GEOLOGICA CARPATHICA, 47, 6, BRATISLAVA, DECEMBER 1996
359–365

CORDIERITE-BEARING MIGMATITES FROM THE VEĽKÁ FATRA MTS., WESTERN CARPATHIANS: GEOTHERMOBAROMETRY AND IMPLICATIONS FOR VARISCAN DECOMPRESSION

MARIAN JANÁK[1] and MILAN KOHÚT[2]

[1]Department of Mineralogy and Petrology, Faculty of Sciences, Comenius University, Mlynská dolina, 842 15 Bratislava, Slovak Republic
[2]Slovak Geological Survey, Mlynská dolina 1, 817 04 Bratislava, Slovak Republic

(Manuscript received December 12, 1995; accepted in revised form March 3, 1996)

Abstract: Cordierite-bearing migmatites are found in the pre-Mesozoic crystalline basement of the Veľká Fatra Mts., Central Western Carpathians as xenoliths and blocks in the granitoid pluton. Cordierite with Fe/Fe + Mg = 0.4 occurs in the assemblages with sillimanite, biotite, plagioclase, quartz, muscovite and ilmenite. Relics of spessartine-rich garnet are only sporadically preserved, replaced by cordierite porphyroblasts, therefore the origin of cordierite is related mainly to the breakdown of garnet, according to the reaction 2 garnet + 4 sillimanite + 5 quartz = 3 cordierite. On the basis of mineral composition, conventional as well as internally consistent geothermobarometry (TWEEQU method), cordierite originated at pressure conditions below 4–5 kbar and a temperature near 600 °C, as a consequence of nearly isothermal decompression. The decompressional P-T path of cordierite-bearing migmatites was associated with the rapid (ca. 2 mm/yr) emplacement of the granitoid pluton during late Variscan (342–338 Ma) time, which was most probably facilitated by tectonic extension.

Key words: Western Carpathians, Veľká Fatra Mts., Variscan basement, decompression, geothermobarometry, migmatites, cordierite.

Introduction

At low to medium-pressure and high temperature conditions of metamorphism cordierite is a common mineral in gneisses, migmatites and granulites of pelitic composition, where the assemblage cordierite+garnet+sillimanite+quartz+biotite+K-feldspar is diagnostic. However, in the Western Carpathians, cordierite has been described only from contact hornfelses and schists, e.g. in the aureole of the Modra granitoid intrusion in the Malé Karpaty Mts. (Korikovsky et al. 1985) and that of the Rochovce Granite in the southern part of the Veporic Unit (Vrána 1964; Korikovsky et al. 1986; Vozárová & Krištín 1987). In these aureoles, cordierite has originated in the assemblages with andalusite, below conditions of high-grade metamorphism and partial melting.

In this paper, we describe cordierite-bearing assemblages in migmatitic gneisses from the Veľká Fatra pre-Mesozoic basement, where cordierite formed in the sillimanite stability field, due to the breakdown of higher-pressure assemblages involving garnet as a major reactant phase.

Geological setting

The Veľká Fatra is a typical "core mountain range" located in the Tatric Unit of the Central Western Carpathians (Andrusov 1968; Maheľ 1986). Pre-Mesozoic basement is exposed in the Ľubochňa Massif, consisting almost exclusively of granitoids (Fig. 1). Metamorphic rocks — gneisses, migmatites and amphibolites — occur mostly in the form of assimilated blocks and xenoliths, only near the eastern margin of the massif do they form a continuous belt.

Several types of granitoids have been distinguished by Kohút (1992), forming a zoned pluton (Fig. 1). The lower parts of the pluton are composed of granodiorite (Kornietov type), granite (Lipová type) and leucogranite (Ľubochňa type), whereas tonalite (Smrekovica type) dominates in the uppermost levels, containing xenoliths and blocks of metamorphic rocks including cordierite-bearing gneisses and migmatites. Contacts between several granitoid types and metamorphic country rocks are rather gradual, only leucogranites as well as veins of aplites and pegmatites show sharp boundaries to surrounding rocks.

Isotopic investigations using Rb-Sr, K-Ar and Ar-Ar methods (Kohút et al. 1993, 1996; Kráľ & Štarková 1995) indicate a polyphase evolution. According to Kohút et al. (1993, 1996), only leucogranites record a solely Variscan (350-340 Ma) age of magmatic crystallization. Other granitoids also show a 420 Ma age (Rb-Sr WR-isochron), interpreted as an "inherited" age of the igneous protolith, partially rejuvenated during Variscan remelting (Kohút et al. 1993, 1996). Ar-Ar cooling ages of 340–330 Ma record relatively very rapid uplift and exhumation to upper crustal levels.

