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METAMORPHIC GRADE AND PACKING INDEX OF COEXISTING BIOTITES AND GARNETS FROM THE MALÉ KARPATY MTS. METAPELITIC ROCKS.

(Figs. 1-5, Tabs. 1-5)

A b s t r a c t: Change of packing indeces (Φ) of coexisting garnets (Φ = 0,7431 — 0,7483) and biotites (Φ = 0,5882 — 0,6026) from metapelitic rocks of the Malé Karpaty Mts. was studied in larger extent of thermodynamically obtained temperatures (460-610°C) and pressures (360-580 MPa) values of metamorphic recrystallization.

In agreement with theoretical and model approaches of evaluation of garnet and biotite coexistences some relations were found between the packing index of natural garnets and biotites, and P-T conditions of the recrystallization.

Biotites have lower, and garnets higher packing index at higher temperatures and pressures of recrystallization.

Р е з ю м е: Изменение плотной упаковки атомов (Φ) сосуществующих гранатов (Φ = 0,7431 — 0,7483) и биотитов (Φ = 0,5882 — 0,6026) из метапелитических пород Малых Карпат было преследовано в большом размере термодинамически полученых температур (460 — 610 °C) и давления 360 — 580 MPa) метаморфной перекристаллизации.

В согласии с теоретическим и модельным подходами оценивания сосуществований граната и биотита мы получим также отношения между плотной упаковкой атомов природных гранатов и биотитов а условиями давления-температуры перекристаллизации.

При биотитах нижшая а при гранатах высшая плотная упаковка атомов при высших температурах и давлении перекристаллизации.

Introduction

Evaluation of geological processes of the individual regions demands wide and complex elaboration of field and laboratory data following from a chosen rock sample.

Tasks of metamorphic petrology ask for a remarkable continuity of the field approach and the given problematics wits detailed geochemical evaluation of mineral associations under dynamical understanding of development of the individual structures. This follows from a reassumption of relations between deforming processes and development of equilibric mineral association. Mineralogic and geochemical analyses of metamorphic paragenesis give by means of the application of the phase rule and the criteria of evaluation of chemical equilibrium in a rock a possibility to find temperatures and pressures of recrystallization process indicating depth and also a type of metamorphism. Also the relations between the recrystallization process and tectonic activity.

The appearence of new mineral paragenesis can be from a certain view-

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point understood then as a process of redistribution of components, determined by thermodynamical properties of existing and originating minerals. Distribution of the individual elements among the coexisting phases creating solid solutions is determined by the distribution coefficient (K_D) in this process.

Distribution of elements, e.g. Mg^{2+} and Fe^{2+} among coexisting minerals in equilibric metamorphic paragenesis is elaborated in details after its beginnings (H. Ramberg — D. DeVore, 1951; R. Kretz, 1959; R. Mueller, 1960). Some approaches lead to obtaining temperatures and pressures of metamorphic process (M. Frost, 1962; A. Albee, 1965; L. Pertchuk, 1967; S. Sen — K. Chakraborty, 1968; A. Hietanen, 1969; S. Saxena, 1969, 1973; J. Lyons — S. Morse, 1970; A. Thompson, 1976; D. Goldman — A. Albee, 1977; R. Tracy, 1978; J. Ferry — F. Spear, 1978; N. Stephenson, 1979) after fulfilling the structural and petrographical criteria for chemical equilibrium.

With the change of distribution of elements among minerals creating paragenesis is connected also the change of their chemical composition and also the change of those physical properties which are conditioned by redistribution of these elements. Then this results in a presumption of continual change of properties of the individual coexisting minerals in which redistribution of elements determined K_D takes place.

As for theoretical view-point those minerals are appropriate to study these relationships, at which solid solutions are dominant and properties of the participating atoms condition also the change of physical properties. Substitution $Mg^{2+} \leftrightarrow Fe^{2+}$ with respect to different refractive properties of atoms Mg (R = 0,36) and Fe^{2+} (R = 2.29) fulfills these conditions and this way it gives presumption for study of this change of physical properties at coexisting minerals (M. Dyda, 1980).

At a mineral pair biotite — garnet there comes to substitutional appearences simplified in the expressed reaction:

$$\text{Fe garnet} + \text{Mg biotite} \langle = \rangle \text{Mg garnet} + \text{Fe biotite} \tag{1}$$

Garnet and biotite coexist in a wide scale of metamorphic temperatures and pressures what, from the theoretical view-point, bases studium of changes of their physical properties.

For comparing these changes without regard to experimental requirements the packing index of coexisting biotites and garnets was determined, since it has close connection with the unit cell volume (V), density (ρ) and refractive index (n) of a mineral. In the same time, it expresses an „empty space" in mineral structures which has from the view-point of resulting metamorphic pressures a large significance.

11 pairs of coexisting garnets and biotites from the Malé Karpaty Mts. metapelitic rocks were evaluated, i.e. that relations between packing index of coexisting garnets and biotites and metamorphic grade could be aproximated.

Methodical approach

For the adequacy of chosen minerals on the individual physical — chemical measurements could be judged, these procedures were proceded by mi-

Table 1

Physical properties of coexisting garnets and biotites from metapelites of the Malé Karpaty Mts (M. Dyda, 1980a).

№	Garnets			Biotites		
	n	ρ	a_0	n_γ	ρ	V
4Y.	1,806	4,17	11,545	1,636	3,09	499,03
6Y.	1,809	4,17	11,549	1,634	2,97	497,37
7Y.	1,806	4,16	11,548	1,640	2,98	499.88
8Y.	1,810	4,19	11,544	1,639	3,00	496,32
9Y.	1,809	4,16	11,554	1,637	2,89	491,50
10Y.	1,808	4,18	11,549	1,637	2,96	
11Y.	1,808	4,18	11,547	1,636	3,04	498,11
12Y.	1,804	4,15	11,539	1,643	3,00	497,42
14Y.	1,808	4,18	11,553	1,634	3,02	498,96
18Y.	1,807	4,18	11,563	1,641	2,92	496,83
KB—1Y.	1,807	4,18	11,560	1,643	3,05	493,06
KB—3Y.	1,806	4,16	11,539	1,633	2,98	495,70
KB3Y.	1,807	4,17	11,549	1,635	2.93	495,76
KB—5Y.	1,807	4,18	11,551	1,636	2,91	495,57

croscopical studium of the chosen samples. Besides common criteria for equilibrium in a rock were considered. Neither zonal, inhomogeneous minerals nor samples with signs of retrogradual changes were accepted. The problem from this view-point of judgement remains at garnets, at which microscopical homogeneity need not mean also homogeneity of their chemical composition. At biotites which easier grow to the chemical equilibrium zonality did not create any analytical problem.

