

PHASE RELATIONS IN OLIVINE-ORTHOPYROXENE-CHLORITE- SPINEL-HORNBLLENDE METAULTRAMAFICS FROM THE MALÁ FATRA MTS., WESTERN CARPATHIANS

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Abstract: Metaultramafic rocks from the Malá Fatra Mts. (Western Carpathians) preserve mineral assemblages characterized by coexistence of hercynitic spinel, Ca-amphibole (Mg-hornblende), Mg-rich chlorite, olivine (forsterite) and orthopyroxene (enstatite). A large amount of hercynite and Ca-amphibole (up to 30–40 %) is characteristic. Prograde metamorphism reached P-T conditions close to the equilibrium chlorite = forsterite + enstatite + spinel + H₂O and the upper stability of Ca-amphibole which corresponds to the temperature of about 700–800 °C in the model system CMASH. Retrograde reactions lead to the replacement of spinel by secondary chlorite, orthopyroxene by talc and olivine by serpentine. Metaultramafic rocks in the Malá Fatra Mts. reached the conditions of the upper amphibolite facies. They most probably represent the fragments of metaperidotites, attached to the lower continental crust during Variscan tectonometamorphic events.

Key words: Western Carpathians, Malá Fatra Mts., Variscan orogeny, high-grade metamorphism, phase equilibria, metaultramafic rocks.

Introduction

Metaultramafic rocks occur only sporadically in the pre-Mesozoic basement complexes of the Western Carpathians (Hovorka et al. 1985; Hovorka 1994).

Among occurrences in the Tatric Unit—one of the major tectonic units of the Western Carpathians, the metaultramafic rocks in the Malá Fatra Mts. have been investigated by Ivanov & Kamenický (1957), Hovorka (1965, 1977), Hovorka & Spišiak (1985) and Hovorka et al. (1985).

According to Hovorka & Spišiak (1985) and Hovorka et al. (1985), the hornblende peridotites from the Malá Fatra Mts. are composed of olivine, clinopyroxene, orthopyroxene, tremolite and spinel whose microprobe analyses were presented. According to the above mentioned authors, these rocks represent so called “deuteroperidotites” whose mineral assemblage has been generated at 640–680 °C by contact-metamorphic recrystallization of serpentinite (tremolite + antigorite + talc + Mg-chlorite + magnetite), due to the thermal effect of granite intrusion. Retrogression at lower temperature led to the formation of lizardite (serpentine), chlorite and talc (Hovorka et al. 1985).

The aim of this paper is to present additional data on mineral compositions together with paragenetic analysis of co-existing minerals. Metamorphic conditions have been estimated using mineral activity-composition relationships together with internally consistent thermodynamic data of Berman (1988). Phase equilibria were calculated using the computer program GEO-CALC.

We suggest that the metamorphic evolution of the metaultramafics in the Malá Fatra Mts. is consistent with high grade, upper-amphibolite facies regional metamorphism and not contact metamorphism. The investigated metaultramafics are isofacial with the surrounding metamorphic crustal rocks, i.e. high-grade metapelites and metabasites, as demonstrated by previous studies (Perchuk et al. 1984; Korikovskiy et al. 1987; Krist et al. 1992; Hovorka & Méres 1991; Lupták 1996; Janák & Lupták 1997).

Geological setting

The Malá Fatra Mts. (Fig. 1) belong to the Tatric Unit of the Western Carpathians and represent a typical core complex located in the northwestern part of Slovakia. In general, the pre-Mesozoic basement of the Malá Fatra Mts. is composed of high-grade metamorphic rocks and granitoids, overlain by Mesozoic and Cenozoic sedimentary cover sequences and nappes.

The granitoids consist of the so called “hybrid” and “Magura” types according to Ivanov & Kamenický (1957) and Kamenický et al. (1987), which correspond to the I- and S- types, respectively (Broska et al. 1997). They are crosscut by lamprophyric dykes (Ivanov & Kamenický 1957). The U-Pb zircon age of a tonalite is 353 Ma, according to Scherbak et al. (1990).

Metamorphic rocks are exposed in the southern part of the Malá Fatra Mts., i.e. “Veľká Lúka Massif” (Fig. 1) and con-

