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MODELLING OF SOME METAMORPHIC PROCESSES (VOLUME CHANGES AT METAPELITIC RECRYSTALLISATION) MALÉ KARPATY MTS., WEST CARPATHIANS

(Figs. 5, Tabs. 5)

Abstract: Densities of Malé Karpaty Mts. metapelites obtained by floating method range from 2.69—2.86 × 10^3 kg/m^3. Comparison of rock densities and their non-crystalline units indicates 6—15 % space reduction in periplutonic zones. Periplutonic recrystallisation is estimated to be at temperatures 510—580° C and pressures 300—550 MPa in approximative depth 12—18 km. During the crystallisation of granitoidic rocks 12.6—13.6 % space reduction occurred. Theoretical approach and model calculations allow to predict the volume changes during magmatic and metamorphic crystallisation.

Резюме: Густоты метапелитов Малых Карпат полученные при помощи флотационного метода колеблются от 2,69 до 2,86 × 10^3 кг м^3. Сравнение густот пород и их некристаллических структурных единиц намечает 6—15 % редукцию пространства в периплутонических зонах гранитоидов. Периплутоническая перекристаллизация проходила при температуре 510—580 °С и давлении 300—550 МРа в глубине около 12—18 км. Во время кристаллизации гранитоидных пород Малых Карпат появилась 12,6—13,6 % редукция пространства. Теоретический подход и модельные вычисления позволяют предсказывать на основе густот изменения объема во время кристаллизации магматических и метаморфических пород.

Introduction

Studies of metamorphic rocks may generaly emphasize different aspects; tectonic, petrographic, or mineralogic. All are mutualy connected and after being elaborated they render many geological data of different significance. Especially in last decades the metamorphic petrology became an interdisciplinary science in geology, accepting the knowledge of physical chemistry, thermodynamics, crystallochemistry and the other laboratory approaches. The petrographic concentration on metapelitic rocks comes from the importance of this lithological group its relation to magmatic bodies, natural extention and its importance in solving many geological aspects. Study of chemical equilibria in these rocks by thermodynamical methods offers, after choosing of proper mineral reactions, sufficiently accurate geothermometric and geobarometric data. The thermodynamical approach enables to incorporate in geological interpretations an important dimension — the depth, a serious point in evaluation various geological processes. The detailed study of volume changes at metamorphic recrystallisation gives the information on space changes and volume differences in certain lithological horizonts. But the complexity of the geological process requires often a simplification which allows to anticipate certain processes even to recognize the measure of the individual volume changes.

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Modelling of some metamorphic recrystallisation processes gives a more detailed image of mutual connection among the chemical composition of minerals in paragenesis, their modal amount and some physical properties of the rock.

Theoretical and model approach

Changes in mineralogical composition during progressive metamorphism may be expressed by chemical reactions in which speciphic reactants and products participate. Following the reactants on the low-temperature side of the isoreaction line and the products on the high-temperature side enables then to locate the isoreaction line on the different basis e. g. mineral appearence, density etc.

If we consider metamorphic reaction

$$7 \text{ muscovite} + 6 \text{ chlorite} = 6 \text{ staurolite} + 7 \text{ biotite} + \text{garnet} + 3 \text{ quartz} + 18\, H_2O$$

the density of reactants is $\rho = 2.71$ and density change after the reaction is completed is $\Delta\rho = 0.62$, what corresponds with the volume decrease 18.6 %. At the same chemical composition, if release of water is not accepted, a significant density change is at the crossing of the isoreaction line given by temperature and pressure. But the volume change may not indicate the range of the metamorphic degree.

If common metamorphic reaction

$$\text{albite} = \text{jadeite} + \text{quartz}$$

Which proceeds at 200 °C (750 MPa; 300 °C) 950 MPa (see e. g. Winkler, 1974) is applied to the model rocks, given below, after reaction is completed, the following volume changes occur:

Model rock I.

Modal	%	Ab	Qtz		Qtz	Jd	V %
	I_1	20	80	→	85.4	14.6	— 3.6
	I_2	40	60	→	70.9	29.1	— 7.7
	I_3	60	40	→	56.3	43.7	—10.8

The above model indicates, that the original mineral composition of the rock influences distinctively the volume changes during metamorphic recrystallisation.

French (1976) published an important diagram in which pressure, to which the metamorphic rock was exposed, density of the rock and normative density given by the relation

$$Dc = 2.6\ [2\ No/(4\ NSi + 3\ NAl)]^{1/2}$$

is in the mutual coherence. Where N is the number of atoms on a unit oxygen basis.

Putting Malé Karpaty Mts. metapelites and model rocks into French's diagram (Fig. 1) reveals, that this approach can not be used for obtaining the detailed data on metamorphic pressures at which the rock recrystallized. The rocks with the simple mineral composition (see model mixtures Ab + Qtz) are less suitable in this approach than polyphase mineral associations. More suitable are then the rocks with different mineral changes and solid solution phenomena during recrystallisation. The positions of the model metapelitic and eclogitic rocks from Tab. IV. in Fig. 1. confirm this.