Garnets and biotites were separated from rocks by the following method. 1-2 kg samples were crushed, sieved, and appropriate grain fraction was divided in a heavy liquid (bromoform). From heavy fractions garnet and biotite were hand — separated in amounts, sufficient for analysis by the electron microprobe, X-ray diffraction and determination of refraceive indices and density.

During the analysis of garnets by the electron microprobe JEOL JXA 5A there were arbitrary chosen 4 grains from the sample presented by 30-40 grains on which the number of pulses per 10 seconds was recorded at measure voltage 15 KV. As a standard synthetic diopside-anorthite glass was used. The obtained data were corrected and elaborated by SIEMENS 4004/150 computer. Results are shown in the Table 2.

At biotites the analysis was determined by method of analytical curves where biotites of known chemical composition stayed for the standard. Composition of some biotites and FeO and Fe_2O_3 contents were at some samples determined by the classical method (Ing. E. Walzel, Geological Institute of the Slovak Academy of Sciences). Chemical analyses of biotites are shown in the Table 3.

For determination of the unit cell parameters of garnets (a_0) and biotites (a, b, c, β) methods of powder diffraction were used at application CuK_α radiation. Elaborating the slow records was provided by evaluation of diffractive intensities within the range 6 — 60 2 θ.

Table 2

Chemical analyses of garnets of the Malé Karpaty Mts. metapelites*

№	4Y.	6Y.	7Y.	9Y.	10Y.	12Y.	14Y.	18Y.	KB-1Y.	KB-2Y.	KB-3Y.	KB-5Y.
SiO_2	37,90	37,91	38,48	38,22	37,66	36,93	38,40	38,33	37,37	39,29	40,08	39,10
Al_2O_3	19,98	20,36	20,28	20,23	19,92	19,21	19,66	19,98	20,46	20,48	21,18	22,06
FeO	33,16	33,01	32,54	32,91	32,50	33,48	34,23	30,19	31,75	35,27	34,07	33,25
MnO	5,66	6,55	5,75	6,65	7,84	6,69	6,80	12,44	8,76	5,09	6,73	7,13
MgO	3,05	2,56	2,88	2,45	2,57	3,32	2,22	2,01	2,52	3,41	3,10	3,00
CaO	1,65	1,37	1,98	1,71	1,16	1,16	1,83	1,45	1,31	1,13	1,65	1,86
	101,40	101,76	101,91	102,17	101,65	100,79	103,14	104,40	102,17	104,67	106,81	106,40
Formula unit of garnets on the basis of 12 0.												
Si	3,021	3,001	3,037	3,014	3,018	2,993	3,038	3,007	2,972	3,037	3,026	2,973
Al	1,876	1,903	1,886	1,879	1,880	1,834	1,832	1,847	1,930	1,862	1,883	1,976
Fe^{3+}	0,031	0,051	0,038	0,069	0,017	0,002	0,025	0,032	0,032	0,023	0,040	0,017
Fe^{2+}	2,210	2,190	2,147	2,170	2,177	2,268	2,263	1,980	2,111	2 278	2,150	2,113
Mn	0,381	0,440	0,383	0,443	0,532	0,459	0,455	0,826	0,589	0,332	0,429	0,458
Mg	0,362	0,302	0,337	0,287	0,306	0,400	0,261	0,234	0,298	0,392	0,348	0,339
Ca	0,140	0,116	0,167	0,144	0,098	0,100	0,154	0,121	0,111	0,093	0,133	0,151
Percentage of cations allocated in the structure.												
% kat.	95,49	98,26	96,78	98,17	94,70	92,19	92,79	94,44	97,93	94,35	96,65	99,53
Ed-member percentage.												
Pyr	12,62	10,32	11,75	9,84	10,73	14,38	9,39	8,25	10,16	13,85	12,02	11,36
Alm	69,14	70,81	69,14	70,07	67,13	65,67	68,74	58,48	66,00	71,09	68,51	68,25
Spes	13,34	14,98	13,31	15,15	18,67	16,49	16,31	29,00	20,03	11,74	14,88	15,30
Gros	3,20	1,19	3,71	1,29	2,47	2,22	4,11	2,43	2,14	2,00	2,31	4,14
Andr	1,68	2,67	2,06	3,62	0,98	1,21	1,42	1,81	1,64	1,28	2,26	0,92

* Obtained on electron microprobe JXA 4A JEOL analysed by Dr. J. Krištín, CSc. and Dr. Grman, CSc.

Table 3

Chemical analyses of biotites*

№	4Y.ˣ	6Y.ˣ	7Y.ˣ	8Y.ˣ	9Y.ˣ	11Y.ˣ	12Y.°	14Y.°	18Y.ˣ	KB-1Y.°	KB-2Y.ˣ	KB-3Y.ˣ	KB-5Y.°
SiO_2	35,62	36,42	36,04	36,12	35,97	36,18	35,46	35,94	36,49	35,43	35,68	35,69	36,23
TiO_2	1,29	1,19	3,16	1,53	1,56	1,42	2,63	1,79	0,91	2,09	2,20	2,42	1,38
Al_2O_3	19,92	20,32	20,23	20,08	20,07	19,96	19,49	19,55	20,38	20,29	19,83	19,85	20,29
Fe_2O_3	10,57	15,32	11,50	13,79	10,64	9,57	7,57	8,73	9,62	7,33	7,19	8,87	8,50
FeO	5,77	5,33	7,28	5,15	6,23	8,69	12,89	11,00	10,18	13,05	11,82	11,26	11,51
MnO	0,04	0,04	0,08	0,05	0,06	0,05	0,06	0,05	0,09	0,05	0,06	0,07	0,05
MgO	9,14	8,62	8,74	8,66	8,96	8,92	8,79	9,09	8,70	8,28	8,91	8,44	8,49
CaO	0,67	1,40	0,68	0,62	1,16	0,58	0,79	0,60	1,04	0,75	0,61	0,62	0,52
Na_2O	0,58	0,59	0,68	0,92	0,51	0,18	0,38	0,68	0,17	0,60	0,62	0,55	0,70
K_2O	8,38	8,31	7,98	7,82	7,24	8,26	8,65	7,50	8,46	7,55	8,31	6,57	7,60
H_2O	4,00	4,00	4,00	4,00	4,00	4,00	2,92	4,16	4,00	3,36	4,00	4,00	3,50
	95,98	101,54	100,37	98,74	96,40	97,81	99,63	99,09	100,04	98,78	99,23	98,34	98,77
Formula unit of biotites on the basis 12 0.													
Si	2,692	2,632	2,709	2,664	2,697	2,704	2,689	2,667	2,688	2,676	2,660	2,662	2,716
Ti	0,073	0,064	0,178	0,084	0,087	0,079	0,149	0,099	0,050	0,118	0,123	0,135	0,077
Al^{IV}	1,308	1,368	1,291	1,336	1,303	1,296	1,311	1,333	1,312	1,324	1,340	1,338	1,284
Al^{VI}	0,467	0,368	0,501	0,409	0,470	0,467	0,431	0,376	0,458	0,483	0,403	0,407	0,509
Fe^{3+}	0,601	0,832	0,650	0,765	0,600	0,543	0,431	0,487	0,533	0,416	0,403	0,497	0,479
Fe^{2+}	0,364	0,334	0,457	0,317	0,390	0,538	0,817	0,682	0,627	0,824	0,737	0,702	0,721
Mn	0,002	0,002	0,005	0,003	0,003	0,003	0,003	0,003	0,005	0,003	0,003	0,004	0,003
Mg	1,029	0,928	0,978	0,951	1,000	0,992	0,993	0,005	0,956	0,932	0,989	0,938	0,948
Ca	0,053	0,107	0,054	0,048	0,092	0,046	0,063	0,047	0,082	0,059	0,048	0,049	0,041
Na	0,084	0,081	0,098	0,131	0,072	0,025	0,055	0,096	0,024	0,086	0,088	0,078	0,100
K	0,808	0,765	0,765	0,734	0,692	0,787	0,836	0,709	0,795	0,727	0,790	0,625	0,726

