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METAMORPHIC PROCESSES IN PARAGNEISSES FROM THE SUCHÝ AND MALÁ MAGURA MTS. (THE WESTERN CARPATHIANS)

(4 Figs., 6 Tabs.)

A b s t r a c t : Intensity parameters of metamorphic processes of the Suchý (S.) and Malá Magura (M.M.) Mts. tectonic blocks indicate differences in their progressive and regressive metamorphic development. M.M. paragneisses have higher temperatures and pressures (640 °C/5 kbar) of metamorphic culmination in which more fluid was released (~2.6 l/m^3; X_{H_2O} = ~0.9) than S. paragneisses (560 °C/4.5 kbar; ~1.6 l/m^3;X_{H_2O} = ~0.6). Uplift trajectory characteristics (dP/dT) in the S. paragneisses prove their isothermal decompression (86 bar/°C^{-1}) and display more uniform trajectories determined by decompression during cooling (18 bar/°C^{-1}) in the M.M. paragneisses.

Р е з ю м е : Параметры интенсивности метаморфического процесса тектонических блоков Сухого (С.) и Малой Магуры (М.М.) показывают отличия в их прогрессивном и регрессивном метаморфическом развитии. Парагнейсы М.М. обладают высшими температурами и давлениями (640 °С/5 кбар) метаморфической кульминации, во время которой они выделяли больше флюида (~2,6 л/м^3; X_{H_2O} = ~0,9) чем парагнейсы С. (560 °С/4,5 кбар; ~1,6 д/м^3; X_{H_2O} = ~0,6). Характеристики траекторий взброса (dP/dT) свидетельствуют о изотермическом уменьшении давления (86 бар/°С$^{-1}$) в парагнейсах С. и проявляют более единые траектории, определяемые уменьшением давления при охлаждении (18 бар/°С$^{-1}$) в парагнейсах М.М.

Introduction

Metamorphic petrology attempts to define temperature, presure and fluid regime of recrystallization process developed as soon as in its beginnings. First studies of index minerals occurrence and metamorphic facies concept were followed by dynamic concepts of metamorphic field gradient. In the latter, the development of metamorphic rock is understood as a complex of factors of tectonics and thermal field. Metamorphic field is then taken not only as a product of metamorphic culmination, but as a product of dynamic development of progressive and retrograde metamorphic stages where recrystallization as a whole is determined by uplift and erosion processes. Deciphering of rock development on the basis of protolite, mineral inclusions, petrogenetic grid and geothermometric approach enables quantitative defining of recrystallization processes in individual stages of tectono-orogenic process.

Obtaining of the intensity parameters of metamorphism of paragneisses from the both tectonic blocks (Suchý and Malá Magura) was one of the aims of the work in order to use these data in petrologic-tectonic comparison of this geological area. Evaluation of these data (T, P, X_{H_2O}, n_{H_2O}) within the geological region studied enables to make a dynamic picture of progressive metamorphic development of these units and their uplift trajectories.

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Geology of the region

Geological and petrographic data on the crystalline complex of the region are based on the papers of Ivanov (1957), Klinec (1958), Kahan (1976, 1978, 1979, 1982), Putiš (1979, 1982), Šarkan (1977), Kráľ et al. (1987), Hovorka et al. (1987) and Dyda (1988). The whole geological region of the Strážovské vrchy Mts. is worked out in detail in the monograph of Maheľ (1985).

The crystalline complexes of the Suchý and Malá Magura Mts. are situated in two individual regions which were separated by the Paleogene movements. Crystalline core is thus separated into two units divided by the so-called Diviaky fault. The both units are similar as far as representation of metamorphic and granitoid rocks and representation of individual formations of tectonic styles of the crystalline cores occurrence are concerned. Southern and eastern borders with the Mesozoic and Tertiary complexes are markedly tectonic, whereas northern and northeastern borders of the crystalline complex and the Mesozoic are stratigraphic. The both cores are built up mostly of granitoid rocks, paragneissic and migmatitic complexes become dominant towards periphery of the cores. There are no distinct diaphtoritic zones in the centre of the crystalline complex and the crystalline body as a whole is compact, not containing remnants of the Mesozoic and younger Tertiary units. The both cores are connected with a paragneissic zone probably representing a tectonic boundary which cannot be proved directly (Kahan, 1979).

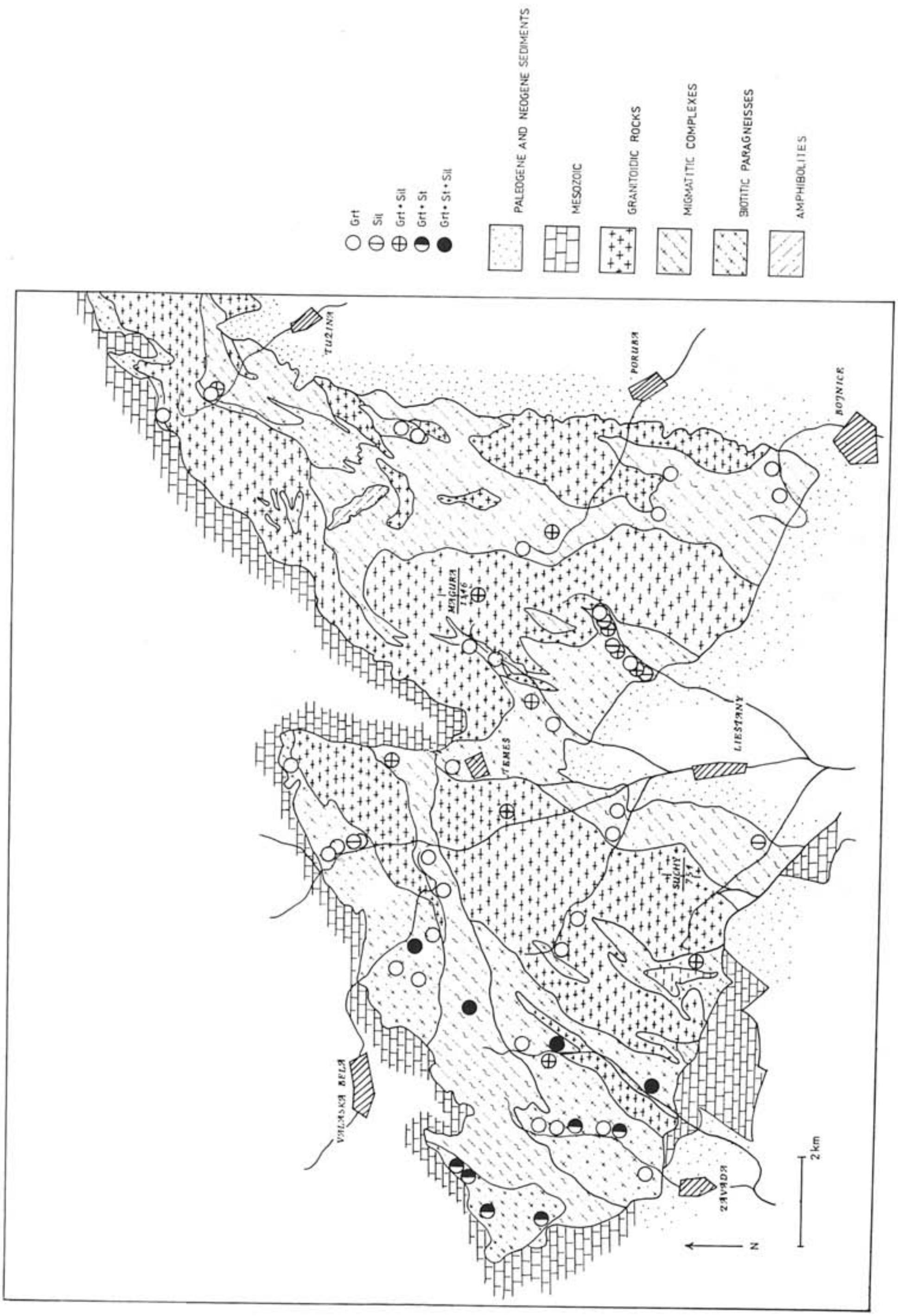
According to the radiometric data obtained by K-Ar method from biotite gneisses, age of metamorphic process is Early Carboniferous ranging from 290 to 300 m.y. (Kantor, 1961). The age of granitoid rocks from the Suchý and Malá Magura Mts. determined by Rb-Sr isochron is 393 ± 6 m.y. (Kráľ et al., 1987).