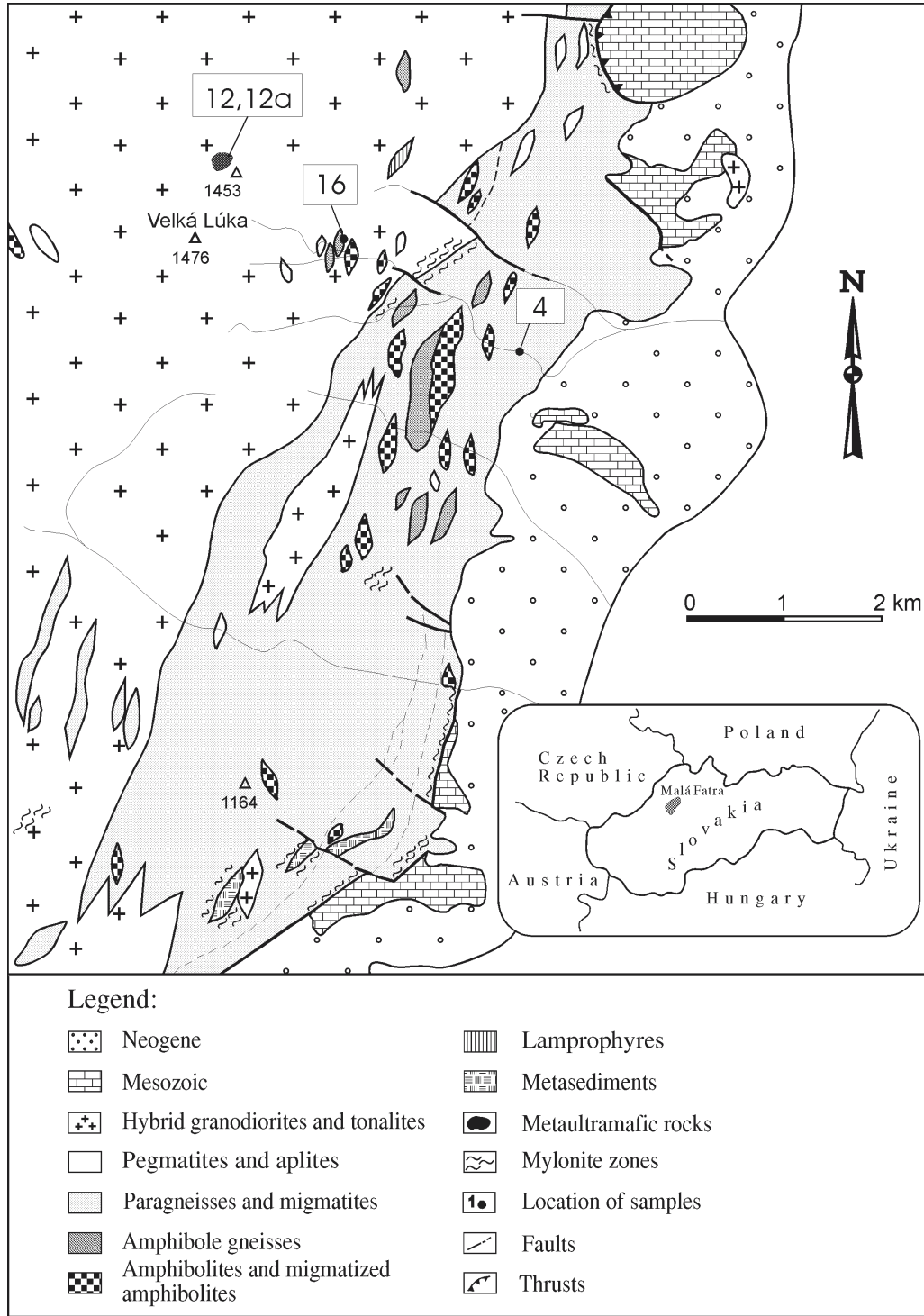


Fig. 1. Schematic geological map of the southern part of the Malá Fatra Mts. — “Velká Lúka” Massif.

tain several lithologies. Among them, metapelites are most abundant. They are represented by biotite-, garnet- and sillimanite-bearing paragneisses, affected by migmatitization. Orthogneisses with characteristic augen texture and mylonitic fabric are thought to be former (pre-Variscan?) granitoids. Metabasites correspond to several rock types: fine- to coarse-grained amphibolites and amphibole gneisses, massive garnet and garnet-clinopyroxene metabasites (retro-

graded eclogites), banded and migmatized amphibolites. Calc-silicates occur only sporadically.

The investigated metaultramafic rocks are only poorly exposed and they were described as “hornblende peridotites” by Hovorka et al. (1985). The largest ultramafic body is exposed near the top of the Velká Lúka (Fig. 1), where it is surrounded by “hybrid” granodiorites and tonalites, which are rather diatexitic migmatites (Janák & Lupták 1997). The ex-

Table 1: Representative microprobe analyses of amphiboles.