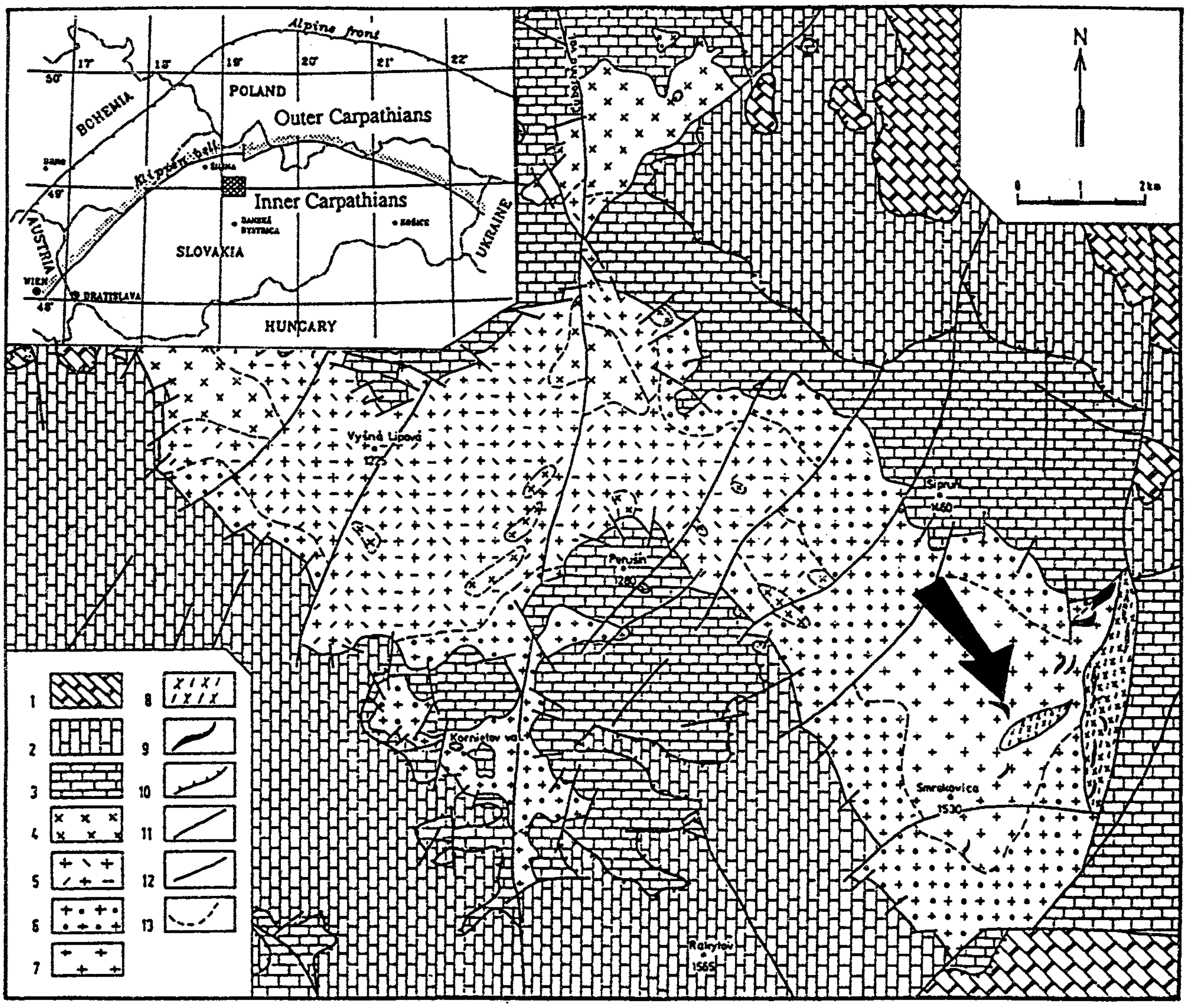

Fig. 1. Geological sketch of the central part of the Veľká Fatra Mts. The location of the investigated cordierite-bearing migmatites is marked by the arrow. *Explanations:* 1 — Choč Nappe, 2 — Krížna Nappe, 3 — Mesozoic cover unit, 4 — Ľubochňa leucogranite, 5 — Lipová granite, 6 — Kornietov granodiorite, 7 — Smrekovica tonalite, 8 — orthogneiss, 9 — paragneiss xenoliths, 10 — thrust faults, 11 — normal faults, 12 — geological boundaries, 13 — boundaries between granitoid types (transitional).

Petrography and mineral chemistry

Chemical compositions of major mineral phases were obtained using a JEOL 737 electron microprobe (Dionýz Štúr Institute of Geology, Bratislava) using synthetic and natural standards at operating conditions of 15 kV and 15 nA. Corrections were made by the ZAF method. Mineral abbreviations are according to Kretz (1983).

The migmatized pelitic gneisses containing cordierite are well-foliated, sometimes fine banded to stromatitic, with leucocratic quartz-feldspar leucosome segregated from the mafic, biotite-rich melanosome. The cordierite is macroscopically visible as dark-grey spots and oval-shaped or lensoid porphyroblasts attaining the size of several (up to 8) mm (Fig. 2a).

The most common mineral assemblages are:

a) biotite+garnet+plagioclase+muscovite+sillimanite+quartz +rutile+ilmenite,

b) biotite+garnet+sillimanite+plagioclase+K-feldspar+muscovite+quartz+rutile+ilmenite,

c) cordierite+biotite+sillimanite+muscovite+plagioclase+quartz+garnet+ilmenite.

The *cordierite* porphyroblasts are mostly pinitized (Fig. 2b), with fine-grained phengitic muscovite (Tab. 3) and chlorite pseudomorphing cordierite relics. They are mostly undeformed, suggesting a post-kinematic growth of cordierite with respect to the penetrative deformation. In some cases, in the presence of sillimanite and quartz, the cordierite encloses minute garnets, apparently the relics of former larger garnets consumed by cordierite owing to the reaction:

2 garnet + 4 sillimanite + 5 quartz = 3 cordierite

similar to descriptions of e.g. Hollister (1977, 1982), Jones & Brown (1990) and others. The chemical composition of cor-