The core of the Malá Magura Mts. displays a lower content of cover rocks, it is more uplifted. The most distinct anticlinal structure is parallel to the main mountain ridge in the central part of the mountain range (Kahan, 1979). Pre-Alpine, Variscan tectogenesis is a dominant tectogenesis of the both cores. The Alpine restructuring of the crystalline complex is relatively poor and it did not change substantially the older tectonic structures (Maheľ, 1985).

Mineral composition of the studied paragneisses is relatively little variable. Paragneisses are composed of plagioclase (20–50 mod.%), biotite (15–30 mod.%), quartz (24–40 mod.%) and muscovite (0.5–6 mod.%) which is missing in some of the samples. From the index minerals there are garnet (Grt), staurolite (St), sillimanite (Sil), whereby St-Sil association has been found only in the Suchý Mts. region (Fig. 1). Paragneisses from the Suchý Mts. (S.) differ from paragneisses from the Malá Magura Mts. (M.M.) in tourmaline presence and higher content of graphitic matter. The latter paragneisses do not show retrograde domains which are more frequent in the Suchý Mts. region. From accessory minerals, ilmenite, rutile, apatite, zircon and graphite were established by microscope. In retrograde domains of the S. paragneisses, muscovite and chlorite were formed.

Some structural-tectonic pecularities of these crystalline complexes referred to by Kahan (1979), Putiš (1979), Maheľ (1985) and others caused detailed thermobarometric study, determination of characteristics of progressive and regressive metamorphic processes and approximation of uplift trajectories.

Fig. 1. Map of occurrence of the index minerals in the paragneisses from the Suchý and Malá Magura Mts. (Dyda, 1988).


Grt
Sil
Grt + Sil
Grt + St
Grt + St + Sil
PALEOGENE AND NEOGENE SEDIMENTS
MESOZOIC
GRANITOIDIC ROCKS
MIGMATITIC COMPLEXES
BIOTITIC PARAGNEISSES
AMPHIBOLITES
TUZINA
PORUBA
BOJNICE
MAGURA
TEMES
LIESTANY
SUCHÝ
VALASKA BELÁ
ZAVADA
N
2 km

Methodic approach and results

Frequent mineral association of the studied paragneisses: biotite, muscovite, plagioclase, garnet, sillimanite, staurolite and quartz enabled to use a number of mineral reactions for quantification of temperature-pressure recrystallization processes. The reactions were as follows:

almandine + phlogopite = pyrope + annite R1
muscovite + pyrope + grossularite = 3 anorthite + + phlogopite R2
muscovite + almandine + grossularite = 3 anorthite + + annite R3
3 anorthite = grossularite + 2 Al_2SiO_5 + quartz R4

The following calibrations were used for individual reactions: R1: Thompson (1976); Ferry – Spear (1978); Newton – Haselton (1981); Ganguly – Saxena (1984); R2: Ghent – Stout (1981); Hodges – Crowley (1985); R3: Ghent – Stout (1981); Hodges – Crowley (1985); R4: Ghent et al. (1979); Newton – Haselton (1981); Edwards – Essene (1988); Powell – Holand (1988).

Thermodynamic parameters of a reaction sometimes quite differ. This difference may cause obtaining of different T, P values. Difference in these values is ascribed to differences in regressive technique of thermodynamic relations evaluation, different activity models and calibration used for obtaining of T, P values (Hodges – Crowley, 1985). An important factor is that these inaccuracies in P-T determinations lie in inaccuracies in ΔH and ΔS of these reactions, whereas inaccuracies in microprobe analyses represent a small part of cumulative inaccuracy. It suggests that determination of P-T differences between the samples what represents main application of thermobarometry to the tectonic purposes, may be carried out more accurately than absolute determination of temperatures and pressures in the individual samples (Hodges – Crowley, 1985). More frequent mistake is ignoring the recommended concentration limits within which individual reactions may be a good indicator of P-T conditions. It leads to application of individual geothermometers even in the samples where it is not recommended and where the limit determining their application is exceeded.

Analyses of coexisting minerals of paragneisses from the studied region presented in Tab. 1 a-d were used for thermobarometric treatment. The calculated temperatures and pressures of the studied samples from the Suchý and Malá Magura Mts. are summarized in Tab. 2 a, b and graphically represented in Fig. 2.