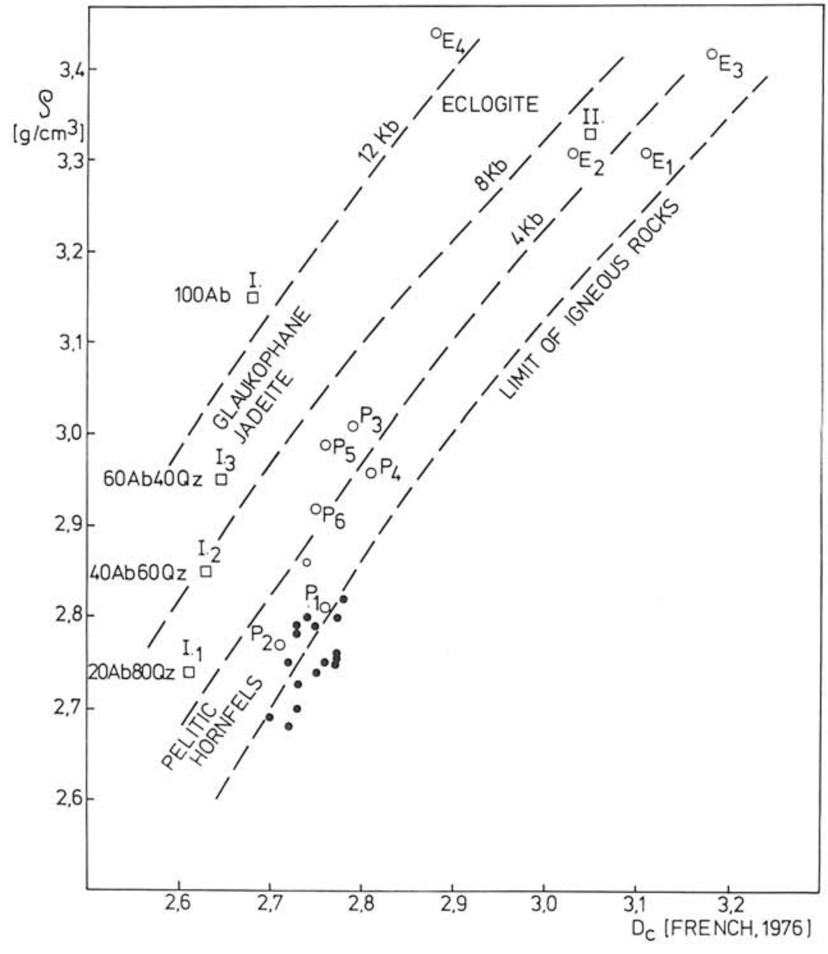

Fig. 1. Relation between measured density (ρ) and normative density (D_c) of metapelites studied (closed circles).

Explanations: Model reactions $Ab = Jd + Qtz$ and $7Ms + 6Chl = 6St + 7Bt + 3Qtz + 18H_2O$ are designated I. and II., respectively. Model eclogitic and metapelitic rocks from Tab. IV. — open circles. Graph according to French (1976).

The same coincidence comes from model rock II., vhith modal composition; 58 mod. % chlorite, 36 % muscovite, and 6 % quartz, which corresponds with the left side of the reaction

chlorite + muscovite + quartz = cordierite + biotite + Al_2SiO_5 + H_2O

occuring at 550° and 400 MPa. When the reaction is completed the density changes from 2.73 to 2.81, that corresponds approximately with the pressure given in Fig. 1., point II.

At increased pressure cordierite may decompose to 61 mod. % almandine, 27 % sillimanite and 12 % quartz. That is connected with the volume change $\Delta V = -32\ \%$. In presence of biotite the decomposition proceeds to

cordierite + biotite = almandine + K feldspar + H_2O

and from the previous rock with the modal composition 58 % Chl, 36 % Ms and 6 % Qtz the new rock is originated with the mineral composition: 46 mod. % almandine, 43 % K feldspar and 11 % sillimanite. The relevant volume changes is $\Delta V = -20.4\ \%$. These reactions are more complex in nature, determined by different quantitative mineral relations which need not lead to such volume changes.

The density change during metamorphic reaction at an isochemical proces is a function of atom redistribution and change in atom packing between reactants and products.

The above given reaction

albite = jadeite + quartz

proceeding at higher pressure and temperature is connected with expressive atom packing change, the reduction of empty space. The packing index — Φ changes from the value 0.5845 to 0.7041 (see Fig. 2). The value $\Phi = 0.7041$ means that 70.41 % of the space is filled up with ions.

The basic assumption, at the numerical modelling of these relations was, that given rock sample approaches during progressive metamorphic process the "density maximum", which is given by chemical composition and atom packing. As a measure of this, the eclogitic rocks were taken with high packing index values ($\Phi = 0.68$ to 0.70) as the consequence of the high temperatures and pressures of metamorphic recrystallisation.

Minimal theoretical density of a given sample was defined by NCS unit (non crystalline solid) for which the density was obtained numericaly from chemical composition by means of atom refractivities.