* o—analyzed by Ing. E. Walzel, Geol. Inst. of the Slovak Acad. of Sci.
x — analyzed by Dr. D. Grman, CSc., on the electron microprobe

Indexing of diffraction intensities at biotites started from a presumption that biotite is polytype 1M with symmetry C2/m. The number of reflexions for getting more precise lattice parameters varied from 7 to 10. These were the following reflexions: 001, 020, 110, $11\bar{2}$, 003, $13\bar{1}$, 023, 004, $\bar{1}32$, $\bar{3}31$.

For calculation of the unit cell edge of garnets (a_0) the diffractive intensities were used: 400, 420, 332, 422, 510, 521, 440, 532, 444, 640, 642, 800.

Refractive index was determined by the immersion method. Reproducibility at biotites was within the range $\pm$ 0,002. As an immersion environment for garnets methylenejodide saturated by sulphur was used. Measuring of the refractive index of liquid was provided by the Leitz-Joly refractometer. The accuracy of measurement is $\pm$ 0,002 — 0,003.

The values of densities were obtained micropicknometrically on 5-8 grains without inclusions. The reproducibility was $\pm$ 0,01.

These experimentally obtained physical properties of coexisting garnets and biotites are shown in the Table 1.

For obtaining correct refractometrical data there was stressed that the obtained values could be used farther for the analytical aims. This followed from remarkable difficulties in determining Fe_2O_3 for studied garnets. Assumption that determination of the elements Si, Al, Ca, Mn, Σ Fe would enable on the basis of the ideal formula X^2_6 Y^3_4 Si_6 O_{24} to calculate the ratio Fe^{2+}/Fe^{3+} did not lead to a sufficient result. Moreover there was not precise calculation of the oxygen basis. Farthermore, a presumption was followed that ΣFe is bound on the almandine and andradite components and that it is possible, knowing an amount of the almandine component, to determine the Fe_2O_3 amount bound in the andradite component. This lead to high contents of Fe_2O_3 (1,2 — 4,4 W %).

Drawing physical properties (a_o, n and ρ) in diagrams (Fig. 1, a, b) the andradite component was determined and Fe_2O_3 amount was substracted from the FeO total according to the equation

$$FeO = FeO\ total - Fe_2O_3 / 1,1113$$

The obtained Fe_2O_3 contents were for the individual samples as follows:

№	W % Fe_2O_3	№	W % Fe_2O_3
4Y.	0,53	14Y.	0,44
6Y.	0,87	18Y.	0,56
7Y.	0,66	KB—1Y.	0,54
9Y.	1,17	KB—2Y.	0,40
10Y.	0,30	KB—3Y.	0,71
12Y.	0,37	KB—5Y.	0,30

These data were taken in consideration at all following elaborations of samples (crystallochemical formulas, garnet end-members, distribution coeficients, percentage of atoms in percentage of cations allocated in the structure).

The packing index (Φ) was obetained on the basis of the ~~unit~~ cell volume and structural formula of the mineral:

$$\Phi = V_O/V = \frac{4\,\pi/3\,\Sigma(f_i r_i^3)}{V}$$

where V_o = unit cell volume; r_i = ionic radius of i atom;
f_i = number of atoms i in the unit cell volume.

Ion radia used for calculation of Φ were according to the worky by R. Shannon and C. Prewitt (1969).

Recrystallization temperatures of the individual samples of the Malé Karpaty Mts. metapelitic rocks were obtained on the basis of the distribution coefficients ($K_D^{Fe\text{-}Mg}$) and their dependence on temperature which was determined for the mineral pair garnet biotite in works by L. Pertchuk (1973) and A. Thompson (1976). Change of the X_{Mg} garnet and distribution coefficient $K_D^{Fe\text{-}Mg}$ with pressure determined in these works served for obtaining approximative pressures of metamorphic recrystallization of studied samples.

Theoretical and model approach

Let us presuppose a theoretical rock of mineral composition: biotite, garnet, andalusite, quartz, on the left side of model reaction

$$2\text{Bio} + \text{Gar} + 2\text{And} + 2\text{Qz} = \text{Bio} + 2\text{Gar} + \text{Mus} + \text{Qz} \qquad (2)$$

which can be realized at temperature ~ 500°C till the temperature limit of coexistence of muscovite and quartz (~ 670°C).

At continual rising of temperature and pressure of recrystallization in this system also composition of coexisting garnet and biotite will be simultaneously changed. Mutual ratio of concentration Mg and Fe^{2+} in garnet and biotite will determine the distribution coefficient $K_D^{Fe\text{-}Mg}$.

