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MICHAEL D. SHENGELIA* — JOZEF HATÁR**

EVOLUTION OF REGIONAL METAMORPHISM OF THE SOPHIAN UPLIFT (THE GREAT CAUCASUS)

(Figs. 6, Tabs. 2)

Abstract: In the paper the results of the microprobe investigation of co-existing ferromagnesian minerals (garnet, cordierite, biotite, chlorite) from zonal complexes of metamorphites in the Buulgen and Lashtrac tectonic slices of the Sophian uplift of the Great Caucasus are presented. It is shown that the polymetamorphic processes not reflected in the character of mineral associations are clearly fixed in the zoning of minerals of variable composition. The P-T parameters of the progressive and regressive stage of regional metamorphism are expressed. It is established that the early stage of formation of the Buulgen series was at considerably higher-temperature and pressure ($T = 630 - 680$ °C; $P = 6 - 6.8 \times 10^8$ Pa) than the later one ($T = 450 - 530$ °C; $P = 0.6 - 2 \times 10^8$ Pa) and in the Lashtrac slice the low-temperature and low-pressure metamorphism ($T = 450 - 465$ °C; $P = 2 \times 10^8$ Pa) changed into higher-temperature and higher-pressure ($T = 600—620$ °C; $P = 6 - 7 \times 10^8$ Pa) regional metamorphism.

Резюме: В работе приводится результаты микрозондового изучения сосуществующих железо-магнезиальных минералов (граната, кордиерита, биотита, хлорита) зональных комплексов метаморфитов буульгенской серии и лаштракской тектонической пластины Софийского поднятия Большого Кавказа. Показано, что полиметаморфические процессы не проявляющиеся в характере минеральных ассоциации, четко фиксируются в зональности минералов переменного состава. Выявлены P-T параметры прогрессивной и регрессивной стадии регионального метаморфизма. Установлено, что ранний этап формирования буульгенской серии был значительно высокотемпературным и высокобарическим ($T = 630—680$ °C; $P = 6—6,8 \times 10^8$ Pa), чем более поздний ($T = 450—530$ °C; $P = 0,6—2 \times 10^8$ Pa), а в лаштракской пластине низкотемпературный и низкобарический метаморфизм ($T = 450—465$ °C; $P = 2 \times 10^8$ Pa) сменился более высокотемпературным и высокобарическим ($T = 600—620$ °C; $P = 6—7 \times 10^8$ Pa) региональным метаморфизмом.

In recent years, by means of microprobe analysis, chemical zoning of metamorphic minerals has been established and thermodynamical characteristics of metamorphism evolution have been deciphered. In particular, it was shown that the whole cycle of regional metamorphism is divided into two clearly defined progressive and regressive stages, and many metamorphic complexes, which were considered as homogeneous, turned out to be polymetamorphic ones. Sometimes polymetamorphic processes do not manifest themselves in the character of mineral associations, but they are fixed in the zoning of minerals of variable composition. Paleozoic metapelites of the Lashtrac suite (tectonical slice) and those of the Buulgen series of the Sophian uplift in the Great Caucasus provide good examples of progressive and regressive metamorphism.

* Dr. M. D. Shengelia, Institute of Geology AN Georgia, st. E. Ruchadze 16, 380015 Tbilisi.

** RNDr. J. Határ, CSc., Dionýz Štúr Institute of Geology, Mlynská dolina 1, 817 04 Bratislava.

The horst-anticlinorium of the Main Range of the Great Caucasus where the pre-Jurassic crystalline core is concentrated was substantially transformed as a result of the Alpine tectogenesis. It is divided into a number of horst-like uplifts of considerable size by large fractures and narrow grabens and grabensynclines, and the Sophian uplift is attributed to these uplifts.

Paleozoic metamorphites of the Sophian uplift are divided into the Maker, Buulgen and Laba series and the Lashtrac suite (tectonic slice). The Buulgen series extends in the Eastern part of the Southern edge of the Sophian uplift, while the Lashtrac suite extends in the western part of the Southern edge of this uplift. The age of the metamorphic and granitization processes dated by the Ar-method can be attributed to the Hercynian age, and these processes are associated with the Bretonian, Sudetian, and Asturian folding phases (Рубинштейн, 1967; Шенгелиа, 1973).

Methods of analysis

To study regularities in the PT-parameters variation during regional metamorphism of the crystalline rocks under consideration we used local X-ray spectrum (microprobe) analysis of zoning in coexisting ferromagnesian minerals and paragenetic analysis of mineral associations. The microprobing was carried out at the D. Štúr Institute of Geology (Czechoslovak SR, Bratislava), VSEGEI (Leningrad), and Metallurgical Institute of the Academy of Sciences of Georgian SSR (Tbilisi).

The P-T parameters were evaluated by fresh contacting minerals and by coupling chemical compositions of the grain centres (the limiting Mg-values in garnet were compared with chemical compositions of the most ferruginous biotites, cordierites, chlorites, and staurolites)[1]. In case when biotite, $\frac{\text{chlorite}}{\text{cordierite}}$ and staurolite exhibit no zoning, the data on garnet of any chemical composition are coupled with the data on biotite, cordierite, chlorite, and staurolite.

Temperature conditions of metamorphism are evaluated according to readings of the garnet-biotite, garnet-cordierite, garnet-staurolite, garnet-chlorite, and graphite geothermometers. To evaluate temperature by the garnet-biotite geothermometer, the authors used the following equation (Перчук — Лаврентьева, 1983): $T°C = \frac{3947.5}{\ln K_D + 2.868} - 273.$

If garnet is rich in manganese, $T°C = \frac{3947.5}{\ln K_D + 12.868} +$

$+ 252.25 (X^{Gar}_{Mn} - 0.035) - 273$

$$X^{Gar}_{Mn} = Mn : (Mn + Mg + Fe);\ X^{gar}_{Mg} = Mg : (MN + Mg + Fe)$$

$$K_D = (X_{Mg} : X_{Fe})\ Gar : (X_{Mg} : X_{Fe})^{Bt}$$

[1] Mg-value — X_{Mg} = Mg (Mg + Fe + Mn) %; ferruginity — Fe (Fe + Mg + Mn).