An important step was the comparison of measured and calculated densities for NCS units of the metapelitic rocks studied, (Tab. III, Fig. 3). This relation had the basic significance in order to find the reliability of the calculated theoretical value ρ NCS, what allows further to calculate minimal density (ρ NCS) for any arbitrary chosen metamorphic rock.

This model approach pressuposed that the rocks of higher metamorphic degrees will proximate to higher packing indices typical e.g. for eclogitic rocks.

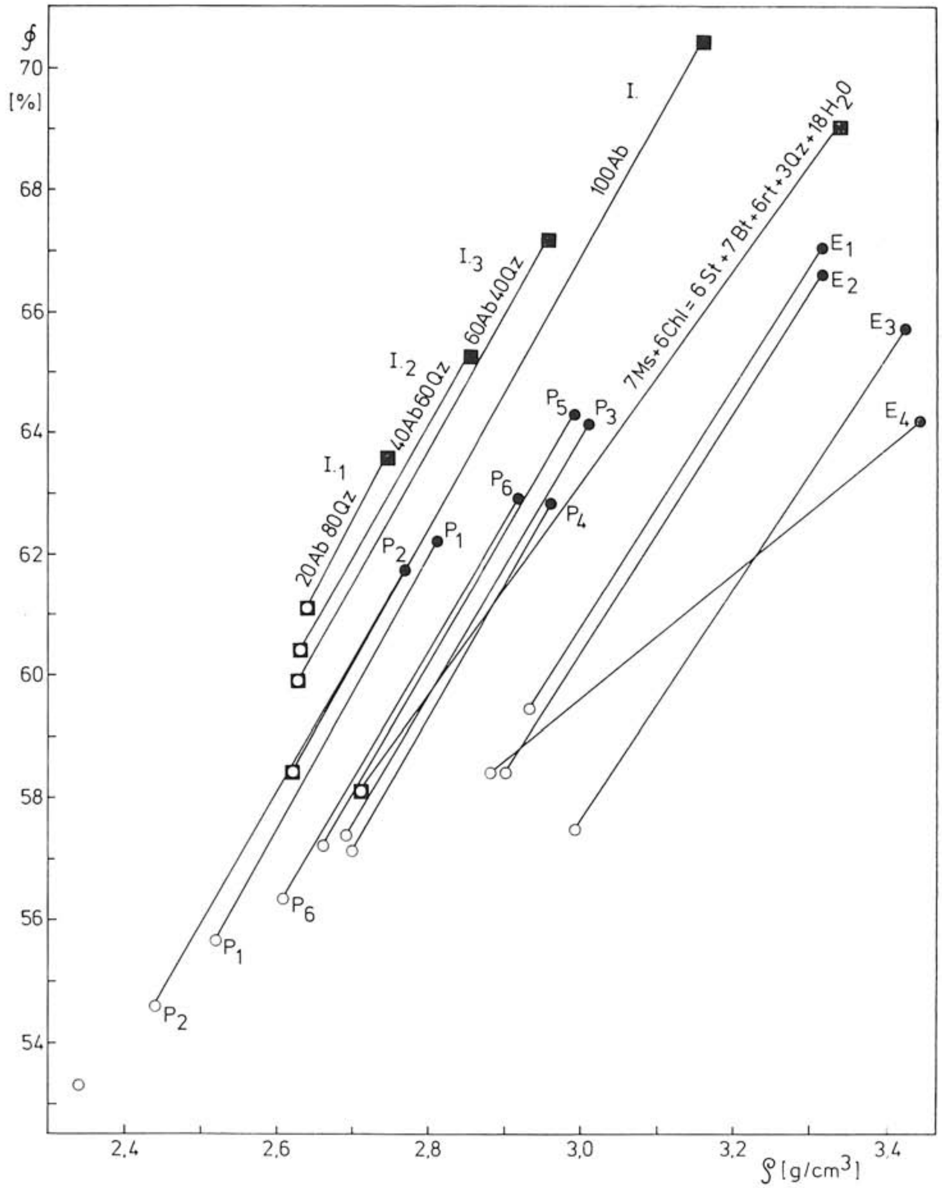

Fig. 2. Model relation between density (ρ) and packing index (Φ) of model metamorphic reactions and model rocks. See Tab. IV.

Numerical comparison of these relations based on model eclogitic and metapelitic rocks (Fig. 2) confirms this assumption.

The reaction given above

$$Ab + xQtz = Jd + Qtz + xQtz$$

was modeled in symplified way by different quantitative relation between albite and quartz (Ab/Qtz = 1.5; 0.66; 0.25) to determine the influence of the original mineral composition on the final value Φ, which may be considered in this approach as the diagnostic value expressing the metamorphic degree.

From the position of the model lines I., I_1., I_2., I_3. in Fig. 2 follows, that lithological composition of the material before metamorphic processes strongly influences the final diagnostic Φ value of a given rock sample.

