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THE ISOCHEMICAL NATURE OF THE CONTACT METAMORPHISM OF HIGH-ALUMINA METAPELITES IN THE AYAKHTA GRANITOID MASSIF, YENISEI RANGE

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Graphite-bearing ferriferous high-alumina hornfelses that occur near a granitoid intrusion were studied to elucidate the behavior of matter and thermal-metamorphism conditions under which mineral assemblages developed. Geothermobarometric study and analysis of mineral equilibria permitted estimation of the P-T-X_{H_2O}-conditions of contact metamorphism. It is concluded that the formation of chloritoid, which is not typical of thermal metamorphism, and the stability of rare parageneses (chloritoid + biotite, chloritoid + biotite + andalusite) in the aureoles are the result of a rare combination of elevated (for thermal metamorphism) pressures (≥3 kbar) and atypical rocks which are rich at once in aluminum and in iron. Special petrochemical studies have shown that minerals in metapelites underwent isochemical transformations and that their compositional evolution during contact metamorphism was governed by the initial PT-conditions.

Isochemical contact metamorphism, metapelites, chloritoid

INTRODUCTION

One of the problems of metamorphic petrology is the behavior of matter during mineral transformations in rocks. This problem is debated in terms of iso- and allochemical regional and contact metamorphism at different scales: from strata and layers to mineral grains, aggregates, and segregations. The contact metamorphism is usually associated with the isochemical behavior of matter near intrusive bodies of basic composition [1, 2]. When associated with acid intrusions, particularly at great depths, it is usually accompanied by global metasomatism [3]. With this taken into account, we have investigated the geochemical composition of rocks in a granite aureole to elucidate the behavior of matter and conditions of thermal metamorphism. The presence of chloritoid atypical of thermal metamorphism and the stability of rare parageneses (Cld + Bt, Cld + Bt + And) in the aureole increase our interest in these hornfelses. Only three findings of the paragenesis Cld + Bt + And in contact aureoles are known [4–6].

GEOLOGIC SETTING AND PARAGENESES OF THE MASSIF

As an object for study, we chose the contact aureole of the Ayakhta granitoid massif, lying in the Angara region of the Yenisei Range, on the middle reaches of the Bol'shoi Pit River. The Ayakhta Massif is a northwestward elongated oval-shaped body 12×18 km^2 in area. It is made up primarily of normal porphyraceous plagioclase-microcline granites of Late Riphean age (850±50 Ma) [7]. The massif has sharp and crossing contacts with the surrounding rocks. The country rocks of the massif are Middle Riphean deposits of the Central-Uderei Formation, which belongs to the Sukhoi Pit series [8]. In the area under study (the northern exocontact of granites), these are regionally metamorphosed pelites, which, judging from the stability of the paragenesis Ms + Chl + Ab + Qtz + Rt, may be related to the muscovite-chlorite subfacies of the greenschist facies. The aureole (Fig. 1) is recognized by the appearance of a new chloritoid-containing paragenesis in the country graphite-bearing phyllites. It is up to 1 km wide. From country rocks to intrusive

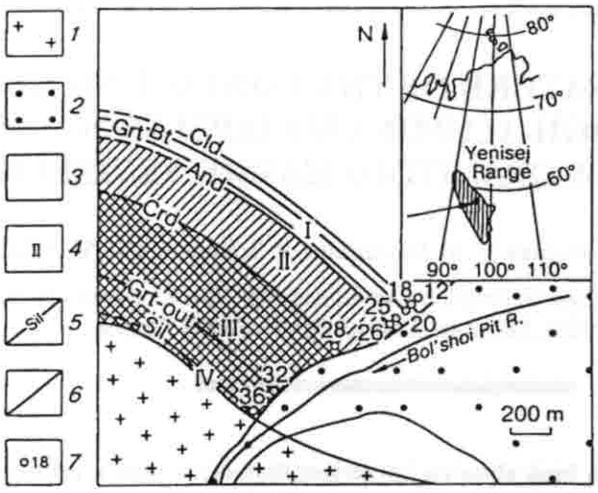

Fig. 1. Fragment of the northern exocontact of the Ayakhta granite massif. ***1*** **– granites;** ***2*** **– alluvium;** ***3*** **– country rocks;** ***4*** **– aureole zones: I – outer, II – middle, III – intermediate, and IV – inner;** ***5*** **– isograds of contact metamorphism, Grt-out – isograd of garnet disappearance from the aureole;** ***6*** **– geologic boundaries;** ***7*** **– numbers of sampling localities.**

contact, the degree of metamorphism increases within the aureole, and the following sequence of parageneses occurs (the name and apparent thickness of the zone are placed in parentheses):