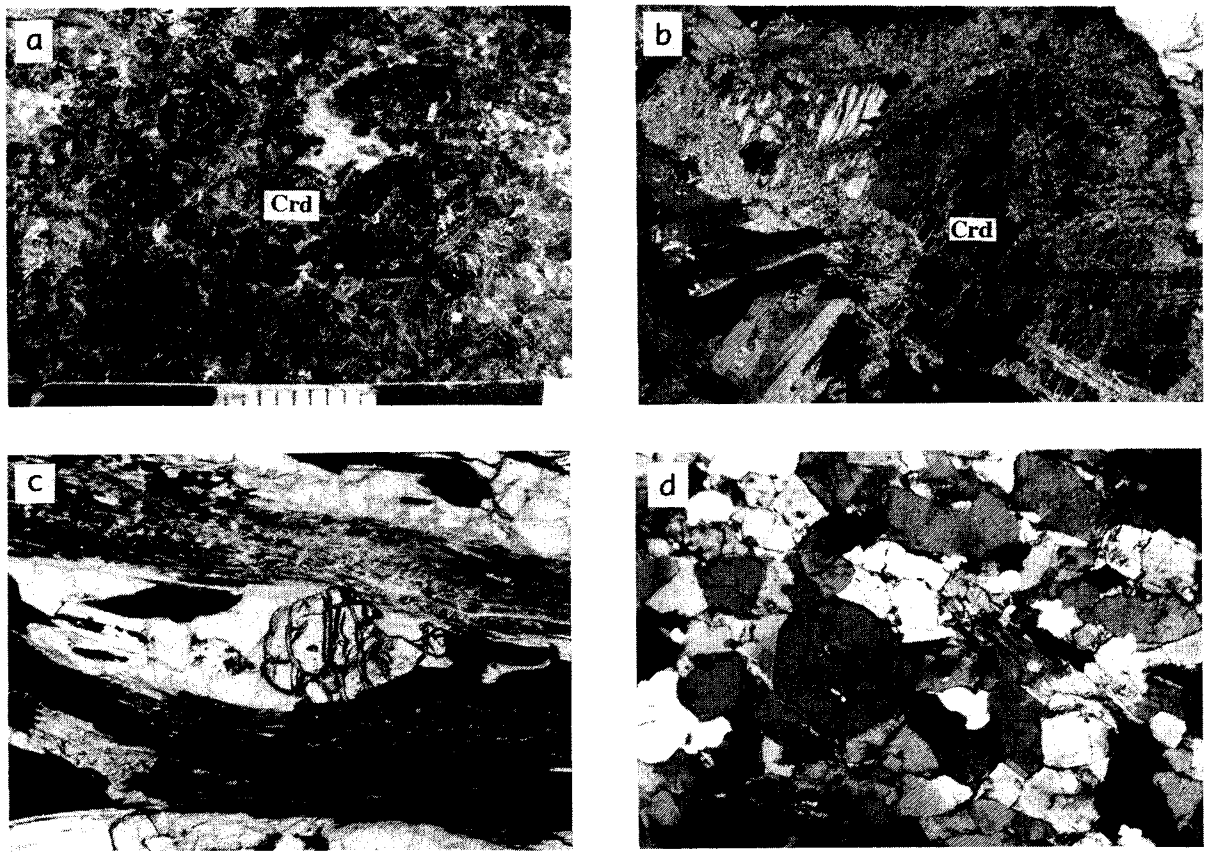

Fig. 2a–d. **a** — Cordierite porphyroblasts in migmatitic gneiss. Sample VF 260, width of view = 35 mm. **b** — Detail of cordierite porphyroblast with phengitic muscovite as a product of cordierite pinitization. Sample VF 260, width of view = 12 mm. **c** — Biotite and sillimanite defining the metamorphic foliation, surrounding the garnet in the cordierite-absent melanosome. Sample VF 264, width of view = 24 mm. **d** — Euhedral garnet in the K-feldspar, albite and quartz leucosome. Sample VF 261, width of view = 24 mm.

dierite (Tab. 1) reveals the mixture of Mg and Fe-end members with XFe = 0.43 on average; no substantial variations in composition have been detected.

Garnet is most abundant in cordierite-free assemblages, where it has formed large poikiloblasts enclosing quartz, biotite and sometimes also rutile. Retrograde chloritization and muscovitization is ubiquitous. In highly migmatized rocks (diatexites) garnet forms small euhedral grains (Fig. 2d), a possible restite after partial melting together with minor sillimanite and biotite. As described above, in cordierite-bearing samples, garnet is rare, preserved only as a relic in the cordierite porphyroblasts.

The composition of the garnet (Tab. 2) corresponds to almandine-rich garnets, individual grains are mostly uniform or only weakly zoned with an increase of spessartine and decrease of pyrope in the rims. This indicates that the earlier growth zonation has been totally obliterated by homogenization at temperatures above 600-650 °C (Spear 1991) and subseqent retrogression was not effective to set up diffusional zonation. There is substantial enrichment of Mn in the garnets enclosed by cordierite, relative to cordierite-free samples. This is considered to be the consequence of preferrential fractionation of Mn into the garnet during reaction with cordierite (Hollister 1977; Okrusch 1966), stabilizing the garnet at a lower pressure than in the pure Fe-Mg system. Moreover, because of relatively fast intracrystalline diffusion of Fe and Mn, small residual garnets may become Mn-rich.

Biotite is most abundant in melanosome, forming segregations of lath-shaped porphyroblasts exhibiting red-brownish pleochroism. They define the metamorphic foliation and lineation, sometimes they are folded as a consequence of ductile deformation. Superimposed kinking and chloritization is due to later retrogression in brittle conditions. Compositionally, biotites in the assemblage with cordierite show lower Ti content as well as the ratio of Fe/Fe + Mg than in cordierite-free rocks (Tab. 3).

Muscovite differs both texturally and compositionally. Large porphyroblasts (Mu I) of muscovite composition (Tab. 3) with only a very low paragonite component are present in all the above described assemblages. Their stability with respect to the presence of K-feldspar in high-grade conditions is equivocal and they may represent either a metastable or retrograde phase. On the other hand, fine-grained phengitic micas (Mu II) have originated only at the expence of cordierite, due to low-temperature pinitization (Fig. 2b).