Hornblende inclusions in opx (1, 2, 3) and olivine (4, 5)					large hornblendes in matrix (6, 7, 8, 9)				
Sample	MF12	MF16	MF4	MF12a	MF16	MF12	MF12a	MF16	MF4
Anal. no.	1	2	3	4	5	6	7	8	9
SiO ₂	50.58	50.00	49.23	49.47	50.16	50.33	48.99	49.86	50.51
Al ₂ O ₃	8.86	10.12	9.62	10.44	9.52	9.1	10.61	9.73	9.44
TiO ₂	0.65	0.76	0.80	0.67	0.76	0.59	0.92	0.61	0.68
Cr ₂ O ₃	0.05	0.18	0.28	0.07	0.09	0.09	0.17	0.12	0.15
MgO	19.23	18.37	19.06	18.16	18.98	18.82	17.86	18.86	18.72
FeO	6.07	5.94	6.20	6.51	5.75	6.51	6.71	5.77	5.97
MnO	0.00	0.07	0.16	0.03	0.19	0.12	0.11	0.08	0.17
CaO	11.89	12.13	11.92	11.92	12.01	12.06	12.03	11.88	11.98
Na ₂ O	0.67	0.40	0.77	0.70	0.70	0.39	0.64	0.63	0.61
K ₂ O	0.13	0.26	0.22	0.28	0.22	0.12	0.25	0.17	0.14
Total	98.13	98.23	98.26	98.25	98.38	98.13	98.29	97.71	98.37
Formulas based on 23 oxygens and 15 cations excluding Na, K									
Si	7.023	6.941	6.844	6.893	6.957	6.984	6.833	6.950	7.006
Al ^{VI}	0.977	1.059	1.156	1.107	1.043	1.016	1.167	1.050	0.994
Al total	1.450	1.656	1.577	1.715	1.556	1.489	1.745	1.599	1.544
Al ^{VI}	0.473	0.597	0.421	0.608	0.514	0.473	0.578	0.549	0.550
Ti	0.068	0.079	0.084	0.070	0.079	0.062	0.097	0.064	0.071
Fe ³⁺	0.160	0.131	0.288	0.111	0.134	0.283	0.159	0.160	0.097
Cr ³⁺	0.005	0.020	0.031	0.008	0.009	0.010	0.019	0.013	0.016
Mg	3.980	3.801	3.949	3.771	3.924	3.892	3.713	3.918	3.870
Fe ²⁺	0.545	0.560	0.433	0.648	0.533	0.473	0.624	0.513	0.596
Mn	0.000	0.008	0.019	0.004	0.022	0.014	0.013	0.009	0.020
Ca	1.769	1.805	1.775	1.780	1.785	1.793	1.798	1.774	1.781
Na(M ₄)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Na(A)	0.180	0.107	0.208	0.190	0.189	0.105	0.173	0.170	0.164
K	0.023	0.046	0.039	0.050	0.039	0.021	0.044	0.030	0.025
Fe/Fe+Mg	0.120	0.128	0.099	0.147	0.120	0.108	0.144	0.116	0.133

act size and shape of metaltramafic body is not known, but it may range up to several tens of metres. Smaller blocks and lenses of several m to dm occur sporadically also on the south-eastern slopes of Velká Lúka (Fig. 1), intimately associated with migmatized paragneisses and amphibolites.

Metamorphic P-T conditions in the Malá Fatra Mts. have been estimated by thermobarometry in the metapelites and metabasites (Perchuk et al. 1984; Korikovskiy et al. 1987; Krist et al. 1992; Hovorka & Méres 1991; Lupták 1996; Janák & Lupták 1997). According to these studies, peak metamorphic conditions reached medium-pressure, upper amphibolite to granulite facies. However, symplectitic and kelyphitic textures in some garnet-clinopyroxene metabasites indicate also a higher-pressure, eclogite facies metamorphism, strongly overprinted by lower-pressure and high temperature recrystallization (Hovorka et al. 1992; Lupták 1996; Janák & Lupták 1997). Most of metamorphic rocks exhibit widespread migmatization due to partial melting, dehydra-

tion-melting during decompression has been suggested by Janák & Lupták (1997). Although the timing of metamorphism in the Malá Fatra Mts. is not well constrained by geochronological data, regional metamorphism and granitoid magmatism are generally thought to be Variscan, with only very weak Alpine overprint (e.g. Krist et al. 1992).

Petrography and mineral compositions

Metultramafics from the Malá Fatra Mts. are dark-grey, medium-grained rocks, massive or only weakly foliated. Their texture is nematogranoblastic.

Mineral compositions were analyzed by CAMSCAN-Link EDS microprobe with a point beam at operating conditions of 10nA and 15 kV using synthetic and natural standards. The data were reduced by the ZAF method.

Amphibole is pale-green and occurs as small inclusions in olivines and orthopyroxenes, as well as large prismatic grains in the matrix. The compositions of amphibole inclusions and larger matrix grains are similar (Table 1). Both correspond to Mg-hornblende according to Leake (1978; 1997) with low Na (Na₂O = 0.24–0.88 wt. %), Ti and relatively high Al (Al₂O₃ = 8.79–10.61 wt. %) contents. The hornblendes are sometimes replaced by tremolite at the rims, which is attributed to retrogression.

