mineralizace uranového ložiska Jasenice. - Hornická Příbram ve vědě a technice, Geol., 67-78. Příbram.

Bowmann, J. R. - Essene, E. J. (1982): P-T-X_{CO_2} conditions of contact metamorphism in the Black Butte aureole, Elkhorn, Montana. - Amer. J. Sci., 282, 311-340. New Haven.

Bubeníček, J. (1968): Geologický a petrografický vývoj třebíčského masívu. - Sbor. geol. Věd, Geol., 13, 133-164. Praha.

Bucher-Nurminen, K. (1976): Occurrence and chemistry of xantophyllite in roof pendants of the Bergell Granite, Sondrio, Northern Italy. - Schweiz. Mineral. Petrogr. Mitt., 56, 413-426. Zürich.

\- (1981): Petrology of chlorite-spinel marbles from NW Spitsbergen (Svalbard). - Lithos, 14, 203-213. Oslo.

\- (1982a): Mechanism of mineral reactions inferred from textures of impure dolomitic marbles from East Greenland. - J. Petrology, 23, 325-343. Oxford.

\- (1982b): On the mechanism of contact aureole formation in dolomitic country rock by the Adamello intrusion (northern Italy). - Amer. Mineralogist, 67, 1101-1117. Washington.

Büttner, S. - Kruhl, J. H. (1995): The evolution of a late - variscan high-T-low P region: the south-eastern margin of the Bohemian Massif. - J. Czech Geol. Soc., 3, 40, 4-5. Praha.

Černý, P. - Staněk, J. - Novák, M. - Badsgaard, H. - Rieder, M. - Ottolini, L. - Kavalová, M. - Chapman, R. (1995): Geochemical and structural evolution of micas in the Rožná a Dobrá Voda pegmatites, Czech Republic. Mineralogy and Petrology, 55, 177-202. Wien, New York.

Cháb, J. - Suk, M. (1977): Regionální metamorfóza na území Čech a Moravy. - Knih. Ústř. Úst. geol., 50. Praha.

Ferry, J. M. (1991): Dehydration and decarbonation reactions as a record of fluid infiltration. *In*: *D. D. Kerrick* (ed.): Contact metamorphism, Reviews in Mineralogy, 26. - Mineral. Soc. Amer., 26, 351-393.

\- (1992): Regional metamorphism of the Waits River formation, Eastern Vermount: Delineation of a new type giant metamorphic hydrothermal system. - J. Petrol., 33, 45-94. Oxford.

Fuchs, G. (1991): Das Bild der Böhmischen Masse im Umbruch. - Jb. geol. Bundesanst., 134, 701-770. Wien.

Glassley, W. E. (1976): High grade regional metamorphism of some carbonate bodies: Significance for the orthopyroxene isograd. - Amer. J. Sci., 275, 1133-1163. New Haven.

Greenwood, H. J. (1975): Buffering of pore fluids by metamorphic reactions. - Amer. J. Sci., 275, 573-594. New Haven.

Heinrich, W. - Metz, P. - Bayh, W. (1986): Experimental investigation of the mechanism of the reaction: 1 tremolite + 11 dolomite = 8 forsterite + 13 calcite + 9 CO_2 + 1 H_2O, An SEM study. - Contr. Mineral. Petrology, 93, 215-221. Berlin, New York.

Högelsberger, H. (1989): Die Marmore und Kalksilikatgesteine der Bunten Serie - Petrologische Untersuchungen und geologische Konsequenzen. - Jb. Geol. Bundesanst., 132, 213-230, Wien.

Holub, F. V. (1988): Hlubinné procesy vzniku draselných lamproidních magmat Českého masívu. - Acta Univ. Carol., Geol., 4, 482-484. Praha.

Holub, F. V. - Rossi, P. - Cocherie, A. (1996): Nové výsledky datování středočeského plutonického komplexu a jejich implikace. - Abstrakta semináře Skupiny tektonických studií, 15-16. Jeseník.

Houzar, S. (1985): Příspěvěk k petrografii reakčních vápenatých skarnů u Sokolí na Třebíčsku. - Přírodověd. Sbor. Západomorav. Muz., 14, 9-21. Třebíč.

Houzar, S. - Novák, M. (1991): Dolomite marbles at contact of the Moldanubicum and Moravicum in the area between Jasenice and Oslavany. - Acta Mus. Moraviae, Sci. nat., 76, 83-94. Brno.