To evaluate the temperature of the garnet-cordierite equilibrium we used the equation (П е р ч у к — Л а в р е н т ь е в а, 1983):

$$T^{\circ}C = \frac{1000}{0.41155 + 0.3198 \ln K_D} - 273$$

where $K_D = (X_{Mg} : X_{Fe})^{Crd} : (X_{Mg} : X_{Fe})^{Gar}$, $X^{Crd}{}_{Mg} = Mg : (Mg + Fe)$
$X^{Gar}{}_{Mg} = Mg : (Mg + Fe)$,

while for the staurolite-garnet thermometer we used the equation (П е р ч у к, 1969):

$$T^{\circ}C = \frac{1000}{(0.2822 \ln K_D + 1.0943)} - 273,\ K_D = \left(\frac{X_{Mg}}{1 - X_{Mg}}\right)^{St} \cdot \left(\frac{1 - X_{Mg}}{X_{Mg}}\right)^{Gar}$$

$$X_{Mg} = Mg : (Mg + Fe + Mn).$$

We used the graphite geothermometer to determine the maximal temperature, reached by a mineral (or rock), since the parameter value of a graphite elementary cell C (Å) is wholly preserved in graphite after lowering mineral forming temperature during metamorphism (Ш е н г е л и а, et al., 1977).

Pressure for the Gar-Crd-Bt-Sil paragenesis is determined according to the following equation (А р а н о в и ч — П о д л е с с к и й, 1983):

$$P = \frac{34203 - 2255 \ln K^{Crd-Gar}{}_D - 12188 \ln K^{Crd-Gar}{}_{Mg}}{0.9161 \ln K^{Crd-Gar}{}_D + 0.07 \ln K^{Crd-Gar}{}_{Mg} + 1.016},\ \text{where}$$

$$K_D = (X_{Mg} : X_{Fe})^{Crd} : (X_{Mg} : X_{Fe})^{Gar}.$$

For the garnet-staurolite paragenesis according to the division coefficient $K_{Mg}{}^{St-Gar}$ (П е р ч у к, 1983):

$$P_s = 55341.6 - 51.9\,T(K) - 56.564\,T(K) \lg K_{Mg}{}^{St-Gar}\ 10^5\ Pa;$$

$$K_{Mg}{}^{St-Gar} = X_{Mg}{}^{St} : X_{Mg}{}^{Gar}.$$

To consider the regularities of P-T parameters variation for regional metamorphism on the basis of the microprobe analysis of minerals, we chose crystalline complexes of the Great Causasus having metamorphic zoning of low and moderate pressure types and clearly defined stage of progressive and regressive metamorphism.

Regional metamorphism of the Buulgen series

The Buulgen series consists of metapelites, amphibole, pyroxene, and epidote shists, and amphibolites; subordinate are quartzites, marble intercalations, and lenses and amphibole diorite gneisses. In this series low-pressure regional metamorphic zoning is expressed as consecutive change of biotite, staurolite (the presence of large fractures and granitoid bodies between the biotite and staurolite zones suggests slipping out the intermediate garnet zone), sillimanite, and migmatite zones (Ш е н г е л и а — К е ц х о в е л и, 1982). Up till now only the progressive character of the metamorphism of mineral associations in the Buulgen series has been shown. The staurolite zone is determined from the first occurrence of staurolite in metapelites. Its upper boundary is determined by disappearance of staurolite. The sillimanite zone is determined by occurrence of sillimanite and disappearance of staurolite in metapelites. Sillimanite develops along biotite and andalusite. Disintegration takes place according to the following reactions: St $\longrightarrow$ Crd + Her[2], St $\longrightarrow$ And(Sil) + Her, also St + + Qtz $\longrightarrow$ Crd + Gar + And $\pm$ Her $\pm$ H_2O and Ms + St + Qtz $\longrightarrow$ Sil + Bt $\pm$ $\pm$ Gar + H_2O.

In the high temperature part of the sillimanite zone the following reaction takes place: Ms + Qtz $\longrightarrow$ Fsp + Sil + H_2O. The migmatite zone is determined by occurrence of migmatite in metapelites undersaturated with K_2O. In metapelites saturated with K_2O migmatization begins in the sillimanite zone. In the high temperature part of metapelites undersaturated wit K_2O we have to note a reaction which takes place at temperature lowering: Crd $\longrightarrow$ Gar + + Sil + Qtz. In metapelites saturated with K_2O of the migmatite zone we also have the reaction: Ms + Qtz + Gar_{Fe-Mg} + Bt_{Mg-Fe} $\longrightarrow$ Gar_{Mg-Fe} $\pm$ Crd + Sil.

A great deal of attention was paid by the authors to Gar-Crd-Bt-Sil equilibrium which is widely shown in the Buulgen series of metapelites undersaturated with K_2O. This paragenesis is formed during maximal progressive regional metamorphism in crystalline rocks of the Buulgen series (Шенгелиа — Кецховели, 1982). Both experimental and theoretical investigations showed that the composition of garnet, cordierite, and biotite served that the composition of garnet, cordierite, and biotite served as indicators of the thermodynamical regime of metamorphism. The above-mentioned made it possible to obtain reliable mineralogical thermometers and barometers (Thompson, 1976; Goldman — Albee 1977; Holdway — Lee, 1977; Ferry — Spear, 1978; Лаврентьева — Перчук, 1981; Перчук, 1983).

To restore the P-T conditions of this equilibrium in metamorphites of the Buulgen series we have carried out 250 local microprobe analyses of coexisting garnet, biotite, and cordierite.

The garnet of these rocks is fresh, porphyroblastic ($0.5 \div 2$ mm) or fine-grained ($0.01 \div 0.1$ mm). Sometimes fresh garnet grains ($0.1 \div 1.5$ mm) are included in large (1—4 mm) cordierite porphyroblasts. In garnet porphyroblasts we can see regressive zoning; in the central part of the garnet the Mg-value is 17—22 %, while along the periphery it decreases to 8—12 % (Tab. 1; Figs. 1, 2, 3). Usually the Mg-value decreases gradually and only in a narrow range ($100 \div 150$ μm) at the contact with biotite its sharp lowering is observed. Simultaneously the MnO content increases from 0.7 to 4.6 %. The content of CaO in the external zone is higher than that in the centre. The lowest Mg-value of garnet is usually observed at the contact of its grains with cordierite and biotite. In the fine grains of garnet inhomogeneity is poorly expressed and chemical zoning is not observed. The fine grains composition is similar to

[2] Hereinafter the following symbols of minerals are used: And — andalusite, Bt — biotite, Chl — chlorite, Crd — cordierite, Fib — fibrolite, Fsp — potash feldspar, Gar — garnet, Iln — illmenite, Her — hercynite, Ms — muscovite, Qtz — quartz, Sil — sillimanite, St — staurolite.