Orthopyroxene is present in the form of rather subhedral, pale-green to brownish porphyroblasts, sometimes enclosing amphiboles. Some orthopyroxenes are replaced by talc at the rims. The compositions of orthopyroxenes (Table 2) correspond to enstatite, containing 1.83–2.49 wt. % Al₂O₃ and 0.19–0.28 % CaO; the ratio of Fe/Fe+Mg is 0.16–0.18.

Olivine forms mostly euhedral, colourless grains, only slightly serpentinized. In some places, the olivine porphyroblasts enclose small hornblendes. The composition of olivine (Table 3) corresponds largely to forsterite and the individual grains are very homogeneous. The Fe/Fe+Mg ratio (0.18–0.21) is higher than that in the coexisting orthopyroxenes.

Spinel occurs as small subhedral grains of green colour, intergrown with amphiboles, orthopyroxenes and olivines. According to their compositions, the spinels are hercynites (Table 4) with 1.35 to 4.1 wt. % Cr₂O₃, the ratio of Fe/Fe + Mg is 0.38–0.40. Individual grains are homogeneous, no relics of chromite were identified. Consequently, the absence of chromite as well as Cr-magnetite indicates that hercynitic spinel has not originated from chromite but most probably from chlorite, i.e. during prograde metamorphism as discussed below.

Chlorite forms pale-green, mostly scattered flakes, which tend to concentrate in the interstices between olivine, ortho-

Table 2: Representative microprobe analyses of orthopyroxenes.

Sample	MF12	MF12a	MF16	MF4
Anal. no.	1	2	3	4
SiO ₂	54.30	54.22	54.65	54.11
TiO ₂	0.09	0.15	0.08	0.15
Al ₂ O ₃	2.36	2.12	2.30	2.13
Cr ₂ O ₃	0.00	0.03	0.00	0.14
Fe ₂ O ₃	1.58	2.06	1.42	2.25
FeO	11.70	11.33	10.76	10.55
MnO	0.27	0.32	0.35	0.29
MgO	29.54	29.72	30.27	30.14
CaO	0.26	0.20	0.28	0.22
Na ₂ O	0.00	0.00	0.00	0.00
K ₂ O	0.02	0.03	0.00	0.00
Total	100.12	100.19	100.11	99.98
Formulas based on 4 cations for 6 oxygens				
Si	1.928	1.924	1.931	1.920
Ti	0.002	0.004	0.002	0.004
Al	0.099	0.089	0.096	0.089
Cr ³⁺	0.000	0.001	0.000	0.004
Fe ³⁺	0.042	0.055	0.038	0.060
Fe ²⁺	0.347	0.336	0.318	0.313
Mn	0.008	0.010	0.010	0.009
Mg	1.563	1.572	1.594	1.593
Ca	0.010	0.008	0.011	0.008
Na	0.000	0.000	0.000	0.000
K	0.001	0.001	0.000	0.000
Fe/Fe+Mg	0.182	0.176	0.166	0.164

Table 3: Representative microprobe analyses of olivines.

Sample	MF12	MF12a	MF16	MF4
Anal. no.	1	2	3	4
SiO ₂	38.29	38.34	38.77	38.56
TiO ₂	0.01	0.00	0.03	0.08
Al ₂ O ₃	0.00	0.00	0.00	0.00
Cr ₂ O ₃	0.00	0.09	0.03	0.00
Fe ₂ O ₃	1.66	1.32	0.73	1.30
FeO	18.84	19.25	18.40	16.80
MnO	0.34	0.35	0.23	0.39
MgO	40.92	40.74	41.78	42.48
CaO	0.00	0.00	0.02	0.04
Na ₂ O	0.00	0.02	0.00	0.00
K ₂ O	0.06	0.00	0.00	0.00
Total	100.13	100.11	99.99	99.65
Formulas based on 3 cations for 4 oxygens				
Si	0.985	0.987	0.992	0.986
Ti	0.000	0.000	0.001	0.002
Al	0.000	0.000	0.000	0.000
Cr ³⁺	0.000	0.002	0.001	0.000
Fe ³⁺	0.032	0.026	0.014	0.025
Fe ²⁺	0.405	0.414	0.394	0.359
Mn	0.007	0.008	0.005	0.008
Mg	1.568	1.563	1.593	1.619
Ca	0.000	0.000	0.001	0.001
Na	0.000	0.001	0.000	0.000
K	0.002	0.000	0.000	0.000
Fe/Fe+Mg	0.205	0.209	0.198	0.181

pyroxene and spinel. Such chlorite is clinocllore with Fe/Fe + Mg = 0.1–0.12 (Table 5) and it is considered to be a relict phase, being partially consumed by olivine, spinel and orthopyroxene during prograde metamorphism. On the other hand, chlorites whose Fe/Fe + Mg and Al contents are lower than those of primary ones (Table 5) form reaction rims around spinels and are considered to be retrograde phases, as discussed below.