Feldspars are mostly segregated in the leucosomes, where plagioclase is of albite composition and K-feldspar is abundant together with quartz. In the melanosome, plagioclase is oligoclase (An12-15) and K-feldspar is lacking.

Sillimanite forms coarse, lath-shaped aggregates of needles, or it is fibrolitic, intimately associated with biotite. Intergrowths of sillimanite + biotite are concentrated along foliation planes, surrounding the garnet in cordierite-free domains

Table 1: Representative analyses of cordierite. Formulas based on 18 oxygens.

Sample	VF 260a	VF 260b	VF 260b	VF 260c	VF 260c
SiO_2	47.64	47.67	48.26	47.71	48.3
TiO_2	0.00	0.00	0.00	0.02	0.01
Al_2O_3	32.66	32.26	32.8	32.67	32.71
FeO_t	9.86	9.02	8.95	7.75	8.73
MnO	0.8	0.69	1.01	0.77	0.56
MgO	6.87	6.79	6.77	6.34	6.08
CaO	0.04	0.03	0.00	0.00	0.00
Na_2O	0.74	0.80	0.63	0.82	0.71
K_2O	0.01	0.00	0.02	0.00	0.02
Total	98.62	97.26	98.44	96.08	97.12
Si	4.954	5.005	5.005	5.033	5.055
Al	4.004	3.993	4.010	4.063	4.036
Ti	0.000	0.000	0.000	0.002	0.001
Fe	0.857	0.792	0.776	0.684	0.764
Mn	0.070	0.061	0.089	0.069	0.050
Mg	1.080	1.062	1.046	1.001	0.958
Ca	0.004	0.003	0.000	0.000	0.000
Na	0.149	0.163	0.127	0.168	0.144
K	0.001	0.000	0.003	0.000	0.003
Fe/Fe+Mg	0.442	0.427	0.426	0.406	0.446

FeO_t = FeO total

Table 2: Representative analyses of garnet. Formulas based on 12 oxygens.

Sample	VF 264	VF 264	VF 260	VF 260	VF 261	VF 261
Analytical point	core	rim	core	rim	core	rim
SiO_2	37.09	36.76	36.65	37.00	37.09	37.47
TiO_2	0.02	0.03	0.00	0.02	0.00	0.00
Al_2O_3	20.67	20.68	21.91	21.47	21.08	21.12
FeO_t	31.35	31.84	26.52	26.73	33.26	33.79
MnO	8.33	8.71	12.29	12.51	6.65	6.75
MgO	1.80	1.57	2.18	1.92	2.25	2.18
CaO	0.67	0.71	0.90	0.77	0.25	0.27
Total	99.93	100.30	100.45	100.42	100.58	101.58
Si	3.018	2.996	2.953	2.985	2.997	3.002
Ti	0.001	0.002	0.000	0.001	0.000	0.000
Al	1.983	1.987	2.081	2.042	2.008	1.995
Fe	2.133	2.170	1.787	1.804	2.247	2.264
Mn	0.574	0.601	0.839	0.855	0.455	0.458
Mg	0.218	0.191	0.262	0.231	0.271	0.260
Ca	0.058	0.062	0.078	0.067	0.022	0.023
Fe/Fe+Mg	0.907	0.919	0.872	0.886	0.892	0.897
Alm	0.715	0.718	0.602	0.610	0.750	0.753
Sps	0.192	0.199	0.283	0.289	0.152	0.152
Prp	0.073	0.063	0.088	0.078	0.090	0.087
Grs	0.019	0.021	0.026	0.023	0.007	0.008

Table 3: Representative analyses of biotite and muscovite. Formulas based on 22 oxygens.

Sample	VF 264	VF 260	VF 261	VF 264	VF 260	VF 260	VF 260	VF 261
Mineral	Bt	Bt	Bt	Ms	MsI	MsII	MsII	Ms
SiO_2	33.69	34.94	33.60	45.57	47.23	45.07	47.00	47.43
TiO_2	3.62	2.74	0.39	1.20	0.10	0.00	0.00	0.00
Al_2O_3	19.33	19.95	21.46	35.10	35.99	31.47	32.53	36.94
FeO_t	23.4	21.05	22.96	1.16	0.89	4.36	2.29	1.37
MnO	0.33	0.38	0.42	0.00	0.07	0.04	0.10	0.04
MgO	5.42	7.55	7.30	0.44	0.60	2.91	2.29	0.51
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na_2O	0.18	0.22	0.20	0.47	0.83	0.17	0.61	0.65
K_2O	9.61	9.52	9.05	10.96	9.25	9.53	9.07	10.05
Total	95.58	96.35	95.38	94.90	94.96	93.55	93.77	96.99
Si	5.248	5.310	5.200	6.110	6.235	6.195	6.338	6.168
AlIV	2.752	2.690	2.800	1.890	1.765	1.805	1.662	1.832
AlVI	0.798	0.885	1.116	3.658	3.836	3.295	3.510	3.832
Ti	0.424	0.313	0.045	0.121	0.010	0.000	0.000	0.000
Fe	3.048	2.676	2.972	0.130	0.098	0.501	0.258	0.149
Mn	0.044	0.049	0.055	0.000	0.008	0.005	0.011	0.004
Mg	1.259	1.710	1.684	0.088	0.118	0.596	0.436	0.099
Ca	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Na	0.054	0.065	0.060	0.122	0.212	0.045	0.160	0.164
K	1.910	1.846	1.787	1.875	1.558	1.671	1.560	1.667
Fe/Fe+Mg	0.708	0.610	0.638	0.596	0.454	0.457	0.372	0.601

(Fig. 2c). Inclusions of sillimanite needles in cordierite are also present, sometimes along with garnet relics. In K-feldspar-bearing rocks, intergrowths of sillimanite + biotite are mantled by later muscovite.