Table 1

Electron microprobe analyses of the garnets and associated minerals from metamorphites of Buulgen series

Sample No	Mineral	Analysis No	SiO_2	TiO_2	Al_2O_3	FeO	MgO	MnO	CaO	K_2O	Na_2O	Total	X_{Mg}*)
1	2	3	4	5	6	7	8	9	10	11	12	13	14
20-4	Gar	core — 1	40.59	0.11	20.16	31.92	5.12	0.94	0.85	0.05	—	99.74	21.7
		core — 2	40.87	0.08	19.76	32.01	5.00	1.20	0.80	0.13	0.01	99.85	21.2
		3	41.90	0.05	21.47	29.82	3.52	2.21	1.29	0.04	0.02	100.32	22
		4	41.09	0.12	21.40	29.73	3.01	2.90	1.39	0.06	—	99.70	14.0
		5	41.31	0.06	21.20	29.98	3.25	2.85	1.42	0.02	—	100.09	15.1
		rim — 6	41.80	0.12	21.60	29.40	1.51	3.52	1.60	0.03	0.01	99.06	7.5
		rim — 7	41.90	0.03	21.65	29.35	1.81	3.13	1.66	0.04	—	99.56	9.1
	Gar	core — 8	41.46	0.10	21.19	30.24	1.99	3.00	1.59	0.06	0.03	99.66	9.8
		9	41.30	0.03	21.08	31.45	1.90	2.91	1.60	0.05	0.02	100.34	9.2
		10	41.06	0.05	21.27	29.92	2.00	3.25	1.65	0.03	—	99.23	10.0
		11	41.39	0.04	21.41	29.62	1.90	3.35	1.70	0.03	—	99.44	9.3
	Crd	core — 12	45.05	0.05	35.39	8.21	7.82	0.20	0.11	0.01	0.01	96.84	63.0
		13	45.17	0.04	35.06	8.36	7.77	0.49	0.10	0.02	0.01	97.02	61.0
		14	45.08	0.03	35.21	8.35	7.83	0.51	0.12	0.02	—	97.15	61.3
		rim — 15	44.98	0.04	35.52	8.00	8.50	0.20	0.12	0.03	0.02	97.41	65.5
	Bi	16	36.77	3.00	19.98	17.43	10.20	0.19	0.14	8.21	0.40	96.32	50.7
		17	36.90	3.00	19.99	17.39	10.00	0.19	0.18	8.30	0.42	96.37	50.3
		18	36.81	2.98	19.87	17.60	9.92	0.20	0.17	8.31	0.39	96.21	49.8
20	Gar	core — 19	40.96	0.13	21.19	29.90	4.52	1.31	1.10	0.04	0.02	99.17	20.5
		20	41.58	0.09	21.79	30.93	3.51	0.72	1.08	0.05	0.01	99.76	16.5
		21	41.40	0.04	21.55	30.71	3.30	1.11	1.16	0.04	0.01	99.32	15.6
		22	41.99	0.12	21.88	30.42	2.90	1.00	0.90	0.05	0.02	99.28	14.0
		rim — 23	40.83	0.10	20.90	30.30	1.51	3.92	1.64	0.03	0.01	99.24	7.2
		24	39.91	0.11	20.98	32.65	2.20	2.53	1.46	0.03	0.01	99.88	10.1
		25	39.50	0.10	19.45	33.70	1.61	3.61	1.67	0.04	—	99.68	7.1

First continuation of Tab. 1

1	2	3	4	5	6	7	8	9	10	11	12	13	14
	Bi	contact with Gar — 26	37.00	2.45	20.01	18.22	10.93	0.41	0.20	7.49	0.25	97.06	48.7
		27	36.79	2.99	20.48	17.51	9.25	0.39	0.20	8.49	0.30	96.40	47.8
		28	37.15	1.80	20.67	18.00	9.60	0.40	0.20	8.38	0.26	96.46	48.1
	Crd	rim — 29	45.76	0.05	34.86	8.00	7.69	0.20	0.51	0.02	0.01	96.75	62.6
		30	44.93	0.04	35.38	8.10	8.09	0.19	0.56	0.03	0.02	97.34	63.4
		31	43.32	0.04	34.80	9.02	8.38	0.18	0.49	0.03	0.01	96.27	61.8
		32	45.09	0.05	34.92	8.50	7.69	0.21	0.44	0.02	—	96.92	61.2
		33	44.83	0.03	35.20	8.39	7.40	0.19	0.55	0.04	0.03	96.66	60.4
16-4	Gar	core — 34	38.79	0.14	19.88	33.00	5.41	0.90	2.01	0.03	0.01	99.87	21.0
		35	39.81	0.13	21.00	32.16	4.00	0.92	1.91	0.01	—	99.94	20.8
		36	39.90	0.13	20.80	32.49	3.70	1.62	1.91	0.03	0.01	99.59	16.7
		37	39.95	0.09	20.99	31.40	3.20	1.81	1.87	0.03	0.01	99.30	14.6
		rim — 38	41.50	0.06	21.45	30.93	1.90	2.10	1.67	0.04	0.02	99.67	10.0
	Bi	contact with Gar — 40	36.69	1.98	20.80	18.39	10.01	0.19	0.36	8.38	0.35	97.15	40.9
		41	35.92	2.59	19.74	18.03	10.45	0.22	0.41	8.51	0.34	97.11	51.0
		42	35.46	2.98	20.06	18.01	11.32	0.21	0.38	8.40	0.34	96.76	48.0
		43	36.20	3.00	20.41	17.87	11.19	0.18	0.40	8.19	0.29	97.73	52.5
	Crd	44	44.86	0.02	35.57	8.00	8.29	0.35	—	0.02	—	97.11	65.0
		45	44.98	0.02	35.38	8.70	7.56	0.40	—	0.02	0.02	97.08	59.6
		46	45.13	0.05	34.34	8.69	7.64	0.38	—	0.01	0.02	96.26	60.1
24-4	Gar	core — 47	38.70	—	21.35	30.35	5.17	2.26	1.92	0.03	—	99.78	22.0
		rim — 48	38.24	0.02	21.73	33.24	3.68	2.38	1.99	0.02	—	101.30	16.0
		core — 49	37.63	—	21.81	33.25	4.33	2.35	1.63	—	0.01	101.00	18.3
		50	37.49	0.01	21.75	33.70	3.75	2.32	1.70	—	—	100.80	15.6
		rim — 51	37.44	0.02	21.15	34.44	3.14	2.81	1.47	—	—	100.48	13.0
	Gar	core — 52	36.02	—	19.38	36.73	4.88	1.08	2.12	—	—	100.21	19.0
		53	36.20	0.01	19.19	34.79	4.24	1.02	1.61	0.01	0.01	100.07	17.4
		54	37.04	0.02	19.71	35.63	4.67	0.90	1.83	—	—	99.80	18.6
		rim — 55	36.81	0.01	19.49	37.05	2.75	1.78	1.73	0.01	0.02	99.64	10.0
		rim — 56	36.70	0.05	19.90	37.47	3.06	1.19	1.99	0.04	0.03	100.43	12.0