Serpentine commonly replaces olivines in the rims. It also occurs in the veinlets crosscutting the matrix, in some cases it contains minor inclusions of magnetite. The composition of serpentine (Table 6) corresponds to antigorite.

Talc mostly replaces orthopyroxenes, or together with other retrograde phases — serpentine and magnesite — it fills the crosscutting veinlets.

Textural relationships in the Malá Fatra Mts. metultramafics as described above suggest that olivine, orthopyroxene, spinel and Ca-amphibole form a stable assemblage, generated close to the peak of prograde metamorphism. The preservation of a small amount of primary chlorite coexisting with olivine, orthopyroxene and spinel indicates that the reaction chlorite₁ = olivine + orthopyroxene + spinel + H₂O

took place during temperature increase. This is similar to observations in the amphibolite facies metultramafics, where Mg-rich chlorite coexists with forsterite, enstatite and spinel (Bucher-Nurminen 1988; Bucher & Frey 1994). The retrograde overprint of peak metamorphic assemblages was only weak, and is manifested by replacement of spinel by secondary chlorite, orthopyroxene by talc and olivine by serpentine.

Phase equilibria

On the basis of mineral compositions, the phase relationships in the Malá Fatra Mts. ultramafics can be described in the system CM(F)ASH (C = CaO, M = MgO, F = FeO, A = Al₂O₃, S = SiO₂, H = H₂O). Phase equilibria of selected reactions were calculated using the thermodynamic data of Berman (1988, updated in June 1993) and the computer program GEO-CALC (Berman et al. 1987). The activity-composition relationships of analysed mineral phases assuming ideal two-site mixing (olivine, orthopyroxene), ideal on-sites mixing (chlorite, talc) and unity activity of antigorite have been calculated by the program AX of T.J.B. Holland, in-

Table 4: Representative microprobe analyses of spinels.

Sample	MF12	MF12	MF12a	MF16	MF16	MF4	MF4
Anal.no.	1-core	2-rim	3	4	5	6	7
SiO ₂	0.00	0.00	0.00	0.00	0.07	0.00	0.05
TiO ₂	0.03	0.00	0.10	0.00	0.06	0.00	0.00
Al ₂ O ₃	60.38	60.63	60.45	61.92	60.69	60.77	57.97
Cr ₂ O ₃	1.61	1.44	2.47	1.70	2.71	2.00	4.10
Fe ₂ O ₃	4.91	4.81	4.04	3.24	3.16	4.41	4.88
FeO	17.93	17.89	17.25	17.36	17.85	18.33	17.66
MnO	0.13	0.29	0.05	0.11	0.16	0.27	0.07
MgO	15.44	15.37	15.96	15.94	15.57	15.22	15.34
CaO	0.00	0.00	0.02	0.02	0.00	0.03	0.04
Na ₂ O	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K ₂ O	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	100.45	100.45	100.34	100.29	100.28	101.02	100.11
Formulas based on 3 cations for 4 oxygens							
Si	0.000	0.000	0.000	0.000	0.002	0.000	0.001
Ti	0.001	0.000	0.002	0.000	0.001	0.000	0.000
Al	1.868	1.875	1.865	1.901	1.875	1.872	1.814
Cr ³⁺	0.033	0.030	0.051	0.035	0.056	0.041	0.086
Fe ³⁺	0.097	0.095	0.080	0.064	0.062	0.087	0.098
Fe ²⁺	0.394	0.393	0.378	0.378	0.391	0.400	0.392
Mn	0.003	0.006	0.001	0.002	0.004	0.006	0.002
Mg	0.605	0.601	0.623	0.619	0.609	0.593	0.607
Ca	0.000	0.000	0.001	0.001	0.000	0.001	0.001
Na	0.000	0.000	0.000	0.000	0.000	0.000	0.000
K	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Fe/Fe+Mg	0.394	0.395	0.378	0.379	0.391	0.403	0.392

cluded in THERMOCALC and described in Holland & Powell (1990) and Will et al. (1990). The phase equilibria have been calculated assuming water-saturated conditions, i.e. pure water ($X_{H_2O} = 1$) in the fluid and H₂O pressure = total pressure. Consequently, the calculated dehydration equilibrium curves may be regarded as the maximum stability limits, which would be shifted towards a lower temperature in the presence of additional fluid components, mainly CO₂, as indicated by the presence of a small amount of magnesite.

The prograde phase equilibria between coexisting chlorite, orthopyroxene, olivine, amphibole and spinel are demonstrated by several diagrams. Fig. 2 shows the chemography of the reaction:



in the system (Mg, Fe)-Si-Al, reflecting the replacement of Mg-rich chlorite by hercynitic spinel, forsterite and enstatite. An equilibrium curve of this reaction (R1) plots between 700–800 °C and 2–10 kbars (Fig. 4).