- (1995): Moldanubian marbles and regional subdivisions of the Moldanubicum. - J. Czech Geol. Soc., 40, 3, 15. Praha.

Kerrick, D. M. - Lasaga, A. C. - Raeburn, S. P. (1991): Kinetics of heterogeneous reactions. *In: D. D. Kerrick* (ed.): Contact metamorphism, Reviews in Mineralogy, 26. - Mineral. Soc. Amer., 26, 583-671.

Kretz, R. (1983): Symbols for rock-forming minerals. - Amer. Mineralogist, 68, 277-279. Washington.

Moore, J. N. - Kerrick, D. M. (1976): Equilibria in siliceous dolomites of the Alta aureole, Utah. - Amer. J. Sci., 276, 502-524. New Haven.

Němec, D. (1973): Das Vorkommen der Zn-Spinelle in der Böhmischen Masse. - Tschermaks mineral. petrogr. Mitt., 19, 95-109. Wien.

- (1982): Randaplite des Massivs von Třebíč-Meziříčí (Westmähren). - Chem. d. Erde, 41, 7-17. Berlin.

Novák, M. (1987): Metamorfované karbonátové horniny při severovýchodním okraji moldanubika. - Acta Mus. Morav., Sci. nat., 79, 5-28, Brno.

- (1988): Petrologie metamorfovaných dolomitických hornin při severovýchodním okraji moldanubika. - MS Kand. dis. práce, Přírodověd. fak. UK. Praha.

- (1989): Metamorfóza dolomitických hornin při severovýchodním okraji moldanubika. - Acta Mus. Moraviae, Sci. nat., 74, 7-51. Brno.

Novák, M. - Houzar, S. - Šrein, V. (1997): Gahnite-bearing marbles in the eastern part of the Bohemian Massif and their implication. J. Czech Geol. Soc. 42, 1-2, Praha

O'Brien, P. J. - Carswell, D. A. (1993): Tectonometamorphic evolution of the Bohemian Massif: evidence from high pressure metamorphic rocks. - Geol. Rdsch., 82, 531-555. Stuttgart.

Olesch, M. - Seifert, F. (1976): Stability and phase relations of trioctahedral calcium brittle micas (clintonite group). - J. Petrol., 17, 291-314. Oxford.

Petrakakis, K. (1986): Metamorphism of high-grade gneisses from the Moldanubian zone, Austria, with particular reference to the garnets. - J. Metamorphic Geol., 4, 323-344. Boston.

Rejl, L. - Sedlák, J. (1987): Přínos geofyzikálního mapování 1:25 000 k poznání geologické stavby a metalogeneze třebíčského a jihlavského masívu. - Geol. Průzk., 5, 134-136. Praha.

Rice, J. M. (1977a): Contact metamorphism of impure dolomitic limestone in the Boulder aureole, Montana. - Contr. Mineral. Petrology, 59, 237-259. Berlin, New York.

- (1977b): Progressive metamorphism of the impure dolomitic limestone in the Marysville aureole, Montana. - Amer. J. Sci., 277, 1-24. New Haven.

- (1979): Petrology of clintonite-bearing marbles in the Boulder aureole, Montana. - Amer. Mineralogist, 64, 519-526. Washington.

- (1980a): Phase equilibria involving humite minerals in impure dolomitic limestones: Part I. Calculated stability of clinohumite. - Contr. Mineral. Petrology, 71, 219-235. Berlin, New York.

- (1980b): Phase equilibria involving humite minerals in impure dolomitic limestones: Part II. Calculated stability of chondrodite and norbergite. - Contr. Mineral. Petrology, 75, 205-223. Berlin, New York.

Sauter, P. C. C. (1983): Metamorphism of siliceous dolomites in the high-grade Precambrian of Rogaland, SW Norway. - Geologica ultraiect., 32, 1-143. Utrecht.

Skippen, G. B. (1974): An experimental model for low pressure metamorphism of siliceous dolomitic marble. - Amer. J. Sci., 274, 487-509. New Haven.

Steyrer, H. P. - Finger, F. (1994): Metamorphic rift basalts and dismembered ophiolites of an early paleozoic ocean in the Southern Bohemian Massif, Austria. - J. Czech Geol. Soc., 39, 1, 108-109. Praha.

Tracy, R. J. - Frost, B. R. (1991): Phase equilibria and thermobarometry of calcareous, ultramafic and mafic rocks, and iron formations. - *In: D. D. Kerrick* (ed.): Contact metamorphism, Reviews in Mineralogy, 26, Mineral. Soc. Amer., 207-289.