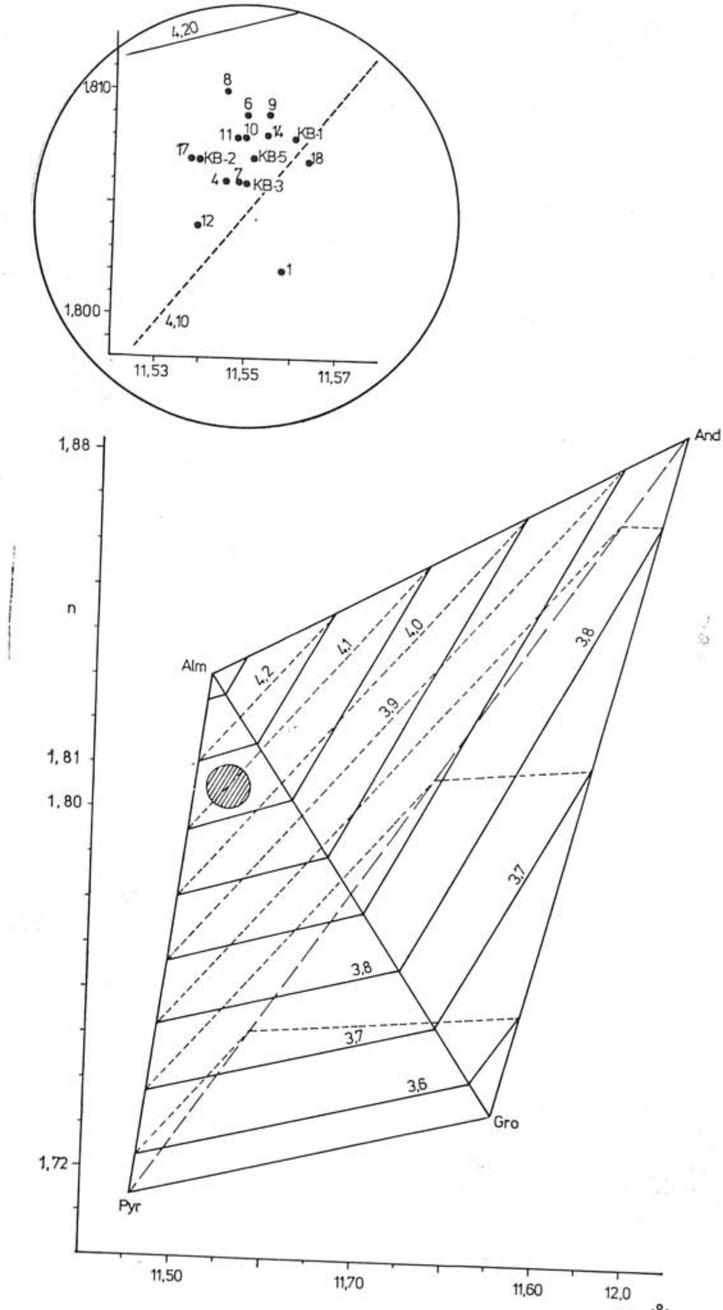
A change of $K_D^{Fe\text{-}Mg}$ value for the given model rock at the same time defined redistribution Mg and Fe^{2+} in coexisting garnet and biotite within the mentioned range of temperatures.

From that change results also the change of chemical composition of coexisting phase which is accompanied by the change of their physical properties, and also their modal composition change in the rock.

These complex changes within the considered theoretical rock could be summarized in this way:

	chem. comp.	Mod. %	Φ	chem. comp.	Mod. %	Φ
biotite	$Phlog_{84}Ann_{16}$	53,41	0,6118	$Phlog_{78}Ann_{22}$	27,85	0,6099
garnet	$Pyr_{42}Alm_{58}$	20,20	0,7505	$Pyr_{48}Alm_{52}$	42,02	0,7512
andalusite		18,25			—	
muscovite		—			25,93	
quartz		8,03			4,18	

The packing index (Φ) is changed in garnet and also in biotite. At garnet it is rising, at biotite — on the other hand — it is falling. The modal amount of biotite is decreased at the same time and the whole mineral association


4,20
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1,800
4,10
11,53
11,55
11,57
1,88
n
And
Alm
4,2
4,1
4,0
3,9
3,8
1,81
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Fig. 1a.

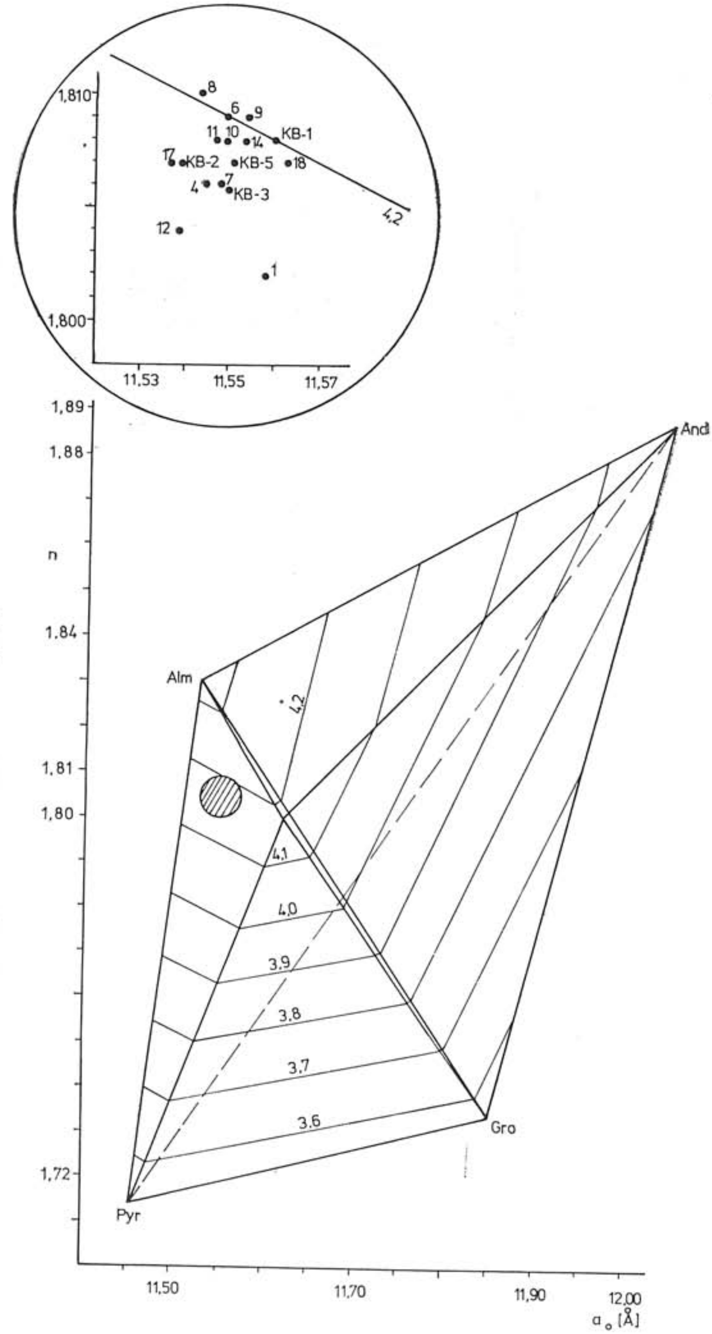

Fig. 1a, b. Physical properties of almandines from Malé Karpaty Mts. metapelitic rocks expressed according to H. Winchell (1958).