Chemography between coexisting Ca-amphibole (Mg-hornblende), olivine (forsterite), orthopyroxene (enstatite) and Mg-rich chlorite is expressed by the projection from spinel in the system (Mg, Fe)-Si-Ca on Fig. 3. This

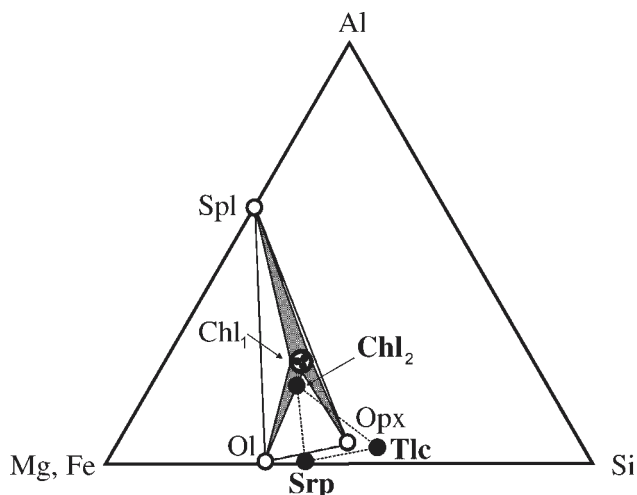


Fig. 2. Chemography of the prograde reaction chlorite₁ = olivine + orthopyroxene + spinel in the system (Mg, Fe)-Si-Al. Chemography of retrograde replacement of olivine, orthopyroxene and spinel by secondary assemblage serpentine + chlorite₂ + talc is shown by dashed lines. Note the shift of the retrograde assemblage towards the Si corner.

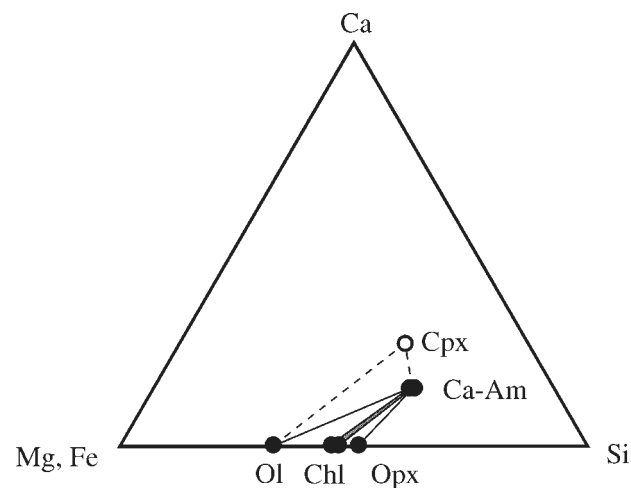


Fig. 3. Chemography between coexisting Ca-amphibole, olivine, orthopyroxene and chlorite in the system (Mg, Fe)-Si-Ca; projection from spinel.

chemography also shows that clinopyroxene is not stable in the assemblage with Ca-amphibole, olivine, orthopyroxene and chlorite. The microprobe analyses of clinopyroxene in Hovorka & Spišiak (1985, Table 1) as well as Hovorka et al. (1985, Table 1) correspond to amphibole and not clinopyroxene. They are similar to our analyses of hornblende in this paper (Table 1). Consequently, the absence of Ca-clinopyroxene (diopside) suggests that a) peak conditions were above low-temperature stability of diopside, i.e. 8 diopside + antigorite = 18 forsterite + 4 tremolite + 27 H₂O (e.g. Spear 1993; Bucher & Frey 1994), b) the peak conditions were below equilibrium reaction Ca-amphibole + olivine = Ca-clinopyroxene + orthopyroxene + H₂O (Fig. 4). As pointed out above, the amphibole is Mg-hornblende, indicating its high-

Table 5: Representative microprobe analyses of chlorites.

Prograde (1, 2, 3) and retrograde (4) chlorites				
Sample	MF12	MF12a	MF16	MF12
Anal. no.	1	2	3	4
SiO ₂	29.73	29.91	30.32	31.81
TiO ₂	0.06	0.04	0.16	0.00
Al ₂ O ₃	22.04	21.63	20.47	18.15
Cr ₂ O ₃	0.13	0.12	0.19	0.00
Fe ₂ O ₃	0.000	0.000	0.000	0.000
FeO	7.18	6.99	5.71	3.55
MnO	0.15	0.01	0.11	0.14
MgO	28.75	29.71	30.34	32.53
CaO	0.07	0.04	0.11	0.00
Na ₂ O	0.00	0.00	0.00	0.07
K ₂ O	0.00	0.00	0.01	0.04
Total	88.11	88.45	87.42	86.29