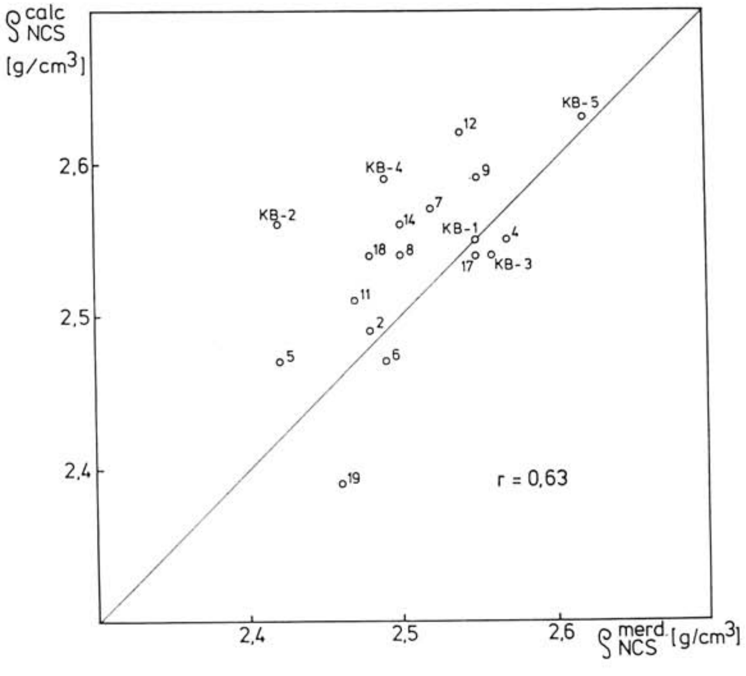

Fig. 3. Relation between measured and calculated ρ_{NCS} values of metapelites studied.

The most suitable are then the mineral mixtures which individual phases enter the metamorphic recrystallisation in an active way. On the other hand, the less suitable mineral paragenesis mainly consist of such minerals which do not participate on metamorphic recrystallisation actively. This is valid especially for quartz, as a problem may arrive in distinguishing the quartz formed by metamorphic reaction from the preexisting quartz grains.

Modelling of metamorphic processes based on the knowledge of metamorphic reactions is rather difficult if applied to natural rock sample. This results from unknown original mineralogical composition of the rock exposed to metamorphic recrystallisation and from the fact that the protolitic mineralogy may be approximated only. But the chemical composition of the material is decisive as we do not expect its main change during the recrystallisation process.

Before evaluating the pressure of metamorphism on the basis of density data, I have determined the T-p conditions of metamorphic recrystallisation thermodynamicaly using equilibrium mineral paragenesis.

Methods

The densities of Malé Karpaty Mts. metapelitic rocks were determined by the floating method. The main steps used are described in work of Proks (1974). Reproducibility of a single measurement was in range ± 0.002 to 0.1. Standard deviation obtained from 15 measurements represents simultaneously the inhomogeneity of the given sample.

The ion diameters given by Schannon—Prewit (1969) were used for calculation of the atom packing indices (Φ). Because of complication in details, the same coordination number for an ion in the rock and in the non crystalline solid unit (NCS) was pressuposed. Theoretical density for NCS was obtained from chemical composition by numericaly aproximated index of refraction and tabeled atom refractivities. Concordance between measured and calculated ρNCS is presented in Fig. 3 and data are given in Tab. III. Real non crystalline solid units — glasses of metapelitic rocks were obtained by fusing rock samples. Methods are given in Dyda (1973), Dyda—Macek (1973). Chemical analyses of coexisting minerals in metapelitic rocks (Dyda, 1981) were used for the calculation of the univariant P-T curves, Fig. 5. For calculation of temperature in periplutonic zones the equilibrium coexistence between biotite and garnet was pressuposed and temperature calibration of Ferry—Spear (1978), Perchuk (Перчук и др., 1984) accepted. The bathymetric determinations used the reaction An = Grs + Sil + Qtz calibrated by Ghent (1976) and thermodynamic properties of the phases given by Robie—Waldbaum (1968).

The petrological model used was based on arbitrary chosen modal composition of the rock. The chemical composition of minerals in rock and their paragenesis corresponded with chemical equilibria in the model rock sample. The chemical composition chosen and modal amount of minerals in the rock sample resulted in the calculation of the all other physical properties of the model rock.

Results and discussion

Chemical and modal composition of the Malé Karpaty Mts. metapelites are given in Tab. I. The measured and statisticaly evaluated density data are presented in Tab. II. The relations between density and chemical composition of the rocks; weight % of oxides, number of atoms on the basis of 160 oxygens, number of atoms in 1 cm^3 of the rock and atom packing in the rock expressed by packing index were studied.