Second continuation of Tab. 1

1	2	3	4	5	6	7	8	9	10	11	12	13	14
24-4	Gar	core — 57	36.90	0.09	20.20	34.89	4.10	1.08	1.84	0.05	0.01	99.16	16.9
		58	36.20	0.08	20.00	35.54	4.52	1.20	1.96	0.06	—	99.56	18.0
		rim — 59	36.70	0.09	20.45	35.36	3.96	1.49	1.85	0.05	0.01	100.37	16.2
		rim — 60	36.40	0.03	20.39	35.77	3.01	1.63	1.79	0.04	0.02	99.08	16.0
	Bi	61	35.66	1.96	17.49	16.21	11.24	0.06	0.03	7.96	0.42	91.23	45.0
		62	35.47	2.03	16.79	18.03	10.80	—	0.05	7.47	0.45	91.41	48.0

*) $X_{Mg} = Mg\ (Mg + Fe + Mn)$ %;

Explanations:

T °C — by Gar—Bi thermometer: Gar1—Bi18 = 680; Gar2—Bi18 = 675; Gar3—Bi18 = 612; Gar4—Bi18 = 582; Gar5—Bi18 = = 597; Gar6—Bi16 = 472; Gar7—Bi16 = 500; Gar19—Bi27 = 686; Gar25—Bi26 = 474; Gar34—Bi42 = 656; Gar39—Bi40 = 502; Gar47—Bi62 = 665; Gar48—Bi61 = 565; Gar49—Bi62 = 616; Gar51—Bi61 = 531; Gar52—Bi62 = 630; Gar55—Bi61 = 478; Gar58—Bi62 = 614; by Gar—Crd thermometer: Gar1—Crd12 = 745; Gar2—Crd12 = 750; Gar3—Crd12 = 664; Gar4—Crd12 = 611; Gar5—Crd12 = 629; Gar6—Crd15 = 448; Gar7—Crd15 = 504; Gar19—Crd33 = = 740; Gar24—Crd29 = 525; Gar23—Crd30 = 456; Gar34—Crd45 = 755; Gar38—Crd44 = 496

P — Pa 10^8 . n — Gar1—Crd12 = 6.1; Gar2—Crd12 = 6.4; Gar3—Crd12 = 4.65; Gar4—Crd12 = 3.7; Gar5—Crd12 = 3.95; Gar6—Crd15 = 0.6; Gar—Cor15 = 1.4; Gar19—Crd33 = 6.4; Gar24—Crd29 = 1.96; Gar23—Crd30 = 0.6; Gar38—Crd44 = 1.84; Gar34—Crd45 = 6.8.

that of the edge of porphyroblast zonal garnet. Their Mg-value is low ($9 \div 13$ %) and the content of Mn is within $1.6 \div 3.4$ %. This probably means that the formation of the garnet fine grains and porphyroblastic garnet edge parts took place simultaneously in the regressive metamorphism stage. Cordierite is fresh or pinitized with garnet and biotite inclusions. Not infrequently along cordierite, garnet and sillimanite (or fibrolite) are developed.

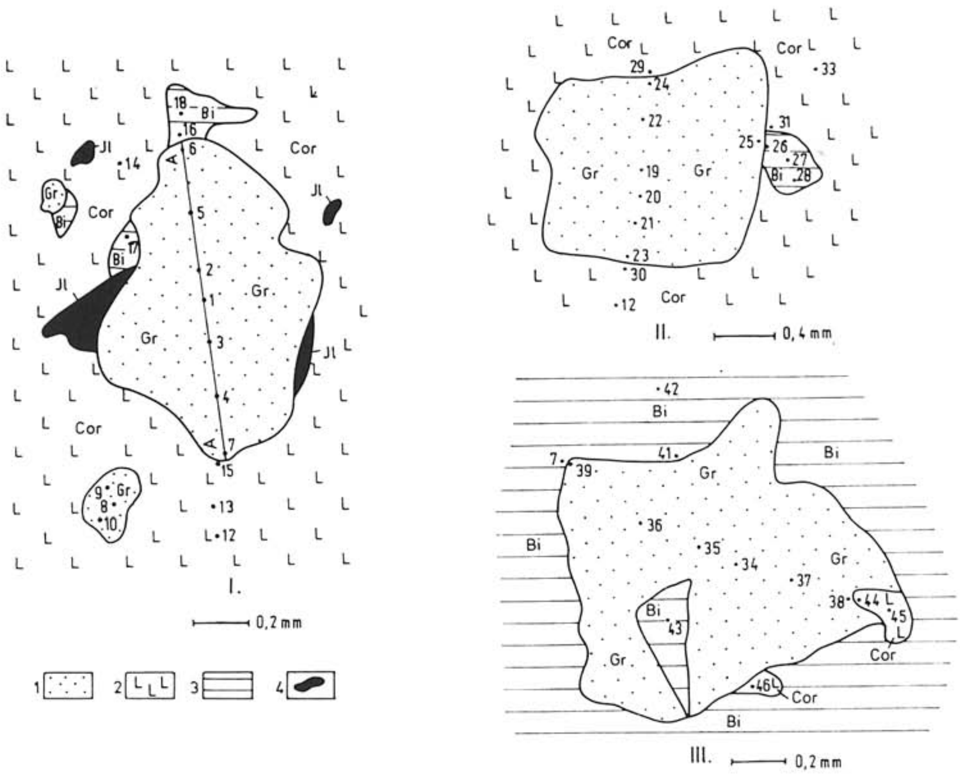

Fig. 1. Sketching of thin section areas for samples 20—4(I), 20(II). and 16—4(III). Figures designate the points at which microprobing was carried out (see Tab. 1). The A—A line is a microprobe profile (see Fig. 2).

Explanations: 1 — garnet; 2 — cordierite; 3 — biotite; 4 — illmenite.