Formulas based on 10 cations for 14 oxygens				
Si	2.817	2.821	2.878	3.022
Ti	0.004	0.003	0.011	0.000
Al	2.462	2.405	2.290	2.033
Cr ³⁺	0.010	0.009	0.014	0.000
Fe ³⁺	0.000	0.000	0.000	0.000
Fe ²⁺	0.569	0.551	0.453	0.282
Mn	0.012	0.001	0.009	0.011
Mg	4.060	4.176	4.291	4.605
Ca	0.007	0.004	0.011	0.000
Na	0.000	0.000	0.000	0.013
K	0.000	0.000	0.001	0.005
Fe/Fe+Mg	0.123	0.117	0.095	0.058

Table 6: Representative microprobe analyses of talc (1, 2) and antigorite (3).

7 cations for 11 oxygens			
Sample	MF12a	MF16	MF12
Anal. no.	1	2	3
SiO ₂	56.82	57.23	42.26
TiO ₂	0.06	0.00	0.03
Al ₂ O ₃	4.67	3.20	0.76
Cr ₂ O ₃	0.08	0.05	0.05
Fe ₂ O ₃	0.54	0.82	0.00
FeO	4.34	6.66	2.69
MnO	0.11	0.03	0.00
MgO	28.30	26.71	40.42
CaO	0.04	0.07	0.00
Na ₂ O	0.36	0.31	0.00
K ₂ O	0.01	0.27	0.00
Total	95.32	95.35	86.21

7 cations for 11 oxygens			
Si	3.699	3.768	1.993
Ti	0.003	0.000	0.001
Al	0.358	0.248	0.042
Cr ³⁺	0.004	0.003	0.002
Fe ³⁺	0.026	0.041	0.000
Fe ²⁺	0.236	0.367	0.106
Mn	0.006	0.002	0.000
Mg	2.745	2.621	2.841
Ca	0.003	0.005	0.000
Na	0.045	0.040	0.000
K	0.001	0.023	0.000
Fe/Fe+Mg	0.079	0.123	0.036

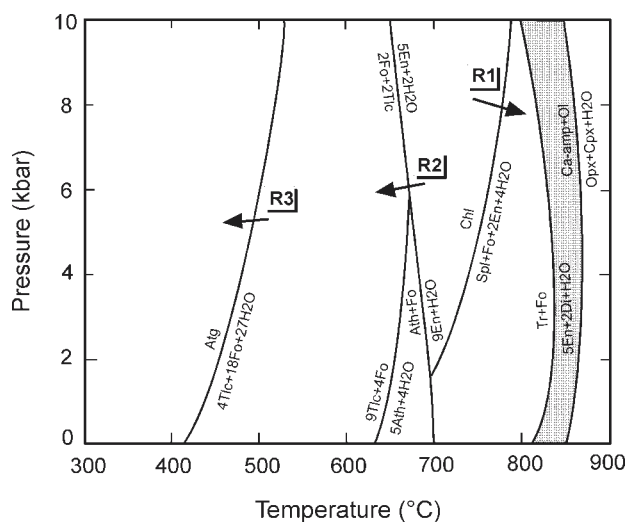


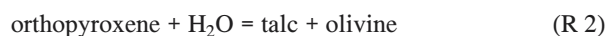
Fig. 4. Phase equilibria of the Malá Fatra Mts. metaultramafics in the system CMASH ($P_{\text{H}_2\text{O}} = P_{\text{total}}$). Reactions R1, R2 and R3 were calculated from the thermodynamic data of Berman (1988, updated in June 1993) and activity-composition relationships of analysed mineral phases (Tables 1–6) using the computer program GEO-CALC. The equilibria involving diopside, tremolite and anthophyllite as well as the upper stability of Ca-amphibole are adopted from Bucher & Frey (1994). The tentative P-T path is shown by arrows.

er-temperature stability than that of pure tremolite end-member (Fig. 4), i.e. close to the amphibolite to granulite facies transition in ultramafic rocks (Spear 1993; Bucher & Frey 1994).

The pressure conditions cannot be constrained precisely because of steep dP/dT slopes of equilibrium reactions in the system CMASH (Fig. 4). However, the absence of anthophyllite may indicate that the pressure was above the stability field of anthophyllite + olivine in the Fig. 4.

Retrograde reactions in the Malá Fatra Mts. metaultramafics are indicated by replacement of spinel by secondary chlorite, orthopyroxene by talc and olivine by serpentine. This is demonstrated by chemographic phase relations in the system (Mg, Fe)–Al–Si on the Fig. 2. This projection, however, shows that the secondary assemblage $\text{Srp} + \text{Chl}_2 + \text{Tlc}$ is slightly shifted towards the Si corner, probably indicating some metasomatic input of silica during retrogression. This assumption may be supported by the slightly silica-enriched bulk composition of the Malá Fatra Mts. metaultramafics (Table 7) with respect to the majority of the mantle rocks, as illustrated in the Fig. 5. Despite possible metasomatic influence, the bulk composition of the Malá Fatra Mts. metaultramafics approach that of the garnet or spinel peridotite and websterite.