In evaluation of the relationships between chemical composition and rock density the connection — density versus number of atoms in standard rock

Table I

Chemical and modal analyses of Malé Karpaty Mts. metapelites*

N°	2Y.	4Y.	5Y.	6Y.	7Y.	8Y.	9Y.
SiO_2	65.32	63.32	63.59	71.07	60.10	61.43	59.14
TiO_2	0.92	0.98	0.94	0.63	0.94	0.90	1.02
Al_2O_3	15.50	16.21	15.65	14.51	16.96	17.50	17.98
Fe_2O_3	3.22	4.28	3.80	4.13	4.27	4.03	4.42
FeO	3.46	3.92	3.60	1.31	4.86	4.16	5.13
MnO	0.14	0.15	0.13	0.15	0.16	0.14	0.16
MgO	2.51	2.29	2.29	1.29	2.73	2.53	2.59
CaO	0.87	1.28	0.48	1.23	1.40	1.15	1.35
Na_2O	2.28	2.33	2.78	2.45	3.12	2.64	2.73
K_2O	3.25	2.92	2.92	1.85	2.71	3.15	3.32
H_2O^+	2.01	1.48	2.65	0.97	1.92	1.94	1.69
	99.39	99.16	98.83	99.59	99.17	99.57	99.53
Qz		41.0	43.0	55.4	36.3	42.3	33.7
Bio		30.1	29.5	18.7	35.8	34.8	33.0
Mus		1.2	3.4	2.7	0.4	1.8	3.1
Plag		22.0	23.0	22.3	22.7	19.8	22.4
Gar		1.1	0.9	0.1	1.8	1.3	2.2
St		2.5	—	0.6	0.1	—	4.8
Sil		1.5	—	—	2.9	—	—
Opaq		0.6	0.2	0.2	—	—	0.8

1st continuation of Tab. I

N°	10Y.	11Y.	12Y.	14Y.	17Y.	18Y.	19Y.
SiO_2	66.37	69.62	58.16	62.15	62.16	57.05	69.03
TiO_2	0.78	0.80	1.06	0.86	0.81	0.99	0.67
Al_2O_3	16.31	13.88	18.72	18.49	17.04	18.65	13.96
Fe_2O_3	5.08	3.30	2.73	3.86	3.82	4.33	4.03
FeO	1.21	3.10	6.09	4.46	4.10	4.55	1.78
MnO	0.11	0.14	0.14	0.16	0.15	0.13	0.04
MgO	1.58	1.63	2.54	2.28	2.18	3.21	2.01
CaO	1.47	1.52	1.80	0.77	1.49	0.60	—
Na_2O	2.81	2.70	3.36	2.24	2.46	2.36	2.10
K_2O	2.13	2.03	3.14	2.62	2.60	4.06	2.74
H_2O^+	1.65	0.76	1.19	1.48	1.79	2.83	2.89
	99.50	99.48	98.93	99.37	98.60	98.76	99.25
Qz	37.7	41.5	33.0	37,8	38.0	25.1	
Bio	22.7	21.5	32.9	30.1	30.0	38.3	
Mus	11.7	0.2	—	4.3	2.6	8.4	
Plag	26.8	28.7	32.6	18.6	26.1	26.7	
Gar	0.3	1.1	1.3	2.8	1.6	0.1	
St	0.6	6.9	—	6.3	1.4	—	
Sil	—	—	—	—	0.2	1.1	
Opaq	0.8	0.1	0.2	0.1	0.1	0.3	

2nd continuation of Tab. I

KB-1Y.	KB-2Y.	KB-3Y.	KB-4Y.	KB-5Y.	KB-6Y.
63.03	62.77	65.26	63.06	56.05	58.11
0.84	0.82	0.69	0.92	1.03	0.95
18.35	17.27	16.55	16.23	19.59	19.43
3.82	4.24	3.58	3.69	4.72	5.51
3.12	3.60	2.67	4.44	5.01	3.29
0.14	0.18	0.13	0.14	0.28	0.16
1.89	2.35	1.46	2.25	2.58	2.68
1.89	1.77	2.48	1.95	2.04	1.30
3.17	2.88	3.84	3.18	3.10	2.40
1.92	2.38	1.85	2.94	2.82	2.94
1.18	1.18	0.65	0.75	1.47	2.91
99.35	99.45	99.16	99.55	98.69	99.68
35.0	34.2	31.2	28.1	24.3	
24.2	27.6	28.1	30.3	34.1	
1.4	0.2	0.2	4.2	2.1	
34.8	32.8	39.2	36.9	35.1	
2.1	3.5	1.2	0.1	1.8	
0.6	0.7	—	0.2	0.2	
1.7	0.9	—	0.1	2.3	
0.2	0.1	0.1	0.2	0.1	

* Sample localisation is given in Dyda (1981).

volume seems to have the highest correlation. As an example may serve the correlation between iron content in the rock and rock density:

$FeO + Fe_2O_3$ v . ρ $r = 0.61$
$Fe^{2+} + Fe^{3+}$ 160/0 v. ρ $r = 0.63$
$N_{Fe}{}^{2+} + N_{Fe}{}^{3+} / 1\ cm^3$ v . ρ $r = 0.68$

The atom packing in the sample has the strongest influence on the sample density ($r = 0.78$). This fact led to detailed modelling of the processes which express the volume change at the same chemical composition as the result of mineral reactions during metamorphic recrystallisation.

Let us have a rock with modal composition 40.5 % muscovite, and 59.5 % chlorite. This corresponds with left side of the equation.