Generalization of the thermobarometric approach in individual regions leads to confirmation of different intensities of metamorphic maxima in the Suchý and Malá Magura Mts. (Hovorka et al., 1987). This metamorphic culmination took place in the Malá Magura Mts. region at the temperatures of 640 °C and the pressures of 5 kbar; in the Suchý Mts. region these metamorphic maxima are characterized by lower temperatures (~ 560 °C) and pressures (~ 4.5 kbar).

The thermobarometric data are in good agreement with mineralogical composition of paragneisses, with stability field of index minerals determined on the basis of monovariant curves (Dyda, 1988), as well as with their spatial and geological relations to migmatitic and granitoid rocks from these regions.

Miscroscopic study of structural relations in the progressive mineral associations took into account the importance of precursor mineral inclusions which may indicate metamorphic

Table 1a

Chemical analyses of garnets from the Suchý (S.) and Malá Magura Mts. (M.) paragneisses

		SiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Sum	% cat.
S-48-Y	C	36.59	20.43	31.93	7.61	2.30	1.06	99.92	97.91
	R	36.19	20.34	32.03	7.20	1.79	1.48	99.03	98.56
S-58-Y	C	37.09	21.04	28.38	12.44	2.32	1.49	102.76	98.02
	R	37.72	20.29	26.81	13.98	2.08	1.35	102.23	95.25
S-59-Y	C	37.22	20.73	29.91	9.97	2.69	1.39	101.91	97.15
	R	36.38	20.60	29.75	10.45	2.72	1.09	100.99	97.51
S-60-Y	C	36.75	20.98	29.67	6.41	2.52	0.91	97.24	103.25
	R	36.64	20.69	29.69	6.69	2.44	0.85	98.00	103.17
S-68-Y	C	37.57	20.61	28.77	7.33	2.65	1.59	98.99	99.04
	R	37.47	20.26	28.36	8.77	2.36	1.27	98.49	98.11
M-03-Y-	C	36.18	20.58	33.52	6.54	3.22	0.97	101.01	97.19
	R	37.57	21.89	31.69	6.93	2.90	0.92	101.90	102.14
M-07-Y	C	37.64	20.21	30.64	9.02	3.74	1.06	102.31	93.95
	R	37.47	21.22	29.11	8.94	3.15	1.04	100.93	99.85
M-31-Y	C	37.57	20.70	32.57	6.87	2.71	0.94	101.36	97.53
	R	37.43	20.44	32.43	7.30	2.59	1.03	101.22	96.58
M-23-Y	C	37.64	21.89	33.12	4.19	3.34	1.02	101.20	102.44
	R	37.33	20.96	32.88	5.63	2.87	1.00	100.67	99.18
M-87-Y	C	37.79	20.80	32.52	7.40	3.18	0.96	102.65	96.59
	R	37.32	21.00	29.87	11.45	2.29	1.11	103.04	97.78

Chemical analyses were obtained using GEOL SUPER PROBE 737: S-48-Y, S-58-Y, S-60-Y, S-68-Y, M-07-Y, M-21-Y, M-23-Y (Dr. F. Caňo, Geol. Inst. of D. Štúr, Bratislava), GEOL JXA 5A: M-03-Y, M-87-Y (Dr. D. Jančula, Slovak Technical College, Bratislava).

Table 1b

Chemical analyses of plagioclases from the Suchý (S.) and Malá Magura Mts. (M.) paragneisses

		SiO_2	Al_2O_3	FeO	MnO	CaO	Na_2O	K_2O	Sum
S-48-Y	C	63.18	22.64			4.32	9.41	0.17	99.72
	R	62.85	23.07			4.76	9.08	0.11	99.87
S-58-Y	C	62.39	24.01	0.07		4.95	8.66	0.14	100.22
	R	61.75	24.09	0.13		5.26	7.94	0.53	99.70
S-59-Y		62.15	23.52	0.10	0.03	4.34	8.92	0.09	100.15
S-60-Y	C	64.39	22.72	0.12		3.48	9.41	0.12	100.24
	R	63.51	22.70	0.05		4.00	9.15	0.13	99.54
S-68-Y	C	63.32	23.08	0.18		3.65	8.65	0.01	98.89
	R	61.96	23.01	0.12		4.89	8.26	0.01	98.25
M-03-Y	C	62.59	23.57	0.09	0.07	4.68	8.14	0.19	99.33
	R	61.80	24.10	0.08	0.07	5.12	8.01	0.17	99.35
M-07-Y	C	62.40	23.51	0.19		4.69	8.51	0.22	99.52
	R	62.63	23.96	0.10		5.48	9.43	0.23	101.83
M-21-Y	C	64.76	21.90	0.16		3.20	9.13	1.36	100.51
	R	63.73	22.45	0.11		3.81	8.76	1.54	100.40
M-23-Y	C	62.43	23.62	0.08		4.73	8.46	0.16	99.48
	R	62.26	23.99			5.30	8.83	0.16	100.54
M-87-Y		62.58	24.34	0.05	0.10	4.66	9.13	0.19	101.06

Table 1c

Chemical analyses of biotites from the Suchý (S.) and Malá Magura Mts. (M.) paragneisses

		SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	H_2O	Sum
S-48-Y	C	37.19	0.75	19.46	20.12	0.13	7.85		0.18	8.89	4.00	97.67
	R	37.54	0.96	19.73	20.11	0.26	8.23		0.27	8.96	4.00	100.76
S-58-Y	C	35.76	1.90	19.17	18.78	0.38	9.01		0.26	9.08	4.00	98.34
	R	35.79	1.81	19.26	18.32	0.01	9.17	0.01	0.25	9.16	4.00	97.78
S-59-Y	C	34.74	1.92	20.20	17.24	0.13	9.66	0.09	0.45	8.46	4.00	96.89
	R	35.38	1.87	20.61	16.49	0.23	9.96	0.01	0.42	8.49	4.00	97.46
S-60-Y	C	37.64	2.88	19.71	14.71		8.59	0.03	0.23	8.36	4.00	96.40
	R	37.31	2.77	19.53	15.67	0.04	9.31	0.02	0.17	8.26	4.00	97.08
S-68-Y	C	36.63	1.37	18.67	17.42	0.10	9.68		0.13	9.43	4.00	97.43
	R	36.76	1.23	18.62	17.29	0.17	9.95		0.10	9.08	4.00	97.20
M-03-Y	C	35.14	1.86	20.15	19.27	0.19	8.56	0.09	0.21	8.56	4.00	98.38
	R	37.08	1.70	21.90	17.02	0.18	8.06	0.01	0.23	7.98	4.00	98.16
M-07-Y	C	35.13	1.92	20.82	19.36	0.48	9.17	0.02	0.15	9.62	4.00	100.67
	R	35.14	1.99	20.70	18.50	0.49	9.13	0.04	0.16	8.62	4.00	98.77
M-21-Y	C	37.40	1.85	19.25	20.97		8.88		0.29	8.74	4.00	101.38
	R	37.02	1.93	19.38	20.78		9.03		0.27	8.65	4.00	101.06
M-23-Y	C	37.58	1.08	19.09	20.95	0.18	8.96	0.02	0.40	9.03	4.00	101.29
	R	37.47	1.12	18.83	20.19	0.15	9.75	0.02	0.28	8.95	4.00	100.76
M-87-Y		35.27	2.47	20.03	19.43	0.38	8.28		0.19	9.26	4.00	99.31