Talc could have originated according to the reaction:



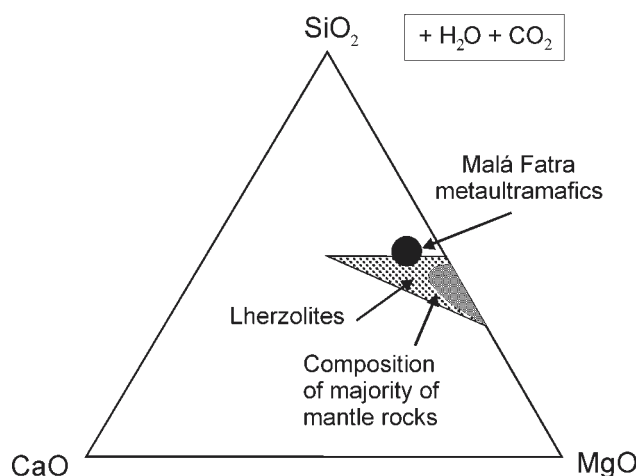


Fig. 5. Chemography of the Malá Fatra Mts. metaultramafics bulk composition in the CMS-HC system, projected onto the plane CaO-MgO-SiO₂. The bulk compositions are from Table 7 and were recalculated to mol. %. Note a slight SiO₂ enrichment of the Malá Fatra Mts. metaultramafics with respect to the composition of majority of mantle rocks as adopted from Bucher & Frey (1994).

Table 7: Chemical compositions of the Malá Fatra Mts. metaultramafic rocks.

SAMPLE	MF-4	MF-12	MF-16
SiO ₂	43.80	43.80	44.13
TiO ₂	0.55	0.55	0.50
Al ₂ O ₃	10.05	10.40	9.80
Fe ₂ O ₃	2.82	3.33	3.09
FeO	8.63	8.59	8.80
MnO	0.21	0.23	0.19
MgO	24.65	23.86	24.74
CaO	5.94	5.94	6.26
Na ₂ O	0.44	0.35	0.05
K ₂ O	0.10	0.10	0.07
H ₂ O ⁻	0.21	0.30	0.34
H ₂ O ⁺	2.03	2.09	1.85
Cr ₂ O ₃	0.24	0.22	n.d.
NiO	0.10	0.08	n.d.
Total	99.77	99.84	99.82

at higher temperature than antigorite during retrogression, the latter being formed by the reaction:



at temperatures below ca. 450 °C (Fig. 4).

The estimated peak temperature in the Malá Fatra Mts. metaultramafics is similar to that in the surrounding sillimanite + K-feldspar bearing metapelites as well as garnet-clinopyroxene metabasites, which have equilibrated at 700–750 °C and 6–10 kbar according to the geothermometric calculations of Korikovsky et al. (1987); Hovorka & Méres (1991); Lupták (1996); Janák & Lupták (1997). Such P-T conditions are higher than those of contact-metamorphism by granitoid magma, i.e. 640–680 °C, proposed by Hovorka et

al. (1985). On the other hand, possible metamorphic evolution from serpentinite to metaperidotite as well as the weak retrograde overprint of the Malá Fatra Mts. metaultramafics are consistent with previous observations of Hovorka et al. (1985).

Conclusions

The metaultramafic rocks from the Malá Fatra Mts. are characterized by coexistence of prograde assemblages containing hercynitic spinel, Ca-amphibole (Mg-hornblende), Mg-rich chlorite, olivine (forsterite) and orthopyroxene (enstatite). A large amount of hercynite and Ca-amphibole (up to 30–40 %) is characteristic.

Prograde metamorphism of the Malá Fatra Mts. metaultramafics reached the P-T conditions close to the equilibrium chlorite = olivine + orthopyroxene + spinel + H₂O, which corresponds to temperature of 700–800 °C in the upper amphibolite facies condition. This is also corroborated by the stability of Ca-amphibole with olivine and the absence of clinopyroxene. The retrogression was only weak, leading to the origin of talc, serpentine (antigorite) and secondary chlorite.

The metaultramafic rocks in the Malá Fatra Mts. may be regarded as isofacial and completely equilibrated with the surrounding high-grade crustal rocks. They most probably represent fragments of metaperidotites or garnet and spinel websterite (e.g. Medaris & Carswell 1990), attached to the lower continental crust during the Variscan tectonometamorphic events (mantle upwelling after delamination or slab detachment of the subducted lithosphere).

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