Ulrych, J. (1971): Zinc spinel from Lukovská hora Hill near Moravské Budějovice. - Čas. Mineral. geol., 16, 419-422, Praha.

Urban, M. (1990): Tektonický vývoj náměšťského granulitového masívu. - MS Přírodověd. fak. UK. Praha.

Veselá, M. - Hrádek, M. - Hrkal, Z. - Manová, M. - Novák, J.K. - Příhodová, A. - Šalanský K. (1988): Vysvětlivky k základní geologické mapě 1:25 000, 23-421 Brtnice. - Ústř. úst. geol. Praha

Vrána, S. (1992): The Moldanubian zone in southern Bohemia: polyphase evolution of imbricated crustal and upper mantle segments.- Proceed. 1st Inter. Conf. Bohemian Massif (1988), 331-336. Praha.

Walther, J. V. - Helgeson, H. C. (1980): Description and interpretation of metasomatic phase relations at high pressures an temperature: I. Equilibrium activities of ionic species in nonideal mixtures of CO_2 and H_2O. - Amer. J. Sci., 280, 575-606, New Haven.

Weiss, J. (1977): Fundament moravského bloku ve stavbě evropské platformy. - Folia Univ. Purkyn. brun., Geol., 17, 13, 1-64, Brno.

Zaydan, A. - Scharbert, H. G. (1983): Petrologie und geochemie Moldanubischer metamorpher Serien in Raume Persenburg (südwestliches Waldviertel). - Jb. Geol. Bundesanst., 126, 181-199. Wien.

HT/LP metamorfóza dolomitických mramorů ve východní části moldanubika; projev tepelného toku spojeného s třebíčským durbachitovým masivem

V dolomitických mramorech strážeckého a moravského moldanubika lze rozlišit 3 samostatné metamorfní fáze. Jsou to: HT/HP-MP metamorfóza M1, HT/LP metamorfóza M2 a retrográdní MT-LT/LP metamorfóza M3. Posttektonická HT/LP metamorfóza M2 vytvořila v okolí třebíčského durbachitového masivu (TDM) výraznou metamorfní zonálnost. Byly vymezeny 4 metamorfní zóny s diagnostickými minerálními asociacemi: Zóna A - tremolit + flogopit + dolomit + kalcit; Zóna B - forsterit + chlorit I + kalcit + dolomit; Zóna C - forsterit + chlorit I + spinel + kalcit + dolomit; Zóna D - forsterit + spinel + kalcit + dolomit; Zóna K - klinohumit + spinel + kalcit + dolomit ± forsterit ± chlorit I. Byly zjištěny dva odlišné směry vývoje metamorfózy, zobrazené v izobarickém T-X_{CO_2} diagramu. Na základě průběhu izográd a rozložení metamorfních zón se zdá být velmi pravděpodobné, že zdroj tepla je vázán na intruzi durbachitových hornin, a tok tepla kombinovaný s přínosem fluid působil velmi pravděpodobně v raných i pozdních vývojových stadiích intruze. Mladší leukokratní granitické horniny vyvinuté lokálně na okraji třebíčského masivu mohly být zdrojem F, a ovlivňovat tak distribuci chondroditu v mramorech, avšak bez podstatného vlivu na uvedenou metamorfní zonálnost. Jiný (magmatický ?) původ tepla v oblasti třebíčského masivu, související s hluboko uloženým krustálním nebo plášťovým zdrojem, nemůže být vyloučen, avšak dosavadní geofyzikální ani petrologický výzkum jej zatím nepotvrdil. Stáří popsané HT/LP metamorfózy M2 je odhadován zhruba na 340-330 Ma. Tento údaj je odvozen od radiometrického stáří intruze třebíčského durbachitového masivu (Pb-Pb, 343 Ma, Holub et al. 1996), a od stáří mladších postmetamorfních lepidolitových pegmatitů (Rb-Sr, 323-306 Ma, Černý et al. 1995), pronikajících studovaným metamorfním komplexem. Studovaná oblast je tektonicky značně heterogenní a dolomitické mramory jsou citlivější na složení metamorfních fluid než např. metapelity. Z těchto důvodů mohou být mramory ovlivněny v jiných fázích metamorfního vývoje než okolní horniny a metamorfóza M2 v dolomitických mramorech nemusí odpovídat metamorfóze M2 v metapelitech.