1) Cld + Bt + Ms + Chl + Pl + Qtz + Grt + Ilm ± Rt (I – outer, 140 m);
2) And + Bt + Grt + Ms + Chl + Pl + Qtz + Ilm ± Cld (II – middle, 30 m);
3) Crd + And + Bt + Ms + Pl + Qtz + Ilm ± Chl ± Grt (III – intermediate, 550 m);
4) Sil + Kfs + Crd + Bt + Pl + Qtz + Ilm ± Ms ± And (IV – inner, 10 m).

Symbols for rock-forming mineral follow [9]: Ms – muscovite, Chl – chlorite, Bt – biotite, Pl – plagioclase, Ab – albite, An – anorthite, Cld – chloritoid, And – andalusite, Grt – garnet, Alm – almandine, Sps – spessartine, Grs – grossular, Prp – pyrope, Crd – cordierite, Sil – sillimanite, Kfs – K-feldspar, Qtz – quartz, Rt – rutile, and Ilm – ilmenite; ± – the mineral is locally missing from the zone.

PETROGRAPHIC AND CHEMICAL COMPOSITIONS OF MINERALS

Zone I. Parageneses in the outer zone are separated by the isograds (appearance) of chloritoid from the outer side of the zone and by those of andalusite, from its inner side. Here rocks preserve almost all features of the host phyllites (schistosity and lamination, clastic grains), differing only in containing chloritoid and biotite. Chloritoid occurs as idiomorphic, polysynthetically twinned porphyroblasts and prismatic crystals up to 1.5 mm in size, oriented at an angle to the lamination and schistosity of the country rocks. Biotite is present as small flakes up to 0.2 mm in size and glomeroblasts in the fine-grained groundmass, which is a recrystallized Ms-Chl-Qtz-Pl aggregate with admixtures of ore minerals. Near the isograd of andalusite, rare small isometric garnet grains up to 0.5 mm in size appear. The structure of metapelites is nonuniformly fine-layered and schistose; the texture of the groundmass is microlepidoblastic.

Zone II. Parageneses in the middle zone are separated by the isograd of cordierite from the inner side of the zone. Here poikiloblastic andalusite crystals up to 2 mm in size appear, which have an irregular, mainly oval, shape. They overlap the primary schistosity of the country rocks. The rock groundmass consists of chaotically oriented Bt-Ms-Chl flakes. Toward the contact, the number (up to 30 vol.%) and size (up to 5 mm) of porphyroblasts gradually increase, and the rocks become more saturated with andalusite "nodes". The hornfelsed schists have a mottled structure, and the groundmass has poikiloblastic, porphyroblastic, and lepidoblastic textures.

Zone III. A typical feature of the rocks in the intermediate zone is the absence of relics of their primary rocks and drastic predominance of cordierite in them. Typical cordierite-bearing hornfelses are dense rocks with massive structure and medium- or fine-grained granoblastic texture. Cordierite crystals up to 1.5 mm in

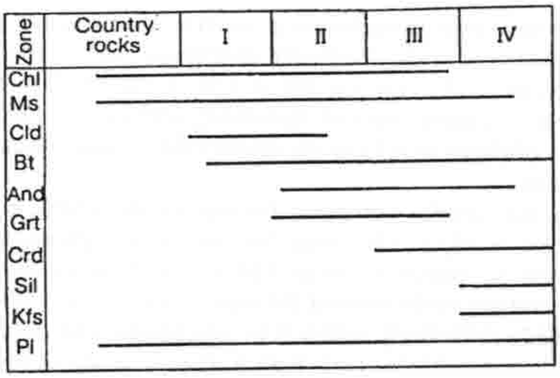

Fig. 2. Distribution of minerals in the contact aureole.

size are often intimately intergrown with idiomorphic crystals of andalusite and are surrounded by chaotically oriented biotite crystals.

Zone IV. In the narrow inner zone, prismatic crystals of sillimanite occur mainly in cordierite grains. Andalusite has both idiomorphic crystals without dissolution traces and skeleton crystals of irregular shape in association with K-feldspar and biotite. The structure and texture of hornfelses here are similar to those of the rocks in the intermediate zone.