Minor phases are represented mainly by ilmenite which is the ubiquitous opaque mineral. In the cordierite-free samples, rutile is also present, mostly in the form of inclusions in the garnets; in the matrix it is mostly replaced by ilmenite.

Geothermobarometry

Pressure and temperature conditions have been evaluated by thermobarometry in the cordierite-absent assemblage (representative sample VF 264):

garnet+biotite+plagioclase+muscovite+sillimanite+rutile+ilmenite+quartz;

and in the cordierite-present assemblage (representative sample VF 260):

cordierite+garnet+biotite+muscovite+plagioclase+ilmenite.

Thermobarometric calculations have been restricted to microtextural domains where local equilibrium between coexisting mineral phases have been asumed, i.e. the average composition of garnet rim, biotite and plagioclase in contact with garnet, as well as that of cordierite replacing the garnet have been utilized in the above mentioned assemblages. Both —"conventional" as well as "internally consistent" thermobarometric techniques have been applied.

Temperatures have been calculated using several calibrations of the garnet-biotite geothermometer, i.e. Ferry & Spear (1978), Hodges & Spear (1982), Perchuk & Lavrentieva (1983), Ganguly & Saxena (1984), Indares & Martignole (1985) and garnet-cordierite geothermometer of Thompson (1976), Holdaway & Lee (1977), Perchuk & Lavrentiava (1983) as well as Bhattacharyia et al. (1988). The calibration of Ganguly & Saxena (1984) includes the effect of Mn in the garnet mixing model, whereas the calibration of Indares & Martignole (1985) also involves the effect of Ti and Al^{VI} in biotite. Calculated temperatures (Tab. 4) in cordierite-free sample VF 264 range between 640-780 °C, with an average around 700 °C. In the cordierite-bearing sample VF 260, the temperature varies between 530-690 °C, mean values are near 600 °C.

Pressures (Tab. 4) have been evaluated on the basis of garnet-plagioclase-sillimanite-quartz geobarometers (GASP) using the calibrations of Newton & Haseltôn (1981), Hodges & Spear (1982), Ganguly & Saxena (1984) and Koziol & Newton (1988). In sample VF 264 (cordierite-free), the pressure ranges between 4-10 kbar, with the mean around 7 kbar. On the basis of the presence of rutile and ilmenite in the sample VF 264, the geobarometers GRAIL (Bohlen et al. 1983) and GRIPS (Bohlen & Liotta 1986) yield a pressure around 7 kbar. The substantially lower pressure of 2-7 kbar with a mean around 4 kbar have been obtained using the GASP method in the cordierite-bearing assemblage (sample VF 260).

As shown in Tab. 4, "conventional" thermobarometric analysis yields a wide range of P-T conditions. We assume that this is mainly because of the internal inconsistency of thermodynamic properties among several calibrations rather than the lack of equilibrium compositions. Therefore, an internally consistent thermodynamic technique TWEEQU (Berman 1991) with the thermodynamic dataset and computer program version TWQ of January 1992 has been applied. Together with a database, the mixing model of Berman (1990) for garnet (involving the effect of Mn), of McMullin et al. (1991) for biotite (incorporating corrections for the effect of Al and Ti) and of Fuhrman & Lindsley (1988) for feldspars has been utilized. For cordierite, thermodynamic data of hydrous Fe-cordierite and an ideal mixing model have been used in the calculations.

The results of the TWEEQU calculations are plotted in Figs. 3 and 4, showing intersections of equilibrium reactions between coexisting mineral phases in the samples VF 264 and VF 260. We reduced all possible equilbria to a minimum of three independent reactions between garnet, plagioclase, biotite, sillimanite, rutile, ilmenite and quartz in sample VF 264 (Fig. 3) and those involving Fe-cordierite, garnet, biotite, plagioclase and quartz in sample VF 260 (Fig. 4). Calculated intersections using the program INTERSX yield:

T = 688 ± 17 °C; P = 6960 ± 234 bar for cordierite-absent sampleVF 264 and

T = 595 ± 6 °C; P = 4243 ± 162 bar for cordierite-bearing sample VF 260.

The above presented data show that the TWEEQU method results average those obtained by conventional thermometry and barometry, i.e., we can approximate the temperature and pressure to about 700 °C and 7 kbar for cordierite-absent assemblages and 600 °C and 4 kbar for cordierite-bearing ones. Thus, thermobarometric data confirm the origin of cordierite at lower pressure than in the cordierite-free assemblages. Based on textural criteria, we assume that a pressure-sensitive

Table 4: Representative temperature T (°C) and pressure (bar) results based on "conventional" geothermometry and geobarometry.

Sample VF 264					
Garnet-Biotite geothermometry					
P ref.	T FS78	T HS82	T PL83	T GS84	T IM85
5000	712	722	650	763	642
7000	721	731	660	771	651
9000	730	739	669	780	660
Garnet-Sillimanite-Plagioclase-Quartz geobarometry					
T ref.	P NH81	P HS82	P GS84	P KN88	
600	5738	4477	3192	6294	
700	7987	5867	4598	8336	
800	10235	7257	6003	10375	
Garnet-Sillimanite-Plagioclase-Quartz-Rutile-Ilmenite geobarometry					
T ref.	P B83	P BL86			
600	6035	5253			
700	6989	6578			
800	7943	7902			
Sample VF 260					
Garnet-Biotite geothermometry					
P ref.	T FS78	T HS82	T GS84	T PL83	T IM85
2000	611	619	658	591	673
4000	619	627	666	601	681
6000	627	635	674	610	689
Garnet-Cordierite geothermometry					
P. ref.	T T76	T HL77	T PL83	T B88	
2000	598	590	524	672	
4000	608	598	533	682	
6000	617	607	543	691	
Garnet-Sillimanite-Plagioclase-Quartz geobarometry					
T ref.	P NH81	P HS82	P GS84	P KN88	
500	2267	2066	1119	3612	
600	4257	3256	2367	5536	
700	6247	4446	3616	7456	