The cordierite composition varies in a relatively narrow range (the Mg-value is 60—65 %, Tab. 1). At the contact with garnet the Mg-value in it is somewhat higher than that in the rock matrix. Biotite is fresh, no chemical zoning in its scales is observed. The Mg-value of biotite is within 45—52 % (Tab. 1), and the content of TiO_2 varies from 1.8 to 3.0 %. The highest P-T parameters are found for the paragenesis $Gar_{20-22} + Crd_{60-63} + Bt_{45-48} + Sil + Qtz$: $T\,°C = 665 \div 685$ °C by the Gar-Bt thermometer ($740 \div 750$ °C by the Gar—Crd thermo-

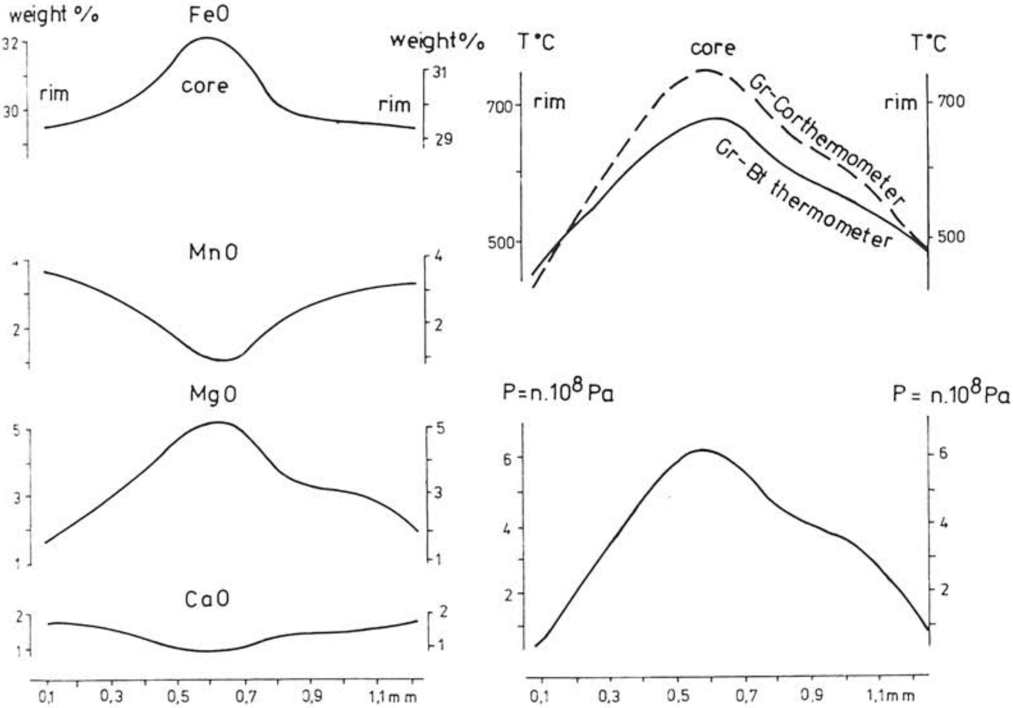

Fig. 2. The microprobe profile through the garnet grain of samples 20—4 by the A—A line (see Fig. 1).

meter)[3] and $P = 6.0 \div 6.8 \times 10^8$ Pa (Tab. 1), while the lowest values correspond to the paragenesis $Gar_{7-14} + Crd_{62-65} + Bt_{45-50} \pm Fib \pm And + Qtz$: $T = 450 \div 530$ °C (the Gar-Bt and Gar-Crd thermotmeters readigs show good similarity). The graphite geothermometer readings for these high-temperature paragenesis of the Buulgen series show lower temperatures ($360 \div 670$ °C) than those of the Gar-Crd and Gar-Bt thermometers, though the graphite thermometer reflects the conditions of the highest temperatures reached by a concrete rock, and the parameter value of an elementary cell C remains constant after the temperature decrease during the metamorphism process. In the Gar-Crd-Bt-Sil association staurolite is replaced by cordierite and hercynite or sillimanite and hercynite, and rarely by andalusite and hercynite. Staurolite is often surrounded tightly by hercynite. They belong among reserved relics and are not balanced paragenesis of the rock.

Thus, in the Buulgen series metamorphites with mineral equilibrium of Gar-Crd-Bt-Sil, regressive metamorphism is well manifested which is expressed by chemical zoning of garnet and to a lesser degree, in cordierite and biotite.

[3] The readings of the garnet-cordierite thermometer are inconsistent with those of the garnet-biotite thermometer, especially in the central part of the grain. The former geothermometer gives too overestimated values of temperature.

The earlier progressive reactions (St $\longrightarrow$ Sil + Her, St + Qtz $\longrightarrow$ Crd + Gar + + Sil $\pm$ Her + H_2O) are eliminated at the retrograde stage of metamorphism and are not seen in the chemical zoning of minerals. It is found that the earlier stage of the Gar-Crd-Bt-Sil paragenesis formation in the Buulgen series was finished at $T = 630 \div 680$ °C and $P = 6 \div 6.8 \times 10^8$ Pa. Then a new stage of metamorphism began at $T = 630$ °C and finished at very low parameters ($T = 450 \div 530$ °C and $P = 0.6 \div 2 \times 10^8$ Pa).

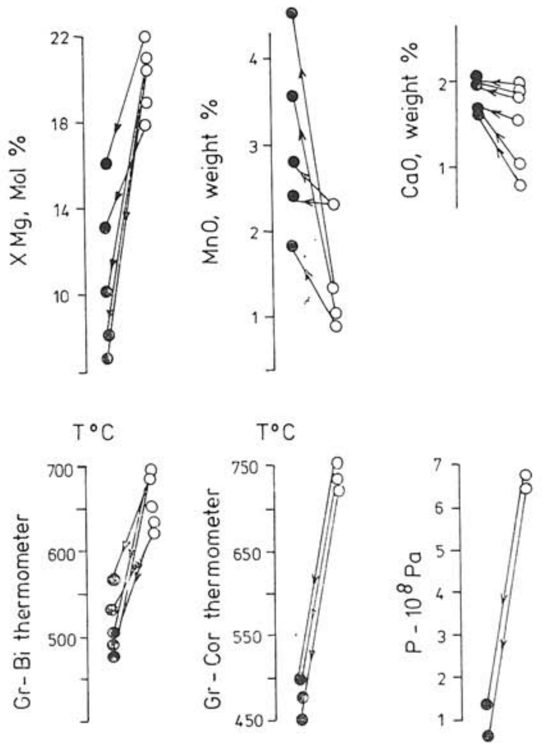

Fig. 3. Regressive zoning of garnets in the Buulgen series metamorphites. 1 — central and 2 — peripheral parts of the garnet grains. The diagrams are plotted according to the data of Tab. 1.