7 muscovite + 6 chlorite = 6 staurolite + 7 biotite + garnet + 3 quartz + + 18 H_2O

After the reaction is completed the space reduction amounts $\Delta V = -18.6$ %, and atom packing increases from 58 % to 69 %, that may represents, from modelling aspects, Φ values typical for eclogitic type of metamorphism (see Fig. 2). Such volume changes are in natural conditions in larger territories

Table II

Densities of Malé Karpaty Mts. metapelites

N°	$\bar{\rho}$	s	V (%)	R	n	Homogen.	Dc^F
2Y.	2.757	0.023	0.82	0.09	12	0.013	2.72
4Y.	2.809	0.024	0.83	0.10	15	0.014	2.74
5Y.	2.700	0.017	0.62	0.06	15	0.010	2.73
6Y.	2.690	0.024	0.88	0.08	14	0.014	2.70
7Y.	2.765	0.027	0.96	0.10	15	0.016	2.77
8Y.	2.742	0.010	0.35	0.04	15	0.006	2.75
9Y.	2.805	0.054	1.87	0.14	12	0.032	2.77
10Y.	2.682	0.010	0.39	0.04	15	0.006	2.72
11Y.	2.747	0.028	1.01	0.11	15	0.016	2.71
12Y.	2.750	0.016	0.57	0.06	15	0.009	2.77
14Y.	2.798	0.013	0.46	0.04	15	0.007	2.73
15Y.	2.688	0.011	0.40	0.04	15	0.006	—
17Y.	2.862	0.046	1.65	0.14	15	0.027	2.74
18Y.	2.757	0.016	0.58	0.07	15	0.009	2.77
19Y.	2.690	0.030	1.14	0.10	15	0.018	2.70
KB-1Y.	2.787	0.038	1.32	0.12	15	0.022	2.73
KB-2Y.	2.792	0.080	2.86	0.20	15	0.047	2.75
KB-3Y.	2.727	0.024	0.89	0.09	16	0.014	2.73
KB-4Y.	2.753	0.016	0.58	0.07	15	0.009	2.76
KB-5Y.	2.825	0.036	1.22	0.10	11	0.021	2.78

$\bar{\rho}$ — mean of sample
s — standard deviation
V — coeficient of variation
R — variance
n — number of measurements

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Homogeneity according to Kamineni—Carrara (1973);
Dc^F — after French (1976).

Table III

Packing indices (Φ) and densities of non crystalline solid units (ρ_{NCS}) of Malé Karpaty Mts. metapelitic rocks

N°	ρ_{ROCK}	Φ_{ROCK}	MEAS. ρ_{NCS}	CALC. ρ_{NCS}	Φ_{NCS}	ΔV [%]
2Y	2.757	60.86	2.48	2.49	54.47	−11.16
4Y	2.809	61.13	2.57	2.55	55.57	− 9.29
5Y	2.700	59.73	2.42	2.47	52.89	−11.57
6Y	2.690	59.74	2.49	2.47	55.07	− 8.03
7Y	2.765	59.95	2.50	2.57	54.19	− 9.72
8Y	2.742	59.85	2.50	2.54	54.33	− 9.68
9Y	2.805	60.55	2.55	2.59	54.79	−10.00
11Y	2.747	60.41	2.47	2.51	54.03	−11.21
12Y	2.750	59.05	2.54	2.62	53.96	− 8.26
14Y	2.798	60.96	2.50	2.56	54.98	−11.92
17Y	2.862	61.73	2.55	2.54	54.94	−12.23
18Y	2.757	60.17	2.48	2.54	53.47	−11.16
19Y	2.690	60.55	2.46	2.39	54.95	− 9.34
KB1Y	2.787	60.85	2.55	2.55	55.32	− 9.29
KB2Y	2.792	60.70	2.42	2.56	52.33	−15.37
KB3Y	2.727	59.54	2.56	2.54	55.42	− 6.52
KB4Y	2.753	59.51	2.49	2.59	53.58	−10.56
KB5Y	2.825	60.52	2.62	2.63	55.40	− 7.82

Table IV

Model rocks
(Density, volume and P—T characteristics)*

	ρ	Φ	ρ_{NCS}	Φ_{NCS}	D_C	ΔV [%]	T [°C]	P [MPa]
E 1	3.31	67.04	2.93	59.44	3.11	−12.8		
E 2	3.31	66.68	2.90	58.45	3.03	−14.0		
E 3	3.42	65.74	2.99	57.50	3.18	−14.3		
E 4	3.44	64.21	2.88	58.41	2.88	−19.3		
P 1	2.81	62.21	2.52	55.70	2.76	−11.6		
P 2	2.77	61.74	2.44	54.63	2.71	−13.3		
P 3	3.01	64.15	2.69	57.39	2.79	−11.7	583	500
P 4	2.96	62.87	2.70	57.19	2.82	− 9.9	633	720
P 5	2.99	64.36	2.66	57.23	2.76	−12.4	653	530
P 6	2.92	62.89	2.61	56.36	2.75	−11.6	641	560

* The characteristics are obtained numerically on the basis of chosen mineral composition. E — eclogitic; P — pelitic model rocks.