Abbreviations: FS78 — Ferry & Spear (1978), HS82 — Hodges & Spear (1982), PL83 — Perchuk & Lavrentieva (1983), GS84 — Anguly & Saxena (1984), IM85 — Indares & Martignole (1985), NH81 — Newton & Haselton (1981), KN88 — Koziol & Newton (1988), T76 — Thompson (1976), HL77 — Holdaway & Lee (1977), B88 — Bhattacharya et al. (1988), B83 — Bohlen et al. (1983), BL86 — Bohlen & Liotta (1986).

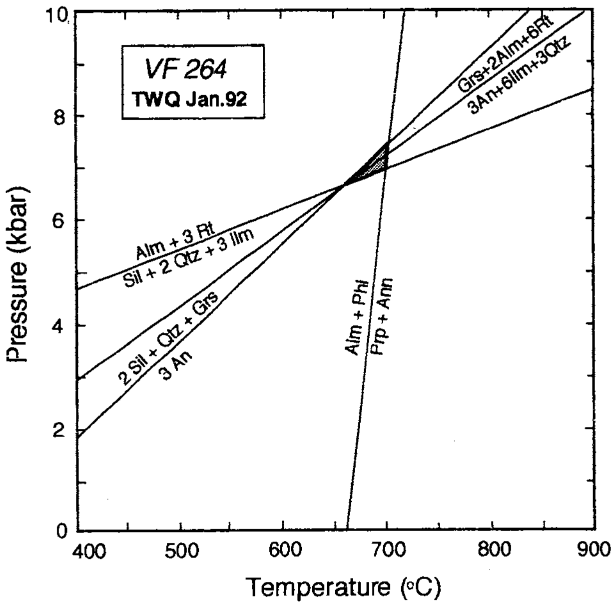

Fig. 3. Plot of TWEEQU results in the cordierite-absent sample VF 264.

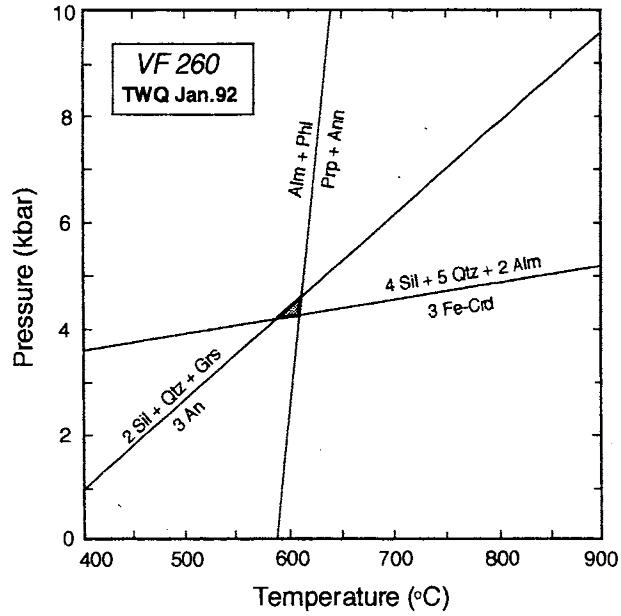

Fig. 4. Plot of TWEEQU results in the cordierite-absent sample VF 260.

net transfer reaction 2 alm+4 sil+5 qtz = 3 Fe-crd was a major cordierite-forming reaction. Because cordierite is much less dense than the breakdown reactants, crossing of this equilibrium during the P-T-t path (Fig. 5) is indicative of a nearly isothermal decompression. The equilibrium curve, calculated with thermodynamic data of Berman (1991) has a flat, slightly positive dP/dT slope (Figs. 4, 5), similar to the theoretical and experimental determinations of Martignole & Sisi (1981), Aranovich & Podlesskii (1983) and Mukhopadhyay & Holdaway (1994).

Discussion

Petrographic observation and thermobarometric data imply that cordierite in the Veľká Fatra migmatites originated at a pressure close to 4 kbar, overprinting higher-pressure assemblages containing garnet as a main reactant phase. However, this may be due to the decompression of relatively hot rocks, which attained temperatures near the upper stability of muscovite and the water saturated granite solidus (Fig. 5). The heat advected from the surrounding tonalite magma may have been effective in keeping high temperature during the uplift of metamorphic xenoliths from middle to upper crustal levels. According to this scenario, both low-pressure (cordierite-bearing) and medium pressure (cordierite-absent) assemblages are expected to have formed during the same, solely Variscan metamorphic event.

Alternatively, we cannot rule out a multistage evolution when cordierite could originate due to heating in the second (M2) stage of metamorphism (Variscan), overprinting the older, medium-pressure assemblages of metamorphism (M1). With limited age data, however, based on petrography and thermobarometry discussed above, the metamorphic P-T path (Fig. 5, full arrow) is characteristic for nearly isothermal decompression. There is no unequivocal evidence on cooling of the medium-pressure assemblages prior to cordierite-forming reaction due to reheating. Consequently, we assume that decompression was a major process facilitating the origin of cordierite in the Veľká Fatra migmatites.