Table 4

Model reaction of coexisting biotite and garnet at increased temperatures and pressures in the system with different ratio $Mg/Mg+Fe^{2+}$

$Mg/Mg+$ $+Fe^{2+}$		X_{Ann}	Φ	ρ	X_{Alm}	Φ	ρ	Temp (°C)	Press (MPa)
I.	0,58	$Phlog_{80}Ann_{20}$	0,6105	2,888	$Pyr_{36,6}Alm_{63,4}$	0,7499	4,048	500	380
		$Phlog_{78}Ann_{22}$	0,6099	2,898	$Pyr_{38,3}Alm_{61,7}$	0,7501	4,036	550	470
		$Phlog_{77}Ann_{23}$	0,6096	2,903	Pyr_{40} Alm_{60}	0,7503	4,023	600	520
II.	0,66	$Phlog_{87}Ann_{13}$	0,6129	2,852	$Pyr_{47}Alm_{53}$	0,7511	3,972	480	510
		$Phlog_{85}Ann_{15}$	0,6121	2,862	$Pyr_{48}Alm_{52}$	0,7512	3,964	580	540
		$Phlog_{82}Ann_{18}$	0,6112	2,878	$Pyr_{52}Alm_{48}$	0,7516	3,935	640	560
III.	0,83	$Phlog_{95}Ann_{5}$	0,6158	2,813	$Pyr_{71,6}Alm_{28,4}$	0,7539	3,791	480	530
		$Phlog_{94}Ann_{6}$	0,6156	2,819	$Pyr_{72,3}Alm_{27,7}$	0,7540	3,785	520	540
		$Phlog_{93}Ann_{7}$	0,6151	2,823	Pyr_{73} Alm_{27}	0,7541	3,780	590	550

+Graphically expressed in the Fig. 4 and Fig. 5.

of the rock reaches higher values of packing index. This follows from the calculated reduction of volume for this model rock, $\Delta V_S = -5{,}91$ %.

These substitutional reactions, conditioned by increased temperature and pressure in the system, condition also change in the packing index of coexisting Mg-Fe minerals on different concentration level. This can be in the simplified model approach defined by different ratio Mg/Mg + Fe. During the recrystallization process this ratio is considered as constant, and then, the change of chemical composition of minerals is understood as a consequence of changed P- T conditions.

From different chemical composition of the system result then different properties of the individual phases at the same temperatures and pressures of recrystallization. Hence we cannot state that garnet with a higher packing index (and different physical properties which can be numerically derived and obtained from Φ) is a product of recrystallization at higher temperatures and pressures. Concentration of Mg and Fe in the system determines simultaneously the resulting physical properties.

Influence of different concentration of Mg and Fe in the system on packing index of coexisting biotites and garnets determines model reactions shown in the Table 4.

From this theoretical approach can be generalized that with increasing temperature and pressure of recrystallization there exists a tendency of increasing packing index in garnet and its decreasing at biotite. Chemical composition of rock at the same time determines what is the level of values on which this structural change is realized.

Results and discussion

The packing index (Φ) of measured garnets and biotites is lower as is expected from the theoretical view-point. This partially occurs at biotites of the structural pattern $X_2Y_6Z_8O_{20}$ (F, OH)$_4$ from the deficiency of cations which occupy structural pozitions Y with coordinative number 8. This deficiency and so deficiency in pozitions X can be caused by accuracy of chemical analysis and with number of vacancies caused by the heterovalent substitution. Chemical composition of the biotites is shown as review in the Figure 2.

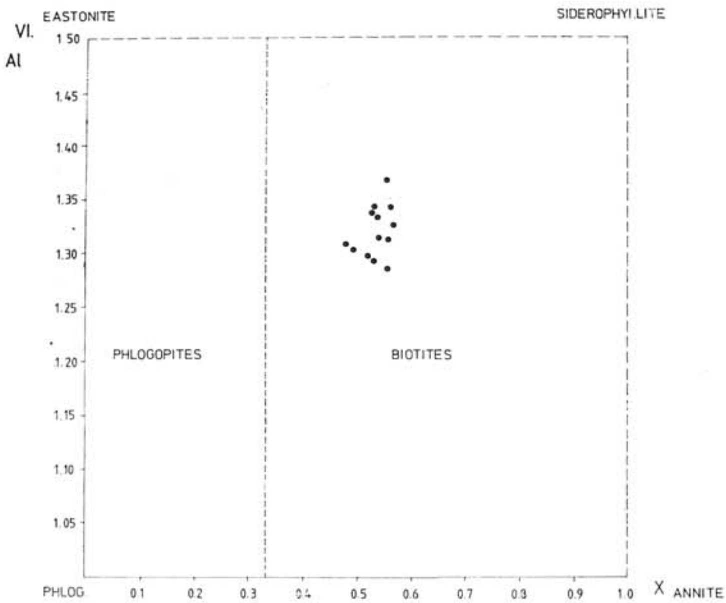

Fig. 2. Chemical composition of biotites from Malé Karpaty Mts. metapelitic rocks expressed by relation Al^{IV} to mole fraction of annite (X_{Ann}) in the termary diagram phlogopite—annite—eastonite—siderophylite. Boundary limit between phlogopites and biotites is given by 0.33 mole fraction of annite.

The number of cations allocated in the structural pozitions of garnets is expressed in the Table No. 2. This ought to express also correctness of the chemical composition of the garnet also when it is expressed by percentages of the end-members. Besides it is presupposed that 5 % deviation from the ideal occupying of the individual corresponding structural pozitions is still adequate for electrostatic equilibrium in the structure of the natural garnet. Studied garnets (Figure 3) in majority complied with these requirements of structural evaluation and they were accepted at evaluation of relation of their packing index to the metamorphic grade.

Comparing theoretical packing indices of garnets and biotites of the individual model reactions and real garnets and biotites coexisting in the metapelitic rocks of the Malé Karpaty Mts. is graphically expressed in the Figure 4 and 5. Φ and thermodynamical conditions of crystallization of these rocks are given in the Table 5.

By the theoretical approach, resulting direct dependence of the packing index of garnets on temperature and pressures of recrystallization is found also in the Malé Karpaty Mts. almandines ($r_{\varphi,T} = 0,599$; $r_{\varphi,P} = 0,669$).

Coexisting biotite in opposite to the garnet has a tendency at higher P - T conditions to reach values of lower packing index. This indirect packing index at biotite ($r_{\varphi,T} = -0,597$, $r_{\varphi,P} = -0,746$) is at the same time greater

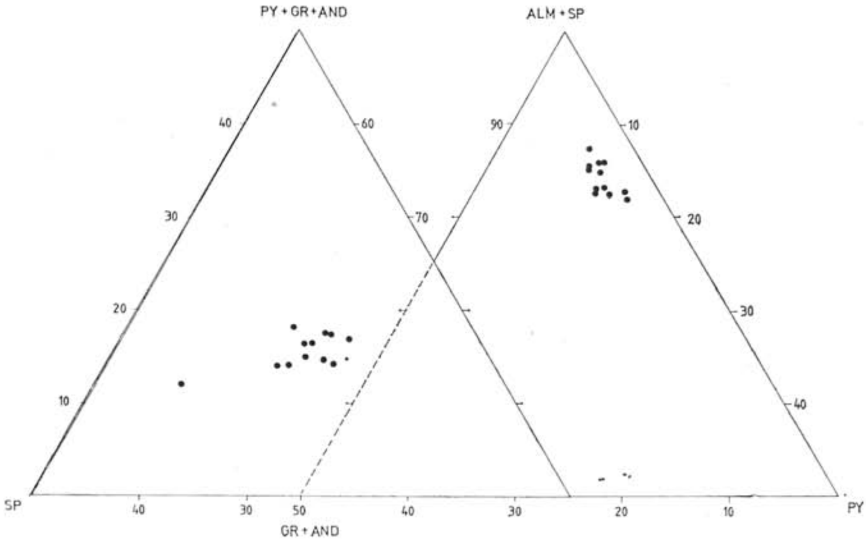

Fig. 3. Chemical composition of almandines from Malé Karpaty Mts. metapelites in garnet end—member diagrams. Pyrope—Pyr: almandine—Alm: spesartine—Spes: grosular—Gro: andradite—And.