Figure 2 shows distribution of major minerals from country rocks toward the intrusive contact. The chemical composition of mineral phases (Table 1) was established by E. N. Nigmatullina (UIGGM) on X-ray Camebax-Micro. Below we consider variations in the composition of major rock-forming minerals throughout the aureole.

Table 1

Compositional Parameters of Minerals from Hornfelses and Host Schists

Sample no.	Ms			Pl			Bt		Crd		
	X_K	X_{Na}	X_{Al}^{VI}	X_K	X_{Ca}	X_{Na}	X_{Fe}	X_{Al}^{VI}	X_{Fe}	X_{Mg}	X_{Mn}
12	0.869	0.129	0.915	0.005	0.010	0.985	–	–	–	–	–
18	0.804	0.194	0.957	0.004	0.073	0.923	–	–	–	–	–
20	0.804	0.194	0.959	0.005	0.096	0.899	0.693	0.113	–	–	–
25	0.825	0.175	0.952	0.005	0.125	0.860	–	–	–	–	–
26	0.839	0.161	0.934	0.006	0.139	0.855	0.661	0.109	–	–	–
28	0.864	0.136	0.955	0.009	0.182	0.809	0.721	0.119	0.589	0.390	0.021
32	0.893	0.104	0.949	0.010	0.303	0.687	0.740	0.127	0.594	0.386	0.393
36	0.912	0.086	0.954	0.009	0.403	0.588	–	–	–	–	–

Sample no.	Grt (rim)			Chl			Cld		
	X_{Fe}	X_{Mg}	X_{Mn}	X_{Fe}	X_{Mg}	X_{Al}^{VI}	X_{Fe}	X_{Mg}	X_{Al}^{VI}
12	–	–	–	0.789	0.208	0.255	–	–	–
18	–	–	–	–	–	–	–	–	–
20	–	–	–	–	–	–	0.863	0.094	0.490
26	0.647	0.286	0.033	–	–	–	–	–	–
28	0.691	0.238	0.047	–	–	–	–	–	–
32	0.708	0.184	0.050	–	–	–	–	–	–

Note. X_K = K/(K + Ca + Na), X_{Na} = Na/(K + Ca + Na), X_{Ca} = Ca/(K + Ca + Na), X_{Al}^{VI} = Al^{VI}/(Fe + Mg + Mn + Ti + Al^{VI}), X_{Fe} = Fe/T, X_{Mg} = Mg/T, X_{Mn} = Mn/T, where T = Fe + Mg + Mn + Ca (in formula units).

Chlorite, along with muscovite, is the major rock-forming mineral in regionally metamorphic country rocks. On the cordierite isograd its content in rock drastically decreases, and in the intermediate zone it completely disappears, probably, as a result of the reaction Ms + Chl + Grt + Qtz → Crd + Bt + H_2O. The Al/(Al + Mg + Fe) ratio of chlorite is almost constant (0.4–0.42), and its f = Fe/(Fe + Mg) decreases toward the contact from 0.79 in the host phyllites to 0.73 in the intermediate zone. According to classification in [10], chlorite belongs to Fe-clinochlores.

Muscovite is present in all zones of the aureole, except for the inner zone, where it disappears as a result of the reaction Ms + Qtz = Kfs + Sil + H_2O. The mole fraction of the phengite component, (Mg + Fe)/(Mg + Fe + Al^{VI}), varies from 0.08 in country rocks to 0.04 in hornfelsed schists. The Na/(Na + K) ratio varies regularly: It increases from country rocks toward the outer zone (0.13–0.19) and decreases in the middle, intermediate, and inner zones (0.16–0.14–0.09), which is in agreement with data on muscovite-plagioclase equilibria in metapelites from Northwestern Maine [11]. With further increase in temperature, the Na/(Na + K) ratio is reduced as a result of the endothermic reaction Ms_{Na} + Qtz = $Ms_{K\text{-}Na}$ + And + Pl + H_2O.

Chloritoid is a typical mineral of the outer zone, where it forms by the reaction Ms + Chl → Cld + Qtz + H_2O, and is absent from the middle zone. It has f = (0.90–0.91).

Biotite forms in the outer zone after chloritoid according to the reaction Ms + Chl + Ilm → Cld + Bt + Qtz + H_2O and is present in rocks as far as the inner zone. With increasing degree of biotite metamorphism, the f value of the mineral grows from 0.66 to 0.75 and TiO_2 content increases from 1.53 to 2.37 wt.% in the inner zone. The stability of the rare paragenesis Cld + Bt depends mainly on the bulk chemical composition of the country rocks. It was established [12] that this paragenesis exists when the total f value of the country rocks is higher than 0.60, which corresponds to the chemical compositions of hornfelses of the Ayakhta aureole.