The uplift history following the cordierite formation (Fig. 5, dashed arrow) can be deduced from Rb-Sr, K-Ar and Ar-Ar

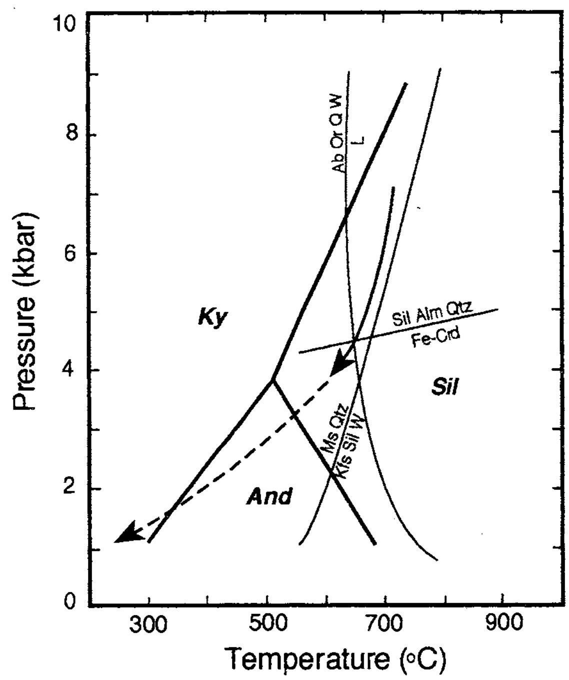

Fig. 5. Tentative P-T path of migmatitic gneisses in the Veľká Fatra Mts. Detailed explanation in the text. Alumosilicate triple point, muscovite dehydration and cordierite stability curves have been calculated using the database and computer programme of Berman (1991). Water saturated granite solidus is according to Johannes (1984).

ages (Kohút et al. 1993, 1996; Kráľ & Štarková 1995; Maluski, unpublished data). These imply that in time span of 4 mil.y., from 342 Ma (the pluton crystallization) to 338 Ma (the closure temperature of biotite), the granitoid pluton was emplaced from about 10–12 km depth (ca. 4 kbar) to 3–4 km (ca. 1.5 kbar), indicating the uplift rate of about 2 mm/yr.

Such relatively rapid uplift, however, was most probably facilitated by tectonic shearing and extension (e.g. Hollister 1992, 1993; Hutton 1988; Dewey 1988).

Our results from the Veľká Fatra Mts., similar to observations from the Tatra Mts. (Janák 1994), suggest that substantial portions of the Western Carpathian basement underwent decompressional uplift during the waning stages of the Variscan orogeny.

Acknowledgements: We thank Pavol Siman and Patrik Konečný for the assistance with microprobe analyses. M.K. gratefully acknowledges Prof. H. Maluski for providing Ar-Ar laser probe data. This paper greatly benefited from constructive rewiev of Patrick J. O'Brien.

References

Andrusov D., 1968: Grundriss der tektonik der Nordlichen Karpathen. *VEDA*, Bratislava, 1-188.

Aranovich L.Y. & Podlesskii K.K., 1983: The cordierite-garnet-sillimanite-quartz equilibrium: experiments and applications. In: Saxena S.K. (Ed): *Kinetics and equilibrium in mineral reactions. Advances in Physical Geochemistry vol.3. Springer,* New York-Berlin-Heidelberg, 173-198.

Berman R.G., 1990: Mixing properties of Ca-Mg-Fe-Mn garnets. *Amer. Mineralogist,* 75, 328-344.

Berman R.G., 1991: Thermobarometry using multi-equilibrium calculations: a new technique, with petrological applications. *Canad. Mineralogist,* 29, 833-855.

Bhattacharyia A., Mazumdar A. & Sen S.K., 1988: Fe-Mg mixing in cordierite: constraints from natural data and implications for cordierite-garnet geothermometry in granulites. *Amer. Mineralogist,* 73, 338-344.

Bohlen S.R. & Liotta J.J., 1986: A barometer for garnet amphibolites and garnet granulites. *J. Petrology,* 27, 1025-56.

Bohlen S.R., Wall V.J. & Boettcher A.L., 1983: Experimental investigations and geological applications of equilibria in the system $FeO-TiO_2-Al_2O_3-SiO_2-H_2O$. *Amer. Mineralogist,* 86, 1049-1058.

Dewey J.F., 1988: Extensional collapse of orogens. *Tectonics,* 7, 1123-1140.

Ferry J.M. & Spear P.S., 1978: Experimental calibration of the partitioning of Fe and Mg between biotite and garnet. *Contr. Mineral. Petrology,* 66, 113-117.

Fuhrman M. & Lindsley D., 1988: Ternary-feldspar modeling and thermometry. *Amer. Mineralogist,* 73, 201-215.

Ganguly J. & Saxena S.K., 1984: Mixing properties of aluminosilicate garnets: constraints from natural and experimental data and applications to geothermo-barometry. *Amer. Mineralogist,* 69, 88-97.

Hodges K.V. & Spear F.S., 1982: Geothermometry, geobarometry and the Al_2SiO_5 triplepoint at Mt. Moosilauke, New Hampshire. *Amer. Mineralogist,* 67, 1118-1134.

Holdaway M.J. & Lee S.M., 1977: Fe-Mg cordierite stability in high grade pelitic rocks based on experimental, theoretical, and natural observations. *Contr. Mineral. Petrology,* 63, 175-198.

Hollister L.S., 1977: The reaction forming cordierite from garnet, the Khtada Lake metamorphic complex, British Columbia. *Canad. Mineralogist,* 15, 217-29.

Hollister L.S., 1982: Metamorphic evidence for rapid (2 mm/yr) uplift of a portion of the Central Gneiss Complex, Coast Mountains, B.C. *Canad. Mineralogist,* 20, 319-332.

Hollister L.S., 1993: The role of melt in the uplift and exhumation of orogenic belts. *Chem. Geol.,* 108, 31-48.