what can be a consequence of „softer" structure of biotite and its easier reaction by change of packing index on different P - T conditions of recrystallization. During recrystallization biotite reacts by greater change of the Φ value than coexisting garnet. It is in the same time more influenced by the chemical composition of the rock than garnet. By this its applicability can be pressed as the indicator of P-T conditions of recrystallization.

From the model approach results that evaluating of coexisting biotites and garnets should be provided on the individual concentration levels of those elements which can condition the change of chemical composition of coexisting phases during their redistribution, conditioned by changed P-T conditions.

Here a remarkable difficulty occurs for the choice of the individual elements which ought to be taken in to consideration. Choice of Mg and Fe as was shown in the model reactions do not be enough for real samples. Complications can result e.g. from regarding concentration Fe^{3+}, Ca, Mn in a rock which displace garnet to andradite—grossularite end—members with greater lattice parameter (a_0). Then a_0 need not indicate lower metamorphic grade as e.g. K. Nandi (1967) mentions. At the same time Ca distribution

Table 5

Packing index (ϕ of coexisting biotites and garnets of the Malé Karpaty Mts. metapelites and temperatures) pressures of their crystallization*

№	Φ_{Bio}	Φ_{Gar}	T (°C)	P (MPa)
4Y.	0,6002	0,7457	535	440
6Y.	0,5974	0,7441	540	430
7Y.	0,5970	0,7446	555	450
8Y.	0,5977		460	380
9Y.	0,6017	0,7435	460	380
10Y.		0,7448	485	420
11Y.	0,5966		450	350
12Y.	0,5818	0,7483	610	580
14Y.	0,5961	0,7450	510	420
18Y.	0,5991	0,7437	420	360
KB—1Y.	0,5893	0,7431	545	480
KB—2Y.	0,6026	0,7460	560	470
KB—3Y.	0,5905	0,7446	555	460
KB—5Y.	0,5882	0,7446	575	520

* Packing index is expressed by coeficient of space filling — Φ which has values <1. Structures with lower packing index have lower values of Φ. E.g., value $\Phi =$ $= 0,6002$ expresses that 60,02 % of unit cell volume is filled by ions.

should be regarded between plagioklase and garnet. Also oxidation degree of rock determining the ratio Fe^{2+}/Fe^{3+}. It is important for biotite to take regard also to content of Al_2O_3 in the rock which by a certain share determines an amount of Al^{IV} in biotite, then partial pressures of the individual volatile components in the system which influence concentration (OH) in biotite.

(OH) — group near Na and K considerably influences the unit cell volume of biotite and also Φ value.

These mentioned correction factors were not regarded during evaluation of Φ of coexisting garnets and biotites of the Malé Karpaty Mts. metapelites. Partly from reasons of close chemical and mineralogical composition of these rocks (M. Dyda, 1977), partly from the reasons of remarkable complications during concentration corrections to the individual elements.

From these evaluations at the same time results that the individual packing indices of garnets and biotiees in different rocks need not have generally the same Φ values at similar temperatures and pressures of recrystallization.

This should condition the individual approach to the evaluation of Φ of the biotite—garnet pairs in the individual metamorphic regions.

Evaluation of packing indices of garnets of metamorphed rocks from different world areas (M. Dyda, 1980 a) should explain this approach, since here a greater continuity between Φ of garnets and the metamorphic grade was found within the framework of the individual region, and so between ϕ of garnet and P-T conditions of recrystallization generally.

From this view-point the author considers also values of unit celly edge of garnets which sometimes are mentioned at evaluation of measure of metamorphic grade (K. Nandi, 1967). However, if chemical composition of

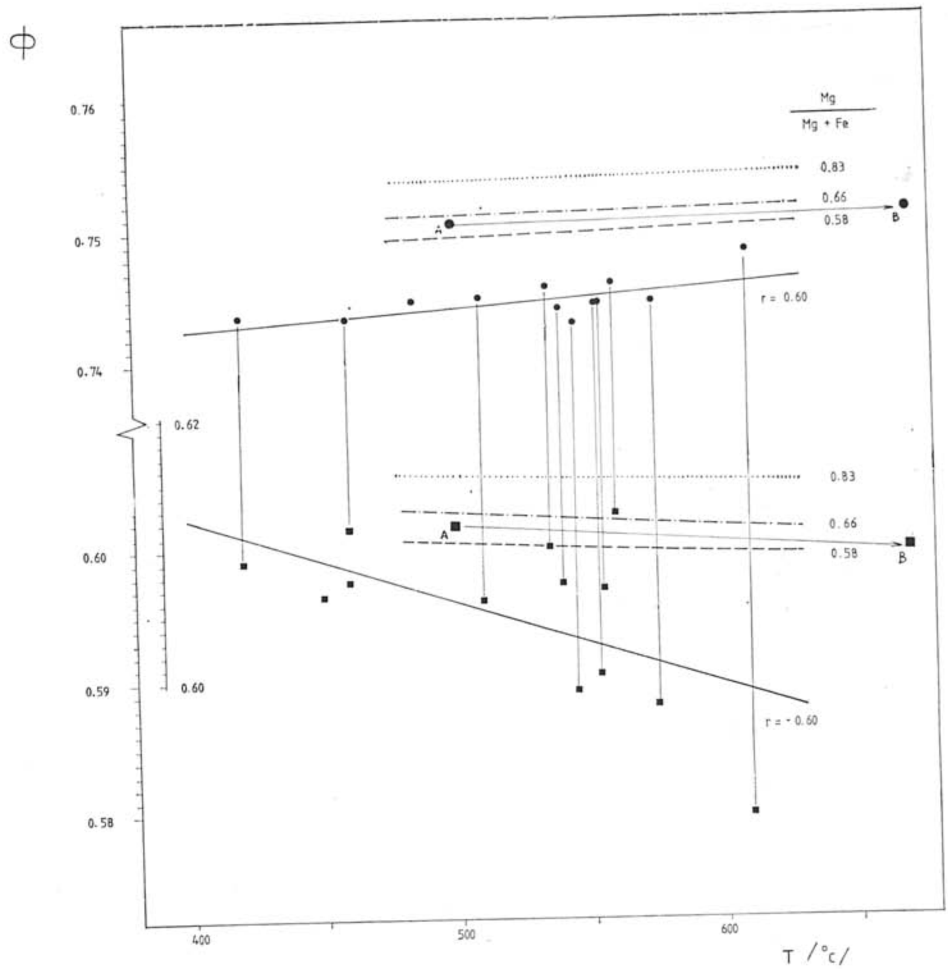

Fig. 4. Relation between packing index (Φ) of coexisting biotites and garnets and temperature of recrystallization ($T_{calc.}$) in Malé Karpaty Mts. metapelitic rocks.