Regional metamorphism of the Lashtrac tectonic slice

The investigations conducted in recent years show that the Lashtrac suite is an allochthonic (Б а р а н о в — Г р е к о в, 1982; Ш е н г е л и а et al., 1984). The slice is mainly represented by metapelites: amphibolic and quartzite-like schists and marbles are of subordinate importance. In the suite equilibrated mineral associations of the garnet and staurolite zones are developed which occur practically only with regional metamorphism of kyanite-sillimanite type.

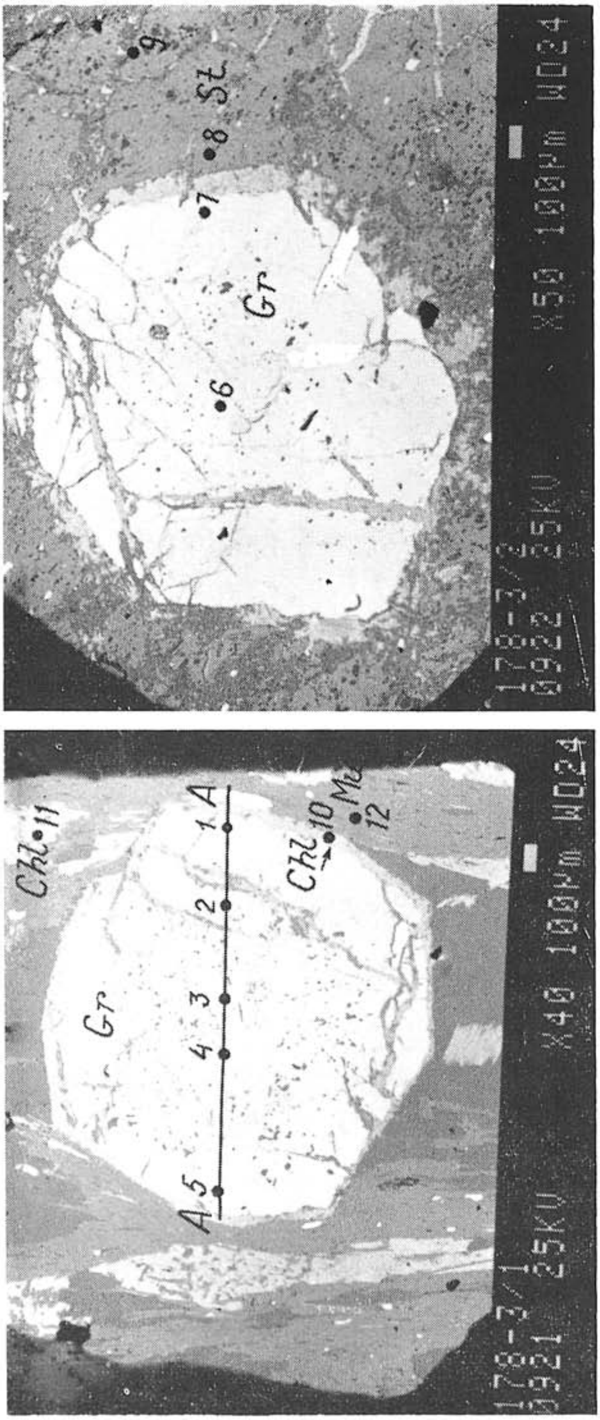

Fig. 4. Thin section areas for samples 178—3. Figures designate the points at which microprobing was carried out (Tab. 2, Fig. 5.).

The upper boundary of the garnet zone is defined simultaneously by the first occurrence of staurolite in the metapelites saturated with K_2O. In the staurolite zone three temperature subfacies can be distinguished (Ш е н г е л и а — К е ц х о в е л и, 1982)[4]: staurolite-chloritoid, staurolite-chlorite, and kyanite-biotite-staurolite subfacies. The high-temperature boundary of the staurolite-chlorite subfacies is determined by disappearance of chloritoid. The staurolite-chloritoid subfacies differs from the previous one not only in the absence of chloritoid but also in an increase of limiting Mg-value in chlorite, garnet, and staurolite. The low-temperature boundary of the kyanite-biotite-staurolite subfacies is determined by disappearance of chlorite. The Mg-value in garnet and ferruginity of staurolite in the subfacies increase.

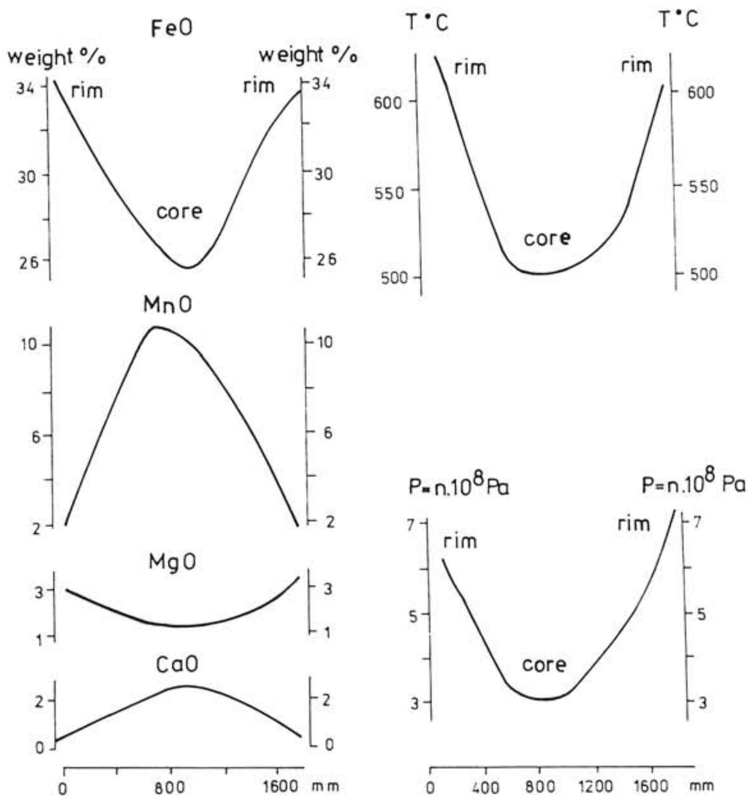

Fig. 5. The microprobe profile through the garnet grain of sample 178—3 by the A—A line (see Fig. 4).

[4]) Facial division of metamorphites is performed according to Korikovski (К о р и к о в с к и й, 1979).