Garnet is the only zonal mineral of the aureole, which forms by the reactions Ms + Chl + Qtz → Grt + Bt + H_2O or Chl + Cld + Qtz → Grt + Bt + H_2O. It has f = 0.93–0.95 and the following compositions of the core and rim: $X_{Sps}(0.53) > X_{Alm}(0.38) > X_{Grs}(0.08) > X_{Prp}(0.02)$ and $X_{Alm}(0.71) > X_{Sps}(0.18) > X_{Prp}(0.05) > X_{Grs}(0.05)$, respectively, which corresponds to progressive zoning.

Polymorphs Al_2SiO_5 are identical in composition. **Andalusite** forms in the middle zone according to the reactions Chl + Ms → Bt + And + Qtz + H_2O or Cld + Chl + Ms → Bt + And + H_2O and is present as far as the inner zone, where it occurs together with sillimanite and K-feldspar.

Cordierite is a typical mineral of the intermediate and inner zones. It is produced by the reaction Ms + Chl + Qtz → Crd + Bt + H_2O and has constant f = 0.61.

Plagioclase is present in all parageneses of the aureole. Toward the intrusion, its composition varies from almost pure albites in the country rocks to andesines in the narrow inner zone (Table 1).

Ore phases are Ti-bearing minerals – rutile and ilmenite. Their compositions coincide with their stoichiometric formulas, although ilmenite has somewhat elevated contents of MnO (up to 1.62 wt.%).

THERMODYNAMIC CONDITIONS OF CONTACT METAMORPHISM

Pressure. Using various methods, we estimated pressure in the Ayakhta massif and in the thermal aureole. Datsenko [7] estimated the relative depths of the basement of the Ayakhta massif. On the ternary Ab–Kfs–Qtz diagram, the normative compositions of granitoids intersect the cotectic line at $P_{H_2O} = 3-4$ kbar near the triple point [13]. At lower pressures, the intersection points shift to albite-poor compositions [14]. These estimates are in agreement with pressures in garnet-bearing hornfelses (P = 3.2±0.3 kbar) determined by geobarometers of four modifications (Table 2). The intersection of the experimentally studied curve of the reaction Ms + Qtz = Kfs + Sil + H_2O [17] with the And-Sil equilibrium line [18] (Fig. 3) confirms the pressure values estimated by granitoids and metapelite equilibria. The pressures estimated in other aureoles with stable rare parageneses (Cld + Bt, Cld + Bt + And) agree with the data obtained for hornfelses of the Ayakhta massif [4, 19].

Temperature. Table 2 presents the PT-conditions of contact metamorphism estimated by eight geothermobarometers. The temperature of the regional greenschist metamorphism, estimated by two thermometers, is 400 °C. The temperature of the initial contact metamorphism on the chloritoid isograd is 430 °C, which is close to the kinetic threshold of contact metamorphism under mesoabyssal conditions. The average temperature of metamorphism on the biotite isograd is 450 °C, which is in agreement with the temperature of the first appearance of biotite in paragenesis with chloritoid for other hornfelses [25]. The average temperatures on the garnet, andalusite, and cordierite isograds are 480, 500, and 560 °C, respectively, which agrees, within the accuracy of the geothermometer [27], with petrogenetic data [18], experimental data

Table 2

PT-Conditions of Contact Metamorphism Estimated by Various Geothermobarometers

Sample no.	*T*, °C							*P*, kbar				
	1	2	3	4	5	6	Average	7	8	9	10	Average
12	400	400	–	–	–	–	400	–	–	–	–	–
18	–	430	–	–	–	–	430	–	–	–	–	–
20	–	448	452	–	–	–	450	–	–	–	–	–
25	–	480	–	–	–	–	480	–	–	–	–	–
26	–	490	–	510	500	–	500	2.9	3.1	–	–	–
28	–	553	–	542	578	560	560	3.2	3.1	2.9	–	3.2
32	–	613	–	–	632	620	620	3.5	3.5	–	3.1	–
36	–	640	–	–	–	–	640	–	–	–	–	–

Note. Geothermometers: 1 — Ms-Chl [20], 2 — Pl-Ms [21], 3 — Bt-Cld [22], 4 — Bt-Ms [23], 5 — Crd-Grt and Grt-Bt [22], 6 — Crd-Grt and Grt-Bt [24]. Geobarometers: 7 — Grt-Bt-Ms-Pl [15] with modification [31]; 8–10 — Grt-Bt-Ms-Pl, Grt-Bt-Pl, and Grt-Ms-Pl [16].

at $P = 3.2$ kbar (Fig. 3), and estimated temperature on the cordierite isograd for graphite-bearing metapelites of the Ballachulish aureole. The average temperature on the isograd (disappearance) of garnet is 620 °C, and that on the isograd (appearance) of sillimanite is 640 °C.