Table 1d

Chemical analyses of muscovites from the Suchý (S.) and Malá Magura Mts. (M.) paragneisses

		SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	H_2O	Sum
S-48-Y	C	45.02	0.57	36.21	1.03	0.03	0.72	0.01	1.27	9.03	4.50	98.38
	R	45.44	0.66	36.82	0.86	0.01	0.65		1.48	9.21	4.50	99.63
S-58-Y	C	46.16	0.36	35.67	0.86		0.74		0.49	9.51	4.50	98.29
	R	46.43	0.68	36.20	0.81	0.02	0.68		0.48	9.30	4.50	99.00
S-59-Y		46.13	0.83	36.22	0.91	0.04	0.46		1.06	9.41	4.50	99.56
S-60-Y	C	44.82	1.22	36.02	0.63		0.53	0.01	0.95	9.26	4.50	97.94
	R	44.94	0.85	35.87	0.45		0.47		1.06	9.54	4.50	97.68
S-68-Y	C	44.90	0.26	35.03	0.68		0.82		0.93	9.22	4.50	96.34
	R	44.82	0.36	35.61	0.67		0.59		0.88	8.87	4.50	96.30
M-03-Y		46.04	0.99	36.11	1.09		0.54	0.06	0.60	10.29	4.50	100.22
M-07-Y	C	44.85	0.33	37.46	0.93	0.07	0.91	0.05	0.42	10.66	4.50	100.18
	R	44.64	0.55	36.16	0.96	0.06	0.97	0.06	0.48	10.72	4.50	99.10
M-21-Y	C	45.29	0.71	36.16	1.42		0.41		0.74	9.60	4.50	98.83
	R	44.64	0.74	36.20	1.41		0.37	0.01	0.80	9.84	4.50	98.51
M-23-Y	C	45.15	0.48	35.87	1.03		0.49	0.02	0.74	9.16	4.50	97.44
	R	45.04	0.58	35.00	1.68		0.62	0.05	0.81	9.04	4.50	97.32
M-87-Y		45.45	0.65	36.36	1.00	0.06	0.55	0.03	0.57	10.68	4.50	99.95

Table 2a
Temperatures of metamorphic recrystallization of the paragneisses from the Suchý and Malá Magura Mts.

		ln K_D	T	F & S	N & H	G & S	P
S-48-Y	C	1.692	571	584	596	616	536
	R	1.989	500	488	504	533	472
S-58-Y	C	1.770	551	557	573	603	535
	R	1.867	528	524	539	579	517
S-59-Y	C	1.835	537	541	556	566	529
	R	1.888	523	521	533	545	514
S-60-Y	C	1.768	552	560	573	566	551
	R	1.793	545	549	560	556	548
S-68-Y	C	1.798	546	554	573	571	541
	R	1.934	512	506	521	534	515
M-03-Y	C	1.532	615	645	656	643	580
	R	1.642	584	599	610	606	561
M-07-Y	C	1.357	669	723	735	709	622
	R	1.516	620	650	662	653	592
M-21-Y	C	1.628	589	609	620	624	556
	R	1.694	571	583	595	604	543
M-23-Y	C	1.446	641	681	693	661	596
	R	1.712	566	575	587	580	548
M-87-Y	C	1.472	632	666	681	671	590
	R	1.716	566	578	590	622	537

Data obtained on the basis of the core zones of Grt-Bt-Pl-Ms (C) and the rim zones (R) using the following calibrations: T - Thompson (1976); F & S - Ferry—Spear (1978); N & H - Newton — Haselton (1981); G & S - Ganguly—Saxena (1984); P - Perchuk (1970).

processes before the formation of the dominant mineral association of the metamorphic maximum. This was valid particularly for the S. paragneisses where high temperatures were not reached in general, and zoning of garnets, as well as way of retrograde process required search of preexisting index minerals. Kyanite, andalusite and cordierite have not been found what makes a more detailed determination of preculmination trajectory on the basis of petrogenetic grid difficult.

In the course of postmetamorphic uplift and cooling, concentration changes appear in the mineral associations. Regressive rims of minerals reflect the lower temperatures and pressures. The temperatures and pressures calculated in such way are real and reliable (Tracy et al., 1976; Ghent et al., 1979; Hodges—Spear, 1982).

Table 2b
Pressures of metamorphic recrystallization of the paragneisses from the Suchý and Malá Magura Mts.

		aAn	aGr	G	G & S	H & C	N & H	P & H	E & E
S-48-Y	C	0.3159	0.0343	4.1	3.8	4.1	3.8	6.6	5.4
	R	0.4367	0.0478	3.4	3.7	3.1	2.6	3.8	4.4
S-58-Y	C	0.4124	0.0463	4.2	3.7	3.7	3.6	4.6	5.2
	R	0.4868	0.0396	2.9	3.0	2.7	2.0	3.1	4.1
S-59-Y	C	0.3646	0.0421	4.0	4.2	4.2	3.5	4.5	5.1
	R	0.4100	0.0330	2.6	3.3	3.1	1.9	3.1	4.0
S-60-Y	C	0.2622	0.0345	4.3	4.7	5.0	4.2	5.2	5.6
	R	0.3205	0.0328	3.5	4.1	4.2	3.1	4.2	4.9
S-68-Y	C	0.4315	0.0519	4.4	5.2	5.2	3.8	4.8	5.3
	R	0.4736	0.0417	2.9	3.5	3.0	2.1	3.2	4.1
M-03-Y	C	0.3573	0.0292	3.6	3.5	4.5	3.5	4.2	5.2
	R	0.4236	0.0290	2.6	3.2	3.7	2.2	3.1	4.5
M-07-Y	C	0.3131	0.0313	4.9	4.0	5.6	5.1	5.6	6.6
	R	0.3564	0.0325	4.1	3.7	4.8	4.0	4.7	5.6
M-21-Y	C	0.2062	0.0288	4.9	4.4	5.0	5.2	6.0	6.5
	R	0.2692	0.0315	4.2	4.0	4.3	4.1	5.0	5.6
M-23-Y	C	0.3313	0.0325	4.6	4.0	5.4	4.7	5.2	6.2
	R	0.4174	0.0318	2.8	3.1	3.3	2.4	3.3	4.4
M-87-Y	C	0.3072	0.0287	4.3	3.8	5.1	4.3	4.9	6.1
	R	0.3550	0.0324	3.5	3.4	3.6	3.1	4.0	4.9