Garnets in the metapelites of the Lashtrac slice are porphyroblastic (0.2 ÷ ÷ 2mm), fresh or intensively chloritized and sericitized. Disintegration of a large garnet porphyroblast into small grains is observed. In the garnet porphyroblast of the staurolite-chlorite and kyanite-biotite-staurolite subfacies progressive zoning is clearly seen. The Mg-value in the garnet core varies from 4.6 to 10 %, while in the direction of the edges it increases gradually up to 16 % (Figs. 4, 5, 6, Tab. 2). The FeO content from the centre to the periphery of the grains grows considerably. A sharp decrease of the MnO content is found in the peripheral parts of garnet (from 10 ÷ 11.5 to 0.7 ÷ 2.0 %); the CaO content also decreases. The staurolite of these rocks is porphyroblastic (1 ÷ ÷ 3 mm), fresh or sericitized, muscovitized and chloritized with a great amount of quartz and graphite inclusions; it often contains garnet grains. The chemical

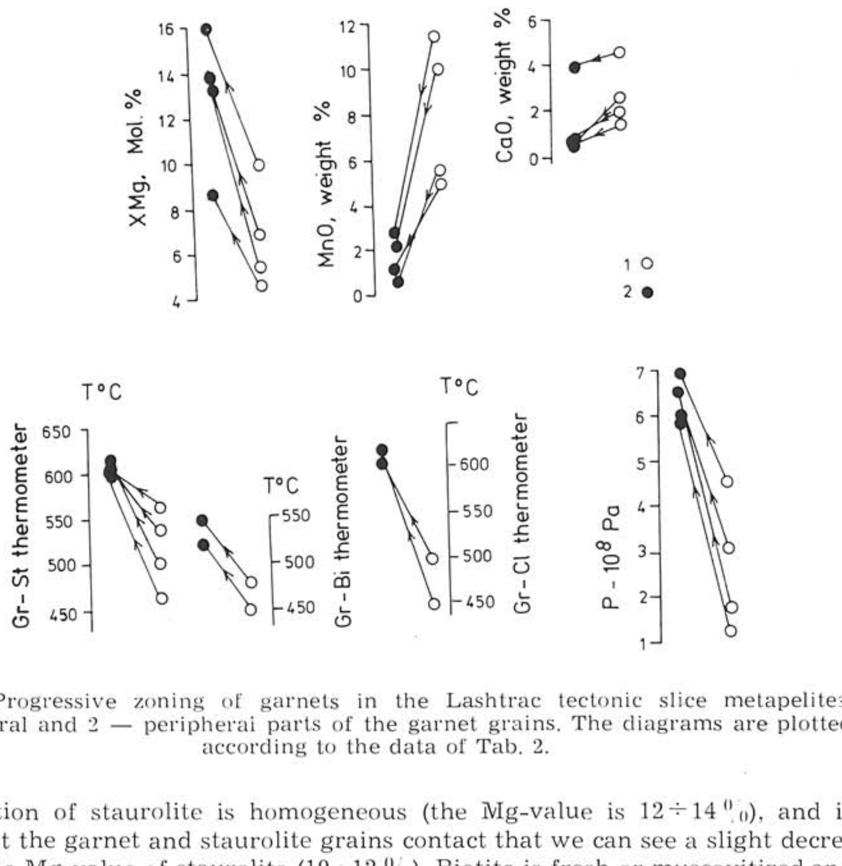

Fig. 6. Progressive zoning of garnets in the Lashtrac tectonic slice metapelites. 1 — central and 2 — peripherai parts of the garnet grains. The diagrams are plotted according to the data of Tab. 2.

composition of staurolite is homogeneous (the Mg-value is 12 ÷ 14 %), and it is only at the garnet and staurolite grains contact that we can see a slight decrease of the Mg-value of staurolite (10 ÷ 12 %). Biotite is fresh or muscovitized and chloritized. Newly formed flakes of biotite over chlorite are observed. No chemical zoning its flakes is revealed. The Mg-value in the chlorite of the Lashtrac suite metapelites varies within 40 ÷ 46 %. Chlorite has very weak zoning. As a rule, the lowest Mg-value (40 ÷ 42 %) of chlorite is at the contact of its flakes with garnet (37 ÷ 42). In the chlorite inclusions in muscovite, staurolite

Table 2

Electron microprobe analyses of the garnets and associated minerals from metamorphites of Lashtrac tectonic slice

Sample No.	Mineral	Analysis No.	SiO_2	TiO_2	Al_2O_3	FeO	MgO	MnO	CaO	K_2O	Na_2O	Total	X_{Mg}*)
1	2	3	4	5	6	7	8	9	10	11	12	13	14
178-3	Gar	core — 1	37.96	0.06	21.14	25.72	1.37	10.15	2.51	—	0.08	99.01	7.0
		2	38.09	0.09	20.69	26.64	1.46	10.84	2.18	—	0.09	100.08	7.0
		3	38.48	0.05	21.48	29.63	1.99	6.28	1.89	—	0.03	100.37	8.0
		rim — 4	38.64	0.08	21.74	32.85	3.14	2.27	0.48	—	0.07	99.27	14.0
		5	38.55	0.05	21.35	33.99	3.09	2.46	0.59	0.01	—	100.09	13.0
	Gar	core — 6	37.88	0.05	21.38	27.02	1.33	11.51	1.99	—	0.03	101.19	5.6
		rim — 7	38.35	0.02	21.03	31.84	3.11	2.53	0.69	—	0.02	97.59	14.0
	St	8	24.72	0.05	53.48	11.74	0.94	0.27	0.01	—	0.04	96.70	12.0
		9	29.52	0.69	53.85	11.77	1.01	0.23	0.03	—	0.05	97.15	13.0
	Chl	10	23.48	0.04	22.00	24.95	9.44	0.34	0.09	—	0.13	80.47	40.0
		11	28.63	0.69	20.49	25.86	10.19	0.12	—	0.54	0.01	86.53	41.0
	Ms	12	47.29	0.32	37.76	0.67	0.39	—	—	6.46	1.92	94.81	
33-3	Gar	core — 13	36.27	0.05	20.72	34.61	1.05	4.14	1.29	—	0.13	98.26	4.6
		14	36.82	0.02	20.12	34.96	1.51	4.05	0.94	—	0.01	98.43	6.6
		15	36.90	0.07	20.27	34.05	1.96	3.71	1.51	—	0.03	98.50	8.6
		16	37.21	0.07	20.90	34.97	1.15	3.72	1.56	—	—	99.58	4.8
		rim — 17	37.36	0.03	20.39	35.85	2.14	2.69	0.82	—	—	99.28	8.9
	St	core — 18	29.66	0.38	53.68	12.11	0.76	0.27	0.01	0.01	0.05	96.97	11.0
		contact with Gar — 19	29.21	0.55	54.28	12.78	0.76	0.21	—	—	0.02	97.81	10.0
	Bi	20	36.91	1.75	19.78	19.73	9.21	0.05	0.41	7.22	0.52	95.58	45.0