Fluid composition. Analysis of mineral equilibria involving a gas phase permits estimation of the partial pressures of volatiles in metamorphic fluid. In studying the composition of metamorphic fluid, we restricted our calculation only to the mole fractions of water in the fluid phase, because at certain *P* and *T*, the quantitative ratios of the components of C-O-H-fluid can be obtained only at fixed oxygen fugacity.

To calculate H_2O fugacity (f_{H_2O}) in metamorphic fluid, we used mineral equilibria on the isograds of biotite (sample 20), garnet (sample 25), andalusite (sample 26), cordierite (sample 28), and sillimanite (sample 36) and the estimated *T* and *P* values of metamorphism (Tables 1 and 2). The mole fractions of H_2O (X_{H_2O}) in fluid were calculated by the model of a subregular solution (nonideal mixing of H_2O and CO_2 in the fluid phase) according to the formula $X_{H_2O} = a_{H_2O}/\exp[X^2_{CO_2}(W_{H_2O} + 2X_{H_2O}(W_{CO_2} - W_{H_2O}))]$, with $X_{H_2O} + X_{CO_2} = 1$ and the Morgulus parameters borrowed from [28]. Thermodynamic data for the final components of phases involved in reactions were taken from [29], and the formulas for mineral activities were

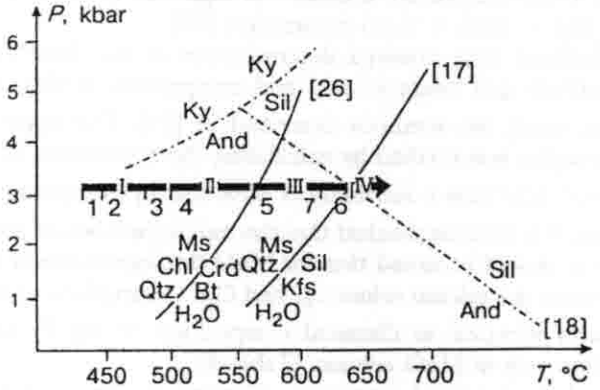

Fig. 3. The *PT*-trajectory of evolution of parageneses in the contact aureole of the Ayakhta massif and its correlation with experimental [17, 26] and calculated [18] mineral equilibria. Position of the triple point is as in [18]. Roman numerals on the solid isobaric *PT*-trajectory are zones of the aureole. Isograds of the first appearance of: 1 – Cld, 2 – Bt, 3 – Grt, 4 – And, 5 – Crd, 6 – Sil; 7 – isograd of Grt disappearance.

Table 3

Fugacity, Activity, and Mole Fraction of H_2O in Hornfelses at Fixed P and T

Sample no.	$f_{H_2O}^0$, bars	f_{H_2O}, bars	a_{H_2O}	X_{H_2O}
20	874.196	774.656	0.89	0.85
25	1028.15	867.329	0.84	0.77
26	1134.38	628.917	0.55	0.38
28	1462.26	900.046	0.62	0.46
32	1895.49	907.281	0.48	0.36

Note. Mineral equilibria: sample 20 — Ms + Chl = 2Cld + Bt + Qtz + $2H_2O$; sample 25 — 2Ms + 3Chl = 3Cld + 2Bt + 2Grt + $9H_2O$; sample 26 — 5Ms + 3Chl = 5Bt + 8And + Qtz + $12H_2O$; sample 28 — Ms + Chl + 2Qtz = Crd + Bt + $4H_2O$; sample 36 — Ms + Qtz = Sil + Kfs + H_2O. $f_{H_2O}^0$ and f_{H_2O} — fugacities of pure H_2O and H_2O in mixture with CO_2, respectively, at fixed T and P; a_{H_2O} — activity of H. ; X_{H_2O} — mole fraction of H_2O in fluid.

borrowed from the following references: chlorite – [29], biotite and muscovite – [30, 31], garnet – [31], cordierite – [32], chloritoid – [33], and K-feldspar [34].