Data obtained from the core (C) and rim (R) zones of mineral domains using the following calibrations: G - Ghent—Robbins—Stout (1979); G & S - Ghent—Stout (1981); H & C - Hodges—Crowley (1985); N & H - Newton—Haselton (1981); P & H - Powell—Holland (1988); E & E - Edwards—Essene (1988).
Activities of anorthite (aAn) and grossularite (aGr) are calculated on the basis of Newton—Haselton's formulation (1981).

Regressive zoning of the M.M. garnets has a narrower concentration range than that of the S. garnets which have different chemical composition of the centres too (Dyda, 1988). Regressive character of the M.M. samples obtained by thermobarometric treatment of the centres and rims of these garnets is manifested by unity of P-T trend which may be approximated by dP/dT slope of ~ 18 bar/°C^{-1}. From the obtained P-T trend, the Suchý Mts. region may be approximated by the dP/dT value of ~ 86 bar/°C^{-1} which is quite close to the values characterizing the isothermal decompression in general.

These P-T trends reflect in general the P-T trajectories of the studied region in uplift and erosion stage. dP/dT values were studied in each sample in detail on the basis of metamorphic

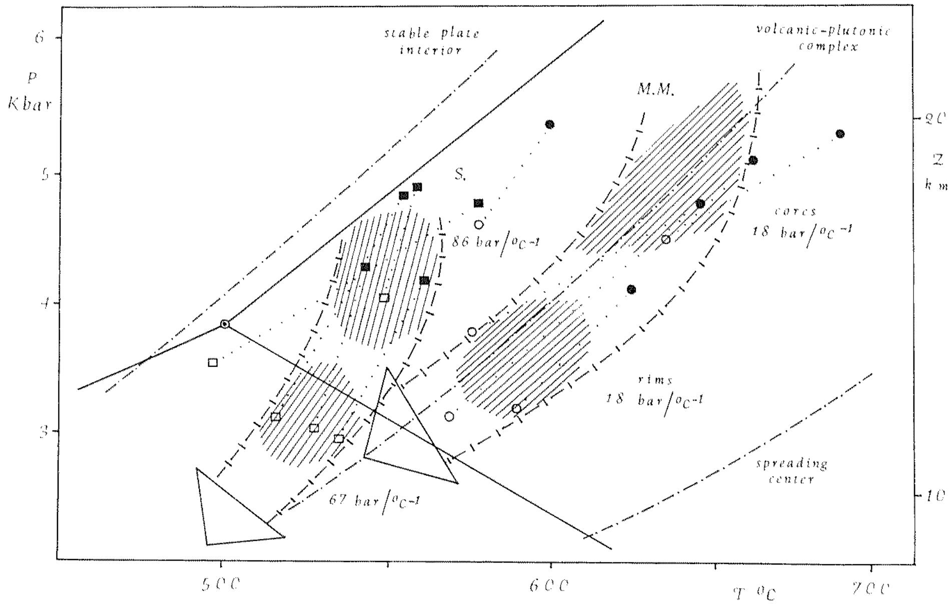


Fig. 2. Generalized temperature-pressure conditions of metamorphism of the Suchý (S.) and Malá Magura (M.M.) paragneisses. P-T characteristics of metamorphic culmination are obtained from the central zones (cores) of the coexisting minerals (Grt, Pl, Bt, Ms). Regressive rims approximate the uplift conditions determined also by the slope (dP/dT) of metamorphic reactions in the simplified metapelitic system (KMFASH). Triple point Al_2SiO_5 after H o l d a w a y (1971). Thermal gradients for individual tectonic units which may be identical with the gradients of metamorphic field are taken over from E r n s t (1988).

culmination reactions (Tab. 3) and metamorphic reactions in which chemical composition of rims of the coexisting phases was applied. Obtaining of ΔS and ΔV for the reaction was given by the methodic approach and data were taken over from S p e a r – S e l v e r s t o n e (1983) and S p e a r (1988). Slopes of these reactions (dP/dT) in a simplified metapelitic KMFASH system including the mineral phases St, Grt, Bt, Ms, Sil, Qtz are given in Tab. 4.

In the Malá Magura Mts. region, similarity of the dP/dT values in the culmination and regressive stages is preserved. The Suchý Mts. region displays, on the other hand, the dP/dT values of ~ 86 bar/°C^{-1} for the metamorphic culmination reactions and of ~ 67 bar/°C^{-1} for the reactions obtained from the rim mineral zones. This difference indicates diversity in the culmination recrystallization conditions, as well as diversity in the course of postmetamorphic uplift stages of these tectonic blocks.