First continuation of Tab. 2

1	2	3	4	5	6	7	8	9	10	11	12	13	14
114-3	Gar	core — 21	38.24	0.09	21.52	29.06	2.21	5.53	4.28	—	—	100.93	10.0
		22	38.12	0.10	21.31	29.33	2.15	5.70	4.56	—	0.03	101.30	9.6
		23	38.01	0.11	21.11	26.74	1.67	7.87	4.41	—	—	99.92	8.6
		24	39.21	0.02	20.03	30.03	2.69	3.48	4.30	—	—	99.76	12.6
		rim — 25	38.40	0.06	21.69	31.42	3.54	0.71	4.02	—	0.01	99.85	16.0
	Chl	in Gar 26	22.04	0.04	18.31	24.37	9.91	0.33	0.03	0.02	0.04	75.09	42.0
		in Bi 27	26.80	0.93	18.92	23.62	10.84	0.32	—	3.77	0.05	85.25	45.0
		28	27.09	0.43	21.50	25.37	11.94	0.31	0.06	0.95	0.12	87.77	46.0
		29	25.44	0.06	21.92	26.04	12.38	0.40	0.01	0.02	0.03	86.30	46.0
		in St 30	29.07	1.14	19.66	23.76	10.46	0.15	0.04	4.27	0.05	88.60	44.0
		31	22.26	0.04	23.19	25.13	11.08	0.44	0.02	0.01	0.02	82.19	44.0
	St	contact with Gar — 32	29.37	0.54	54.69	11.77	1.09	0.41	—	0.01	0.03	97.91	14.0
		core — 33	28.58	0.50	54.51	12.15	1.09	0.49	—	0.03	0.03	97.36	13.0
	Ms	in Bi 34	40.34	0.50	32.12	1.96	0.96	—	—	8.71	1.07	85.39	
		35	46.30	0.27	34.90	0.88	0.80	—	—	8.24	1.10	92.49	
		in St 36	41.70	0.46	30.58	1.25	0.60	0.03	0.02	8.47	0.15	83.26	

*) X_{Mg} = Mg : (Mg + Fe + Mn) %;

Explanations:

T °C — by Gar—St thermometer: Gar4—St8 = 600; Gar2—St9=521; Gar1—St9 = 503; Gar3—St9 = 503; Gar5—St8 = 619; Gar17—St19 = 611; Gar13—St18 = 462; Gar25—St32 = 605; Gar23—St33 = 543; by Gar—Bi thermometer: Gar17—Bi20 = 527; Gar13—Bi19 = 455; by Gar—Chl thermometer: Gar4—Chl10 = 630; Gar5—Chl10 = 620; Gar1—Chl11 = 450; Gar23—Chl29 = 500; Gar25—Chl26 = 615.

P—Pa $10^8 . n$ — Gar4—St8 = 6.7; Gar2—St9 = 4.9; Gar1 —St9 = 3.2; Gar3—St9 = 3.2; Gar5—St8 = 6.1; Gar17—St19 = 6.1; Gar13—St18 = 1.4; Gar25—St32 = 6.9; Gar23—St33 = 4.73.

and biotite or at the contacts with these minerals an increase of the chlorite Mg-value ($41 \div 46$ %) is observed.

Large flakes of the muscovite balanced with ferro-magnesian minerals of the rock (garnet, staurolite, biotite, muscovite) are poorer in fengite ($11 \div 25$ %) and richer in paragonite ($20 \div 30$ %) molecules than secondary muscovites (with $29 \div 43$ % fengite and $3 \div 17$ paragonite molecules) which replace biotite, staurolite, and garnet.

The highest values of T and P were obtained by pairing the peripheral chemical compositions of garnet and staurolite grains and garnet and biotite grains (Tab. 2). The garnet-staurolite thermometer shows higher temperatures than the garnet-biotite one. Apparently high temperature metamorphism of the Lashtrac slice rocks will be completed at $T = 600 \div 620$ °C (under the conditions of the kyanite-biotite-staurolite subfacies) and $P = 6 \div 7 \times 10^8$Pa. The temperature values below $540 \div 550$ °C, corresponding to the temperature conditions of the garnet, staurolite, chloritoid, and staurolite-chlorite subfacies, and pressure of $1.4 \div 4.7 \times 10^8$Pa were obtained by pairing the chemical composition of the garnet cores and that of the intermediate zones with biotite or staurolite. All these temperature parameters are in good agreement with the graphite geothermometer data obtained by Shengelia — Ketskhoveli (Шенгелиа — Кецховели, 1982) for various metamorphic zones of the Lashtrac slice.

Thus, in the Lashtrac slice the earlier stage of metamorphism took place at low temperatures ($450 \div 465$ °C) and low pressure (2×10^8Pa) corresponding to the garnet zone conditions, while the later one was high-temperature and high-pressure; it took place in the kyanite-biotite-staurolite subfacies regime and completed at $T = 600 \div 620$ °C and $P = 6 \div 7 \times 10^8$Pa.

Conclusion

Up to the present on the basis of mineral associations character and microscope observations examples of progressive and regressive metamorphism were only considered in the metamorphites of the Buulgen series and Lashtrac slice, respectively; while examples of regressive regional metamorphism in the former and those of progressive metamorphism in the latter either were not noticed or described as rather limited ones. As a result of microprobe analysis of the chemical composition of garnet grains and co-existing ferro-magnesian minerals of these complexes, it turned out that the polymetamorphic processes often not reflected in the character of mineral associations are clearly fixed in the zoning of minerals of variable composition. The present paper allows us to reveal the P-T parameters of the progressive and regressive stages of metamorphism. It is established that the early stage of the Buulgen series formation took place at much higher temperature and pressure ($T = 630 \div 680$ C°; $P = 6 \div 6.8 \times 10^8$ Pa) than the later one ($T = 450 \div 530$ °C, $P = 0.6 \times 10^8$Pa), while in the Lashtrac slice low temperature and low-pressure metamorphism ($T = 450 \div 465$ °C, $P = 2 \times 10^8$Pa) changed into higher-temperature and higher-pressure ($T = 600 \div 620$ °C, $P = 6 \div 7 \times 10^8$Pa) regional metamorphism.

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