Hutton D.H.W., 1988: Granite emplacement mechanisms and tectonic controls: inferences from deformation studies. Transactions of the Royal Society of Edinburgh. *Earth Sci.,* 79, 245-255.

Indares A. & Martignole J., 1985: Biotite-garnet geothermometry in granulite facies: influence of Ti and al in biotite. *Amer. Mineralogist,* 70, 272-278.

Janák M., 1994: Variscan uplift of the crystalline basement, Tatra Mts., Central Western Carpathians: evidence from $^{40}Ar/^{39}Ar$ laser probe dating of biotite and P-T-t paths. *Geol. Carpathica,* 45, 5, 293-300.

Johannes W., 1984: Beginning of melting in the granite system Qz-Or-Ab-An-H_2O. *Contr. Mineral. Petrology,* 86, 264-273.

Jones K.A. & Brown M., 1990: High-temperature "clockwise" P-T paths and melting in the development of regional migmatites: an example from southern Brittany, France. *J. Metamorphic Geol.,* 8, 551-578.

Kohút M., 1992: The Veľká Fatra granitoid pluton — an example of a Variscan zoned body in the Western Carpathians. In: J.Vozár (Ed.): *Paleozoic geodynamic domains and their alpidic evolution in the Tethys. GÚDŠ,* Bratislava, *special vol. IGCP Project No.* 276, 79-92.

Kohút M., Carl C. & Michalko J., 1996: Granitoid rocks of the Veľká Fatra — Rb/Sr isochrone geochronology (Western Carpathians, Slovakia). *Geol. Carpathica,* 47, 81-89.

Kohút M., Carl C. & Michalko J., 1993: Isotopic investigations of granitoids of the Veľká Fatra and a proposed geodynamic model (Western Carpathians, Slovakia). In: M.Rakús & J.Vozár (Eds.): *Geodynamic model and deep structure of the Western Carpathians. GÚDŠ,* Bratislava, 175-188 (in Slovak, English abstract).

Korikovsky S.P., Cambel B., Boronikhin V.A., Miklóš J. & Putiš M., 1985: Phase equilibria and geothermometry of metapelitic hornfelses around Modra granitoid massif (Malé Karpaty Mts.). *Geol. Zbor. Geol. Carpath.,* 36, 51-74 (in Russian, English abstract).

Korikovsky S.P., Janák M. & Boronikhin V.A., 1986: Geothermometry and changes in mineral equilibria during recrystallization of garnet mica schists to cordierite hornfelses in the aureole of Rochovce granite. *Geol. Zbor. Geol. Carpath.* 37, 5, 607-633 (in Russian, English abstract).

Koziol A.M. & Newton R.C., 1988: Redetermination of the anorthite breakdown reaction and improvement of the plagioclase-garnet-Al_2SiO_5-quartz geobarometer. *Amer. Mineralogist,* 73, 216-233.

Kráľ J. & Štarková J., 1995: $^{40}Ar/^{39}Ar$ dating of selected minerals from the Tatric and Veporic crystalline complexes. *Open file report, GÚDŠ,* Bratislava, 1-72 (in Slovak).

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

Maheľ M., 1986: Geology of the Czechoslovak Carpathians, paleoalpine units. *Veda,* Bratislava, 1-503 (in Slovak).

Martignole J. & Sisi J.C., 1981: Cordierite-garnet-H_2O equilibrium: a geological thermometer, barometer and water fugacity indicator. *Contr. Mineral. Petrology,* 77, 38-46.

McMullin D.W.A., Berman R.G. & Greenwood H.J., 1991: Calibration of the SGAM thermobarometer for pelitic rocks using data from phase equilibrium experiments and natural assemblages. *Canad. Mineralogist,* 29, 889-908.

Mukhopadhyay B. & Holdaway M.J., 1994: Cordierite-garnet-sillimanite-quartz equilibrium: I. new experimental calibration in the system $FeO-Al_2O_3-SiO_2-H_2O$ and certain P-T-XH_2O relations. *Contr. Mineral. Petrology,* 116, 462-472.

Newton R.C. & Haselton H.T., 1981: Thermodynamics of the garnet-plagioclase-Al_2SiO_5-quartz geobarometer. In: Newton R.C., Navrotsky A. & Wood B.J. (Eds.): *Thermodynamics of minerals and melts. Advances in Physical Geochemistry, Vol. 1, Springer-Verlag,* New York, 129-145.

Okrusch M., 1971: Garnet-cordierite-biotite equilibria in the Steinach aureole, Bavaria. *Contr. Mineral. Petrology,* 32, 1-23.

Perchuk L.L. & Lavrentieva I.V., 1983: Experimental investigations of the exchange equilibria in the systems cordierite-garnet-biotite. In: Saxena S.K. (Ed.): *Kinetics and equilibrium in mineral reactions. Advances in Physical Geochemistry, Vol. 3, Springer-Verlag,* New York, 199-240.

Spear F.S., 1991: On the interpretation of peak metamorphic temperatures in light of garnet diffusion during cooling. *J. Metamorphic Geol.,* 9, 379-388.

Thompson A.B, 1976: Mineral reactions in pelitic rocks. II. Calculation of some P-T-X (Fe-Mg) phase relations. *Amer. J. Sci.,* 276, 425-454.

Vozárová A. & Krištín J., 1987: Thermodynamic conditions at the contact of Alpine granitoids with metasediments of Slatvin Formation in Krokava surroundings (southern Veporicum). *Geol. Práce, Spr.,* 21, 33-38 (in Slovak).

Vrána S., 1964: Petrogenesis of the Veporic crystalline complexes in the area of Slavošovce. *Geol. Práce, Spr.,* 5-29 (in Slovak).