The next evaluating factor in comparison of metamorphic development of paragneisses from individual regions was study of the fluid regime of the culmination stages on the basis of the following reaction:

$$\text{paragonite} + \text{quartz} = \text{albite} + \text{sillimanite} + H_2O \qquad (R5),$$

having the following thermodynamic characteristics:

$$\Delta H = 21{,}795 \text{ cal}, \ \Delta S = 40.422 \text{ cal/°K},$$
$$\Delta Vs = -0.107 \text{ cal/bar} \ (\text{F e r r y}, 1980).$$

Table 3
Reactions of metamorphic culmination normalized to 1 mol of released H_2O

	S-48-Y	S-59-Y	S-60-Y	S-68-Y
H_2O	1.0	1.0	1.0	1.0
Qtz	−1.076	−0.060	−1.265	−0.724
Sil	4.085	4.360	3.905	4.080
Ilm	0.029	0.037	0.020	0.031
Plag	−0.224	−0.830	−0.374	−0.515
Grt	0.502	0.623	0.740	0.646
Bt	0.123	0.074	0.063	0.067
Ms	−0.136	−0.075	−0.062	−0.077
St	−0.486	−0.499	−0.500	−0.490
	M-03-Y	M-21-Y	M-23-Y	M-87-Y
H_2O	1.0	1.0	1.0	1.0
Qtz	2.263	0.285	0.689	1.618
Sil	7.784	5.535	4.700	6.613
Ilm	−2.696	−1.692	−1.271	−1.913
Plag	1.197	1.304	0.568	1.327
Grt	−3.600	−2.237	−1.512	−3.091
Bt	5.784	3.292	2.449	4.221
Ms	−5.561	−3.380	−2.643	−4.194

Reactants of metamorphic reaction are denoted by negative signs.

Table 4
Thermodynamic data and calculated reaction slopes (dp/dT) in the simplified KMFASH metapelitic system including St, Grt, Bt, Ms, Sil, Qtz

		Δ V (cm^3)	Δ S	dP/dT (bar/° K^{-1})
S-59-Y	C	22.66	29.90	55.19
	R	24.63	29.27	49.72
S-59-Y	C	7.71	21.95	119.18
	R	15.20	25.78	70.96
S-60-Y	C	11.67	26.82	96.11
	R	16.03	29.67	77.46
S-68-Y	C	15.00	27.72	77.30
	R	16.23	27.50	70.85
M-03-Y	C	19.71	9.07	19.25
	R	20.25	10.04	20.75
M-21-Y	C	18.04	7.64	17.73
	R	19.73	7.63	16.18
M-23-Y	C	15.86	6.75	17.81
	R	15.37	7.48	20.35
M-87-Y	C	18.74	8.95	19.98
	R	18.61	8.11	18.24

C and R denote data obtained from the core (C) and rim (R) zones of chemically analyzed phases.

Table 5
Quantitative characteristics of dehydratation reactions of metamorphic culmination of the Suchý and Malá Magura Mts. paragneisses

Sample	Sil (mol/m^3)	H_2O (mol/m^3)	H_2O (l/m^3)	X_{H_2O}
S-48-Y	260.5	63.77	1.48	0.63
S-59-Y	240.4	55.14	1.11	0.71
S-60-Y	300.6	76.97	1.70	0.78
S-68-Y	440.8	108.05	2.31	0.65
M-03-Y	521.0	66.93	1.64	0.97
M-21-Y	561.1	101.36	2.26	0.88
M-23-Y	841.6	179.06	4.20	1.11
M-87-X	641.2	96.96	2.33	0.78

Muscovite from the metapelitic rocks is a simplified solid solution of muscovite–paragonite and its coexistence with sillimanite and plagioclase (K-feldspar has not been found in the samples) enables to evaluate the mole fraction of water in the metamorphic fluid according to the above-mentioned equation. In idealized system, activity of the component equals to its mole fraction. In the system where solid solutions deviate from ideality, knowledge of activity coefficients (γ) is important for calculation of the activities of individual components. They were calculated for the equation under consideration (R5) from Eugster et al. (1972) and are given in Tab. 6. Chemical composition of minerals listed in Tabs. 1b, 1d was used for calculation of the mole fraction of albite (X_{Ab}) and paragonite (X_{Pa}).

Table 6
Fugacity (f) and mole fraction of water (X_{H_2O}) in metamorphic fluid calculated from the equilibrium: Par + Qtz = Ab + Sil + H_2O for the Suchý (S.) and Malá Magura Mts. (M.) paragneisses

Sample	X_{Ab}	X_{Pa}	γPa	f H_2O (bar)	X_{H_2O}
M-03-Y	0.751	0.080	6.149	1659	0.972
M-21-Y	0.738	0.109	6.040	1924	0.884
M-23-Y	0.744	0.119	5.729	1675	1.121
M-87-Y	0.772	0.083	6.394	1434	0.780
S-48-Y	0.770	0.196	5.368	749	0.636
S-59-Y	0.783	0.146	5.722	884	0.712
S-60-Y	0.799	0.144	5.808	1170	0.785
S-68-Y	0.752	0.131	6.334	718	0.651

Fugacity values of H_2O depend largely on calculated temperature and pressure, and inaccuracy in recrystallization temperature determination for individual association is reflected in unreal values of the mole fraction of water (X_{H_2O}) . X_{H_2O} value of the metapelitic rocks is most often $0.5<X_{H_2O}<1$. It is in accordance with the assumed values indicating that $P_{H_2O} \leq P_{total}$.

The S. paragneisses show lower X_{H_2O} values than the M. M. paragneisses (Tab. 6). These values represent difference in composition of the metamorphic fluid produced in the stage of metamorphic culmination of individual regions.

In the graphite present in the S. paragneisses, equilibrium of fluid phases comprising also CO_2, CO, CH_4, H_2, O_2 within the C-H-O system (French, 1966; Kerrick, 1974) is presupposed in general. Calculation of mole fractions of the fluid component is, however, dependent on temperature and pressure. Reliability of X_{H_2O} determination is therefore a subject of the thermobarometric approach. These values have thus mainly a comparative meaning for substantial components of the metamorphic fluid – H_2O and CO_2.

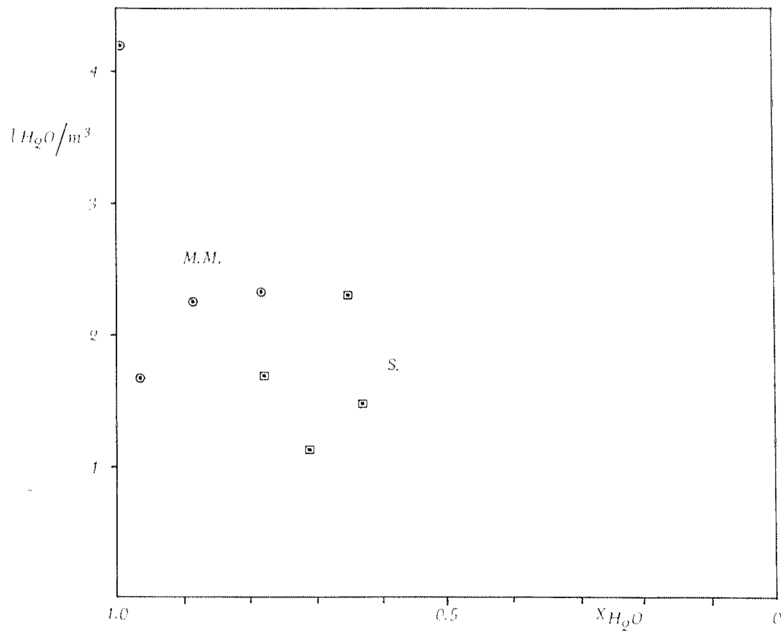


Fig. 3. Quantity (litre/m^3) and composition (X_{H_2O}) of metamorphic fluid released by dehydratation reactions during the metamorphic culmination of the S. (▣) and M.M. (⊙) paragneisses.