perhaps not actual, as the volume changes of model metapelites Tab. IV. and Malé Karpaty Mts. metapelites do not exceed $\Delta V = -15$ %, Tab. III. The calculated volume change for model metapelites range approximately from −9 to −12 volume % (these values are considered to be ΔV maximum) and

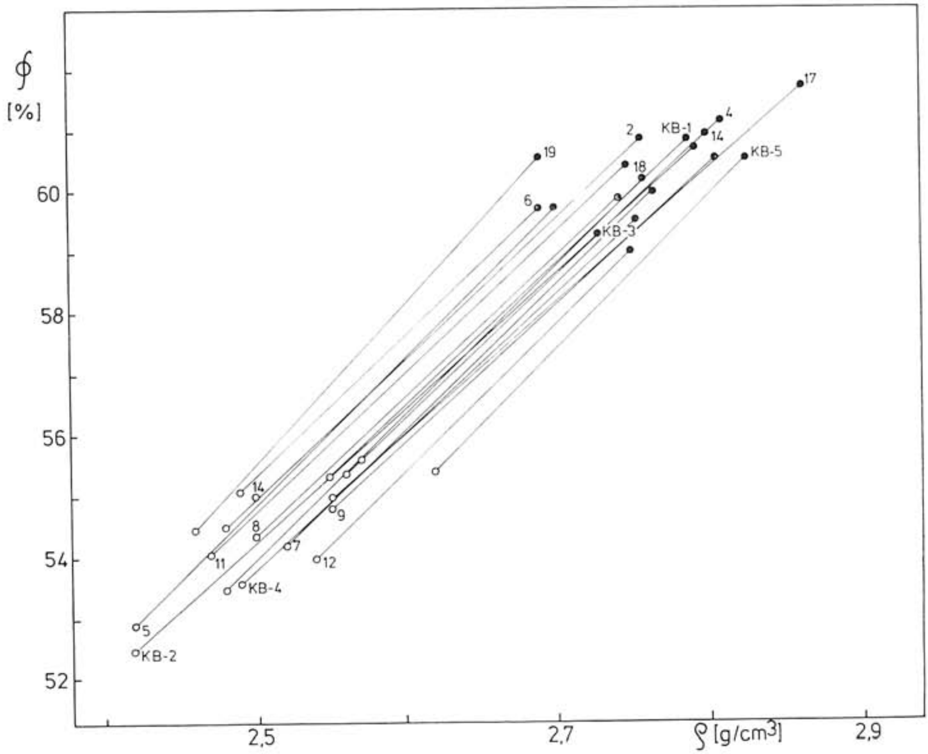

Fig. 4. Relation between density (ρ) and packing index (Φ) of Malé Karpaty Mts. metapelites and their non-crystalline solid units (NCS).

measured densities of metapelites studied, indicate space reduction to 15 %, Tab. III.

The ΔV value need not indicate the intensity of metamorphism for a given rock sample (Tab. IV). From Fig. 2 and Fig. 4 it is obvious, that volume reduction as the consequence of metamorphic recrystallisation and water release at given temperatures and pressures moves at certain level which is given also by original lithological factors. It is necessary to suppose different volume changes in different lithological horizonts as well. In periplutonic processes are the space reduction phenomena proportional to the distance from magmatic body, which alone is subjected to the volume change during crystallisation.

Let us consider a model magmatic liquid from which crystallizes 30 % Qtz, 20 % An$_{20}$, 25 % Kfs, 13 % Ms and 12 % Bt and intrudes into regionaly metamorphosed phylitic rocks of mineral camposition: 58 % Chl, 36 % Ms and 6 % Qtz. The intruding granitoidic body may cause the recrystalisation in periplutonic zones according to the reaction

chlorite + muscovite + quartz = almandine + K feldspar + sillimanite + H$_2$O

Table V

Volume changes at crystallisation of Malé Karpaty Mts. granitoidic rocks*

N°	$\rho_{\mathrm{MEAS.}}$	$\rho_{\mathrm{CALC.}}$	MEAS. ρ_{NCS}	CALC. ρ_{NCS}	$\Delta V\ ^0/_0{}^{\mathrm{CALC.}}$	$\Delta V\ ^0/_0{}^{\mathrm{MEAS.}}$
8.	2.66	2.65	2.36	2.46	− 7.7	−12.7
37.	2.70	2.68	2.37	2.45	− 9.3	−13.9
46.	2.64	2.66	2.38	2.44	− 9.0	−10.9
50.	2.67	2.67	2.37	2.46	− 8.47	−12.6
51.	2.65	2.64	2.34	2.39	−10.4	−13.2
52.	2.66	2.66	2.38	2.48	− 6.9	−11.7
15.	2.63	2.64	2.41	2.44	− 8.0	− 9.1
17.		2.69		2.51	− 7.1	
18.	2.70	2.69	2.44	2.48	− 8.3	−10.6
23.	2.71	2.64	2.45	2.49	− 6.1	−10.6
33.	2.81	2.79	2.58	2.67	− 4.2	− 8.9

* Sample localisation is given in Dyda–Macek (1973).

Accepting the above model, this process means 11 $^0/_0$ of space reduction during granitoid crystallisation and $\Delta V = -20\ ^0/_0$ at the recrystallisation of phylitic rocks in periplutonic zone.