Theoretical relation at different Mg/Mg+Fe ratio is given by dotted line. ● —garnet; ■ — biotite. Position of the model rock is designated A→B.

parent rocks is not regarded a_0 need not enable distribution of the individual metamorphic zones.

Similarly content of Mg and Al^{IV} in biotites of different regions need not generally correlate with metamorphosis degree, since Al^{IV} content in biotite is given by the natural rock. Influence of the original chemical composition of the rock can wipe out relation between the Al^{IV} content in biotite and P-T conditions of metamorphic recrystallization. In the metapelites from the Malé Karpaty Mts. these relations were not demonstrated althogh they

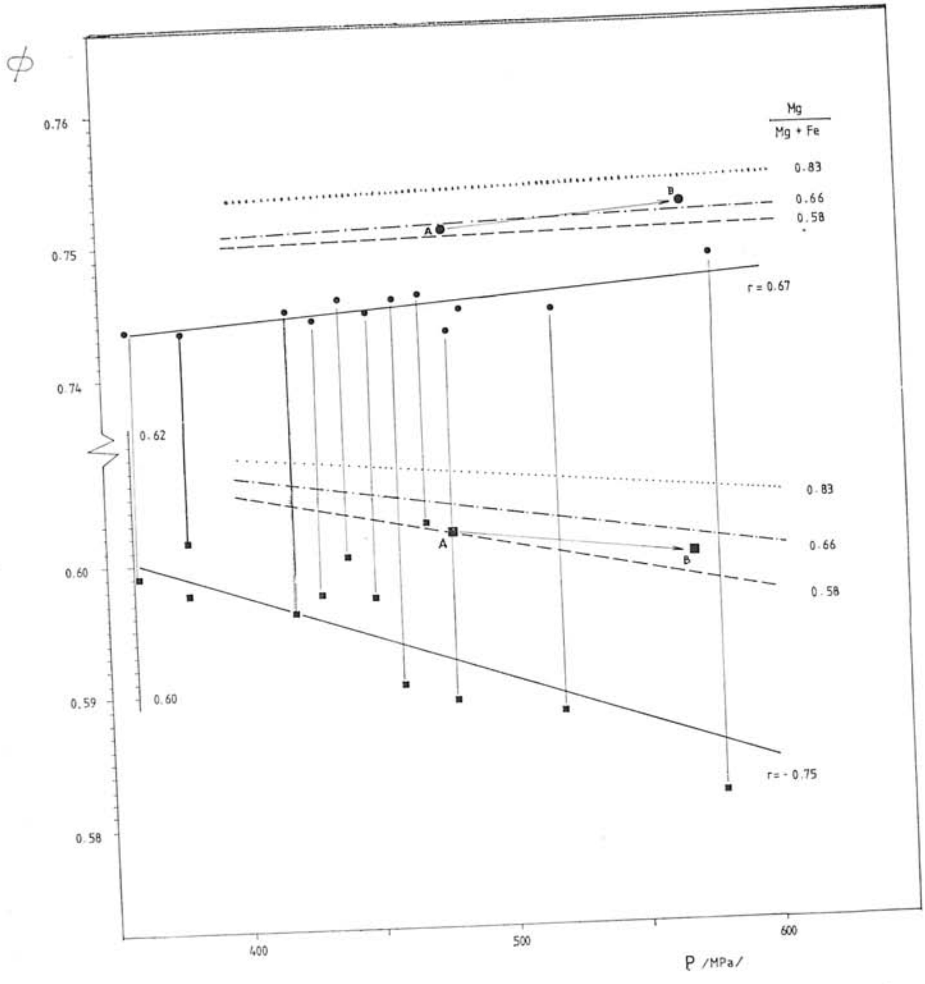

Fig. 5. Relation between packing index (Φ) of coexisting biotites and garnets and pressure of recrystallization ($P_{calc.}$) in Malé Karpaty metapelitic rocks. Symbols as in Fig. 4.

could be conditioned by the similarity of mineralogical and chemical composition of the rocks.

Conclusions

Theoretical and model solving of the garnet and biotite coexistences in metamorphed rocks enables to presuppose a systematic change of packing index (Φ) of these minerals as the consequence of P-T-X conditions of metamorphic recrystallization.

Studying of these relations between biotite—garnet pairs in the Malé Karpaty Mts. metapelitic rocks confirm these connections.

Packing index (Φ = 0,7431 — 0,7483) is increased in garnet with the degree of metamorphosis ($r_{\varphi,T}$ = 0,65; $r_{\varphi,P}$ = 0,78). This change Φ_{Gar} in comparison to Φ_{Bio} is lower within the range of studied temperatures (460 — 610° C) and pressures (360 — 580 MPa).

Coexisting biotite has an opposite tendency as garnet. The packing index of biotite (Φ = 0,5882 — 0,6026) is lowered with the increased temperatures and pressures of recrystallization ($r_{\varphi,T}$ = — 0,59; $r_{\varphi,P}$ = —0,74) and probably, it reacts more sensible on the change of P-T conditions of recrystallization as the garnet does.

The change of modal amount of garnet and biotite with the increasing degree of metamorphosis, follows as results from the model reactions, origination of mineral association with higher packing index.

Evaluation of these mineral changes can considerably contribut to picturing of zone—graphical relations in fields with different grade of progressive recrystallization of rocks.

Translated by Ľ. Halmová

Localities of samples

The Malé Karpaty Mts. are the most western and external core mountain chain of the Westcarpathian Arc. Mostly here occur only postkinematic granitoid rocks of intrusive character which reached the higher parts of sedimentation mantel. Sedimentation mantel was epizonally metamorphed before intrusion and periplutonic proces which was caused by intrusion became on many places a prevalent metamorphosis. This process was realized during the last folding of the variscan mountains (T. Buday — B. Cambel — M. Mahel, 1962), B. Cambel (1976).

Amon the rocks of the Malé Karpaty Mts. metamorphic crystalline belong biotitic phyllites, biotitic paragneisses with garnet, staurolite and accessory andalusite and fibrolitic sillimanite.

Sample №:

4Y.: Sillimanite—starolite—biotitic paragneiss (p), fine—grained. Bratislava, Hrebienok.