Quantification of the produced fluid was evaluated on the basis of metamorphic culmination reactions presented in Tab. 3. After modal-texture test, sillimanite and garnet, or only sillimanite served as reaction products in individual reactions. The presented values of released water (Tab. 5) represent probably minimum values (l/m^3) of the released fluid, since in majority of the samples $X_{H_2O}<1$. The results document the fact that the M.M. paragneisses released more water during dehydratation of the metamorphic culmination than the S. paragneisses (Fig. 3).

Discussion

From the study of microscopic texture domains of the paragneisses followed a statement about the progressive and regressive metamorphic reactions in the Suchý Mts. and dominant presence of the progressive culmination reactions in the Malá Magura Mts.

Evaluation of the domains proved that metamorphic reactions characterized by general stechiometric coefficients are rare and they take place at specific values of these coefficients. Modal testing of these reactions showed that volume ratios of the reactants do not always fit in the relation resulting from the defined metamorphic reaction. It proves a presumption of complexity of these reactions.

Some of the metamorphic reactions defined in the Suchý Mts. region did not take place in the M.M. paragneisses. Different protolite composition and different P-T-X_{H_2O} recrystallization conditions were probably necessary for their progressive development. Mineral reactions of the metamorphic culmination took place in the Suchý Mts. region at lower temperatures and pressures than in the Malá Magura Mts.

This difference of the metamorphic maxima is considered by Hovorka et al. (1987) as a certain form of metamorphic zonality whose intensity increases from the N through the Malá Magura Mts. to the NE, to the Malá Fatra Mts. Metamorphic zonality limited to the Suchý Mts. region is described by Korikovsky et al. (1987) on the basis of staurolite and andalusite occurrence. Staurolite occurrence is localized in the northwestern part of the crystalline complex (see Fig. 1), but its occurrence need not prove only the metamorphic zonality. Indications of protolite differences of these regions require proofs that staurolite occurrence is conditioned only thermally. In the same way, andalusite occurrence cannot be for its rarity (it has not been found by the author) a clue for distinguishing of the metamorphic zonality. For the above reasons, the metamorphic zonality in the Suchý Mts. region remains an open question, for the time being.

Hovorka (1975) and Hovorka et al. (1987) express a serious presumption that clastic garnet may occur in protolite of the S. and M.M. gneisses, since protolite of the major part of paragneisses was geochemically immature sediment of a graywacke type. Among clasts of these sediments there was also material with high-temperature garnet (Precambrian metamorphites of "deep" amphibolite to granulite facies?) (Hovorka et al., 1987, p. 305).

The obtained results prove distinct difference of garnet cores. It holds mainly for the Suchý Mts. region. The M.M. garnets have not so distinct difference of chemical composition between the core and the rim. Their zoning is in concentration ranges usual in the paragneisses of a similar type. They have a regressive rim formed during the uplift stage after the metamorphic culmination. This regressive rim is present also in the S. garnets with a difference representing rather isothermal decompression. It is probable that if clastic grains were present also in the M.M. protolite, metamorphic grade would probably cause a sufficient diffusion "to wipe off" their former zoning. It is supported by a number of findings that garnets recrystallized at the similar temperatures are mostly homogeneous, excluding a possible retrograde development of their rims (Tracy et al., 1976; Woodsworth, 1977; Olympio – Anderson, 1978; Loomis, 1978; Dempster, 1985).

Though these findings of various types of garnet chemical zoning prove a statement of Hovorka et al. (1987), I do not consider them, for the time being, as a further evidence of the presence of the oldest Precambrian rockclasts in these paragneisses. Differences in garnets are considered as an evidence of different development of paragneisses from the Suchý and Malá Magura Mts.

There are differences in the fluid regimes of progressive stages too. Graphitic matter content in the S. paragneisses is probably only residual left in the rock after the interaction of graphite with metamorphic fluid when the components as CO_2, CO, CH_4 had been probably formed. Presence of these components lowers the X_{H_2O} value in the metamorphic fluid. This finding is in accordance with experimental conclusions of Ohmoto – Kerrick (1977) who assume that max. 90 mol. % H_2O in the metamorphic fluid are in equilibrium with graphite at

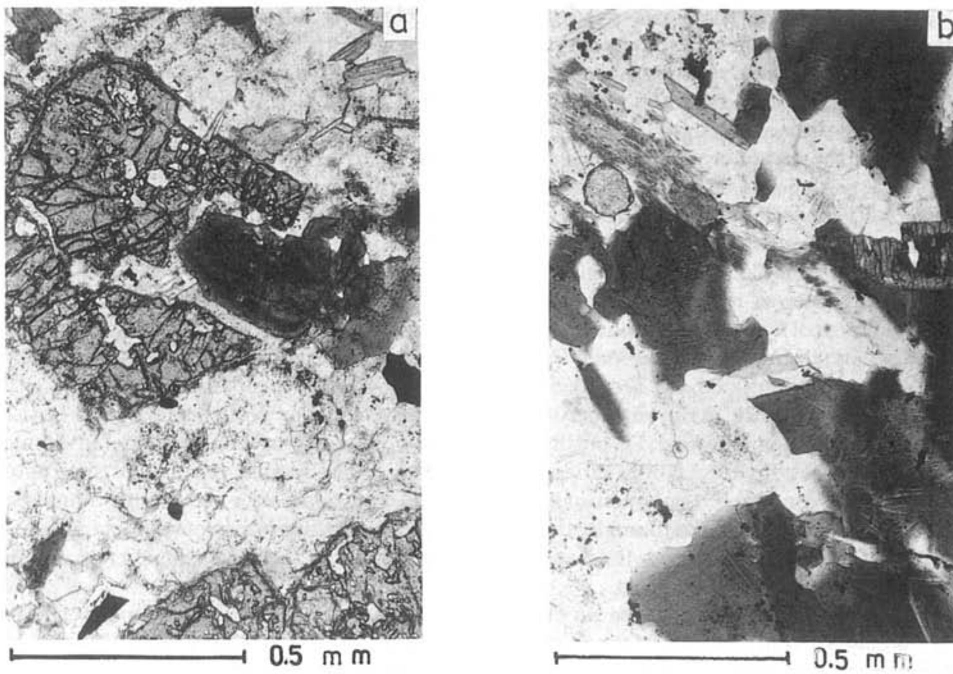


Fig. 4. a) Tourmaline in the S. paragneisses in association with staurolite. Sample S-65-Y. b) Tourmaline does not show any decomposition marks during the fibrolitization process. Sample S-60-Y. Photo: author.