If we accept the measured ΔV values for Malé Karpaty Mts. granitoidic rocks (Tab. V) and the ΔV for metapelites, we may conclude, that during granitoidic rocks crystallisation approximately 12 $^0/_0$ space reduction occured and periplutonic zones were reduced by recrystallisation approximately by 10 $^0/_0$.

The range of these changes in geological terain depends heavily on the size of cooling magmatic body, to which probably also the size of produced pegmatitic contraction leaks have the relation. But the size of leak pegmatites is obviously given by crystallisation speed, depth horizonts of the cooling, tectonic moovement, thermal gradient and the viscosity of the rest magmatic liquid which determines the difusion in these zones. The created leaks with probably high vacuum may suck the rest solutions from their surrounding containing useful components. Slow crystallisation process and cooling which enables the migration of the components within cooling body, where volume changes create the pegmatitic leaks, is probably one assumption for useful elements concentration.

This experimental approach is supported by fact, that pegmatitic leaks are more frequent in granitoides of Bratislava massif than in Modra massif (Tab. V).

Thermodynamical elaboration of the mineral associations in periplutonic zones of Bratislava granitoidic massif indicates (Fig. 5), that periplutonic zones were metamorphosed at temperatures 510—580 °C and pressures 300—550 MPa (Dyda, 1977; Dyda, 1981; Cambel et al., 1981). The determined pressures indicate the crystallisation in considerable depth. Thermodynamical calculations determine the depth of periplutonic recrystallisation to 12—18 km.

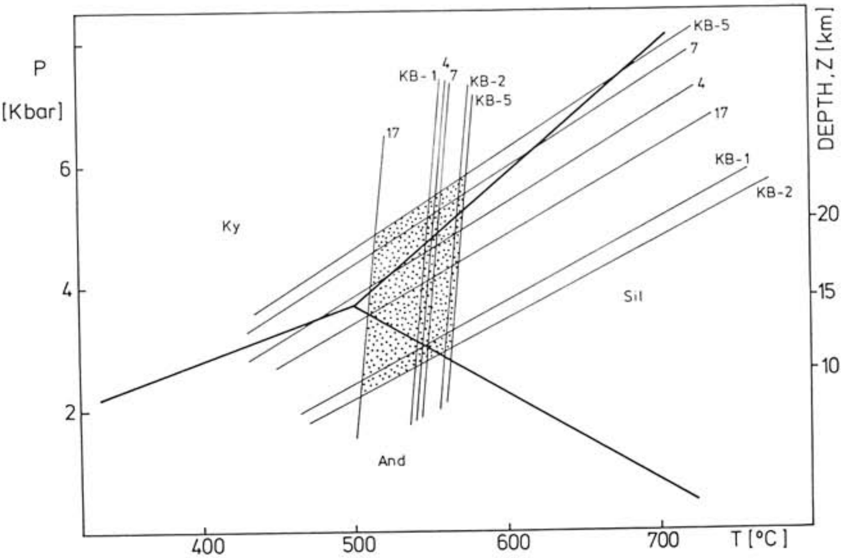

Fig. 5. Univariant P—T curves based on assumption of equilibrium between biotite and garnet (inferred from K_D calibration of Ferry—Spear, 1978) and among plagioclase, garnet, sillimanite and quartz (K_D calibration of Ghent, 1976). *Explanations:* Thermodynamic data from Robie—Waldbaum (1968) are accepted. Al_2SiO_5 equilibrium lines were calculated from tabulated data (Helgeson et al., 1978).

Later uplift and erosion of these zones wiped away the upper parts of the intrusions where useful elements may have been concentrated.

Conclusions

Theoretical approach and model calculations of metamorphic reactions make possibble to pressupose the density changes connected with the recrystallisation process. Volume changes appearing during magmatic crystallisation have considerable significance at evaluating of leak pegmatites in these rocks. The comprehensive evaluation of the volume changes during magmatic crystallisation and periplutonic metamorphic recrystallisation permits to follow space changes of geological environment in its dynamical development. Thermodynamical characteristics of the recrystallisation make simultaneously the depth approximation of these processes.

At the crystallisation of the Malé Karpaty Mts. granitoidic rocks, approximately 12.6—13.6 % space reduction occured (Tab. V). The granitoids of Bratislava massif were subjected to larger volume changes than the Modra granitoids, that contributed to more frequent appearence of leak pegmatites in Bratislava massif.

The periplutonic process in Bratislava massif area is estimated to be at temperatures 510—580 °C and pressures 300—550 MPa (Fig. 5). The pressures indicate the depth of 12—18 km of the recrystallisation process caused by magmatic rocks intrusion. The reduction of metamorphic periplutonic zones ($\Delta V = -6.5$ to $-15.3\,\%$) followed numericaly and by experiments (Tab. III) on the basis of density data are in agreement with the model calculations.

Numerical approach thus enables to follow the recrystallisation process in more detail and the anticipation of the volume changes during magmatic and metamorphic crystallisation process.

Translated by D. Ďurišová

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