6Y.: Biotite—quartzitic paragneiss (p), fine—grained. Bratislava, Dúbravka near waterworks.

7Y.: Garnet—sillimanite—biotitic paragneiss (p), fine—grained. Limbach, valley Slnečné údolie, altitude 306.

8Y.: Biotitic paragneiss (p), fine—grained. Road Pernek-Baba, ~500 m in front of the hotel.

9Y.: Garnet—staurolite—biotitic paragneiss (p), fine—grained. Baba, near park place.

10Y.: Biotitic paragneiss (p), very fine—grained. Bratislava, Dúbravka, near football playground.

11Y.: Staurolite—biotitic paragneiss (p) fine—grained. Limbach, valley Slnečné údolie, gallery near gamekeeper's cottage.

12Y.: Arteritic migmatite, fine—grained. Jur near Bratislava, road NW from Jur village, truning near migmatite outcrop.

14Y.: Garnet—staurolite—biotitic paragneiss (p), fine—grained. Road Baba — Pernek, ~300 m from the Baba cottage.

18Y.: Biotitic paragneiss (p), fine—grained. Road Bratislava-Devín, ~300 m to S from the big quarry.

KB-1Y.: Sillimanite—garnet—biotitic, paragneiss (p), fine—grained. Bratislava, Železná studnička, ~100 m from the concrete bridge, on the left bank of brook.

KB-2Y.: Garnet—biotitic paragneiss (p), fine—grained. Bratislava, Železná studnička, Cesta mládeže, ~150 m from houses on the left bank of the brook.

KB-3Y.: Biotitic paragneiss (p), fine—grained. Bratislava, Železná studnička, ~100 m above the Klepáč Restaurant.

KB-5Y.: Garnet—sillimanite—biotitic paragneiss (p), fine—grained. Bratislava, Lamač, cottoge area, ~200 m from the last cottage in the narrowed valley of the brook.

REFERENCES

ALBEE, A. L., 1965: Ditribution of Fe, Mg asd Mn between garnet and biotite in natural mineral assemlages. J. Geol. (Chicago), vol. 73, p. 155—164.

BUDAY, T. — CAMBEL, B. — MAHEĽ, M., 1962: Vysvetlivky k prehľadnej geologickej mape ČSSR 1:200 000. Wien—Bratislava, Geofond, 248 p.

CAMBEL, B., 1976: Probleme der Metamorphose und der Stratigraphie des Kristallins der Westkarpaten mit Hinsicht auf die Forschungen in dem Bereich der Kleinen Karpaten. Geol. Zborn. Geologica Carpathica (Bratislava), 1, p. 103—116.

DYDA, M., 1977: Indexové minerály pararúl v oblasti bratislavského granitoidného masívu. Manuskript, Dizertačná práca, GÚ SAV Bratislava, 136 p.

DYDA, M., 1980: Physical properties and temperatures of crystallization of coexisting garnets and biotites from Little Carpathian paragneisses. Geil. Zborn. Geologica Carpathica (Bratislava), 1—2, p. 257—276.

DYDA, M., 1980a: Metamorphic grade and packing index in garnets. Geol. Zborn. Geologica Carpathica (Bratislava), vol. 31, p. 359—374.

FERRY, J. M. — SPEAR, F. S., 1978: Experimental calibration of the partitioning of Fe and Mg between biotite and garnet. Contrib. Min. Petrol. (Heidelberg), 66, p. 113—117.

FROST, M, J., 1962: Metamorphic grade and iron—magnesium distribution between co—existing garnet—biotite and garnet—hornblende. Geol. Magaz. (London), 99, p. 427—438.

GOLDMAN, D. S. — ALBEE, A. L., 1977: Correlation of Mg/Fe partitioning between garent and biotite with $^{18}O/^{16}O$ partitioning betwøen quartz and magnetite. Amer. J. Sci. (New Haven), 67, p. 750—767.

HIETANEN, A., 1969: Distribution of Fe and Mg between garnet, staurolite, and biotite in aluminium—rich schists in various metamorphic zones north of Idaho Batholith. Amer. J. Sci. (New Haven), 276, p. 422—456.

KRETZ, R., 1959: Chemical study of garnet, biotite and hornblende from geisses of southwestern Quebeck, with emphasis on distribution of elements in coexisting minerals. J. Geol. (Chicago), 67, p. 371—402.

LYONS, J. B. — MORSE, S. A., 1970: Mg/Fe partitioning in garnet and biotite from some pelitic, and calcic rocks. Amer. Mineralogist (Washington), 55, p. 231—245.

MUELLER, R. F., 1960: Compositional characteristics and equilibrium relations in mineral assemblages of a metamorfhosed iron formation. Amer. J. Sci. (New Haven), 258, p. 449—493.

NANDI, K., 1967: Garnets as indices of progressive metamorphism. Min. Magaz. (London), 36, p. 89—93.

PERČUK, L. L., 1967: Biotit—granatovyj geotermometer. Dokl. Akad. Nauk SSSR (Moskva), 177, p. 411—414.

PERČUK, L. L., 1973: Termodynamičeskij režim glubinnogo petrogeneza. Moskva, Nauka 1973, 318 p.

RAMBERG, H. — DeVORE, D. G. W., 1951: The distribution of Fe^{2+} and Mg^{2+} in coexisting olivines and pyroxenes. J. Geol. (Chicago), 59, p. 193—210.

SAXENA, S. K., 1969: Silicate solid—solution and geothermometry. Distribution of Fe and Mg between coexisting garnet and biotite. Contrib. Min. Petrol. (Heidelberg), 22, p. 259—267.

SAXENA, S. K., 1973: Thermodynamics of rocks—forming crystalline solutions. Springer—Verlag Berlin-Heidelberg-New York. 188 p.

SCHANNON, R. D. — PREWITT, C. T., 1969: Effective ionic radii in oxides and fluorides. Acta Cryst. (Cobenhaven), B 25. p. 925—946.

SEN, S. K. — CHAKRABORTY, K. R., 1968: Magnesium—iron exchange equilibrium in garnet—biotitite and metamorphic grade. N. Jb. Miner. Abh. (Stuttgart), 2, p. 181—207.

STEPHENSON, N. C. N., 1979: Coexisting garnets and biotites from Precambrian gneisses of the south coast of Western Australia. Lithos (Oslo), 12, p. 73—87.
THOMPSON, A. B., 1976: Mineral reactions in pelitic rocks: II. Calculation of some P-T-X (Fe—Mg) phase relations. Amer. J. Sci. (New Haven), 278, p. 425—454.
TRACY, R. J., 1978: High grade metamorphic reactions and partial melting in pelitic schists, West-Central Massachusetts. Amer. J. Sci. (New Haven), 278, p. 150—178.
WINCHELL, H., 1958: The composition and physical properties of garnets. Amer. Mineralogist (Washington), 43, p. 595—598.

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