the temperature of 520 °C and the pressure of 4 kbar (they may be considered as approximate values of the metamorphic culmination in the Suchý Mts.).

Fluid regime of the uplift and regressive stages was evaluated on the basis of reactants and reaction products (Dyda, 1988). The fluid effect was small ($2-18$ l H_2O/m^3) and appeared mainly in the Suchý Mts. region. From the index minerals, especially staurolite was affected by retrogenesis during muscovite, chlorite and sometimes also ilmenite formation. Volume evaluation of these reactions proves a retrograde process under the decompression conditions.

Since the fluid/rock volume ratio necessary for the formation of more intensive metasomatism is 10 : 1 (Yardley – Baltatzis, 1985), I exclude this process in the studied S. paragneiss samples and in some of granitoids from this region described by Korikovsky et al. (1987).

Spatial relationship of paragneisses and granitoids may explain sillimanite occurrence in these granitoids. Its occurrence must be still characterized by detailed reactions and distinguished definitively whether it is the reactant or the reaction product of the retrograde process in the above-mentioned granitoids. But the presumption of Hovorka – Fejdi (1983) that the high-alumina granitoids from this region have primarily magmatic nature associated with gneiss anatexis is still topical.

A special attention must be paid to hitherto undescribed tourmaline in the S. paragneisses (Fig. 4 a, b). It is metamorphic, stable to the borders of biotite and muscovite fibrolitization. Its occurrence is conditioned by primary lithology and boron content in the clay fraction bound probably to illite. There are a lot of proofs that the boron – illite equilibrium reflects the sedimentary environment and salinity, and it does not change during diagenesis and lithification (Walker, 1968). If we presuppose the boron source in, for example, recycled detrital tourmaline or in illite sediments, it is evident that it refers rather to the mineral composition of original material and its source than to the paleosalinity.

Therefore, the tourmaline presence in these rocks is considered as an indication of the sedimentary environment. The next proof is graphitic matter occurrence which is in lower concentrations or missing in the Malá Magura Mts. This important fact of the difference mentioned above was already referred to by Kahan (1979, 1982).

Conclusions

Mutual quantitative relation of main minerals places nomenclaturely the studied rocks to the plagioclase paragneisses whose protolite material has probably a graywacke character.

Content of the index minerals: garnet, staurolite and sillimanite is, however, different. Paragneisses from the individual regions may be distinguished by staurolite occurrence. It is quite frequent mineral in the Suchý Mts. region, in the M.M. paragneisses, on the other hand, it has not been found even in the form of relics. In the Suchý Mts. it occurs especially in the northwestern part. Its lithologically and thermally conditioned occurrence cannot be taken only as manifestation of thermal zoning on wider regional scale.

Evidence of the thermal zoning which would include the whole Suchý crystalline core requires not only stating of dominant thermal cycle, but also tectonic entirety of the formed thermal zoning. Thermal effect of granitoid rocks on the surrounding is proved by the progressive reactions in paragneisses which do not always correspond with the presupposed zoning dependent on the magmatic body.

Tourmaline occurrence in the S. paragneisses is probably a good indicator of primary lithology representing character of the sedimentary environment. Occurrence of graphitic matter may be correlated with this occurrence. I consider these features of mineral composition an indication of differences in the protolite from individual regions.

This difference results also from the occurrence of zonal garnets with grossularite-spessartite cores described already by the other authors (Hovorka et al., 1987) and proved in this paper. Types and development of garnet zoning may serve also as a proof of differences in metamorphic process during the progressive and regressive stages.

Progressive dehydratation reactions of the metamorphic culmination indicating characteristics of metamorphic fluid (Tabs. 5 and 6) determine lower X_{H_2O} values in the S. paragneisses. It is due to range of these reactions and interaction of the metamorphic fluid with the present graphitic matter. Its occurrence in these rocks represents a relic of the dehydratation reactions.

Water fugacity calculated from the equilibrium phase coexistence is higher in the M.M. paragneisses. This explains also higher water activity in these rocks exposed to higher temperatures and pressures of the metamorphic culmination.

Thermodynamic analysis of these recrystallization conditions (Tab. 2) sets metamorphic culmination of the Malá Magura Mts. region at the temperatures of ~ 640 °C and the pressures of ~ 5 kbar. In the Suchý Mts. region, the metamorphic maximum conditions are characterized by the temperatures of 560 °C and the pressures of 4.5 kbar (Fig. 2). These values may serve as a proof of different thermal gradients what might complicate interpretation of progressive development of metamorphism in geographically so small region.

The uplift stages studied thermobarometrically and by the equilibrium equations (Tab. 4) support isothermal decompression (86 bar/°C^{-1}) in the S. paragneisses. The uplift took place probably during a simultaneous intrusion of the granitoid rocks. The M.M. paragneisses display different (18 bar/°C^{-1}) and more uniform uplift trajectories determined by decompression during the cooling. In comparison with the S. paragneisses, they represent development at higher pressures and deeper erosion level what is in agreement with the field studies and the scarcity of cover rocks occurrence.

Formation of retrograde domains caused by water infiltration was realized during the uplift stages only in the S. paragneisses. Water infiltration was, however, local and low, preserving dominant progressive metamorphic structures.

The present tectonic division of the crystalline complex into two individual cores separated by the so-called Diviaky fault is completed by the above-mentioned statement of genetic differences in the progressive and regressive metamorphic development and in the uplift trajectories of individual crystalline cores.

Translated by O. Mišániová

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