Table 3 presents the results of calculations. One can see that the relative content of water (X_{H_2O}) in metamorphic fluid decreases toward the intrusive contact, which is in good agreement with data on the evolution of C-O-H-fluid in graphite-bearing metapelites [35].

The established correlation between the calculated T and X_{H_2O} values indicates that parageneses determine the composition of metamorphic fluid, which, in turn, confirms the concept of the buffering properties of parageneses with respect to volatiles.

Wang and Spear [12] carried out detailed petrological studies of the stability of the paragenesis chloritoid + biotite in regionally metamorphosed rocks of the Barrovian sequence. They established that it depends more on the bulk chemical composition of rocks ($f_{tot} > 0.60$) than on the PT-conditions of metamorphism. Our studies have shown that the presence of chloritoid atypical of thermal metamorphism and the stability of rare parageneses (chloritoid + biotite, chloritoid + biotite + andalusite) in contact aureoles are due to a rare combination of elevated pressures (≥3 kbar) and atypical rocks rich in both Al and Fe.

ISOCHEMICAL CHARACTER OF CONTACT METAMORPHISM

The bulk chemical composition of rock samples from the aureole was determined on a multichannel X-ray fluorescent spectrometer CPM-25 at the UIGGM, Novosibirsk. It is noteworthy that, according to chemical composition (Table 4), the rocks studied are classified as high-iron (Fe/(Fe + Mg + Mn) = 0.81) and high-alumina (Al/(Al + Fe + Mg + Mn) = 0.61) metapelites [36].

Statistical processing of geochemical data involved determination of the distribution of rock-forming components in the samples of hornfelses and country rocks and comparison of their average contents and dispersions σ^2 by F- and t-criteria, using the methods described in [37]. The hypotheses of the normal distribution of components in the samples was verified by calculating the coefficients of asymmetry (A_a) and excess (C_a) in the confidence interval $\pm 2\sigma$ with a reliability of 95% and by comparing selective and critical values for a given number of samples. We have established that the null hypothesis of normal distribution may be adopted for all components. But it should be noted that for MnO this hypothesis is arbitrary, because the C_a value for this component lies between the critical values C_{05} and C_{01}. Comparison of hornfelses and country rocks has shown that they are almost identical in chemical composition. Using F- and t-criteria, we have established that the above rocks differ only in MnO content (Table 4).

Contact metamorphism, related to granitoid intrusions at great depths, is usually accompanied by metasomatism, because deep-seated acid magmas are most enriched in water and transfer for short distances from the site of their origin (palingenesis) [1]. In this case, metasomatic replacement of exocontact rocks usually occurs in the inner parts of contact aureoles [3]. Taking this factor into account, we divided the hornfelsed rocks of the contact aureole into two groups: hornfelses of the inner and intermediate zones, occurring at ≤100 m from the intrusive contact, and those at a distance of >100 m from it. A comparison of

Table 4

Mean and Standard Deviations for Components, Estimates of the Normality of Their Distribution, and *F*- and *t*-Criteria

Parameter	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O
Hornfelses ($n = 18$)									
$\overline{X}$	60.81	1.11	20.16	10.34	0.37	2.08	0.53	1.25	3.01
σ	0.72	0.07	0.29	0.44	0.06	0.19	0.11	0.13	0.18
A_α	0.14	0.09	0.04	–0.09	–0.01	0.07	0.21	0.03	0.24
$\ae_\alpha$	–0.45	0.23	0.85	0.18	0.81	0.62	0.03	–0.63	0.18
Country rocks ($n = 17$)									
$\overline{X}$	60.87	1.06	20.19	10.53	0.25	2.13	0.60	1.28	2.93
σ	0.68	0.09	0.32	0.57	0.02	0.15	0.15	0.11	0.15
A_α	0.25	0.16	0.27	0.02	0.29	0.01	0.06	0.13	0.24
C_α	–0.12	–0.24	–0.58	0.65	0.90	0.68	–0.12	0.46	0.85
F_α	1.12	1.65	1.22	1.68	$\underline{9.00}$	1.60	1.86	1.40	1.44
t_α	0.16	1.21	0.18	0.73	$\underline{6.79}$	0.57	0.88	0.47	0.92

Note. Critical values of statistical parameters: $A_{\alpha 0.05} = 0.71$ and $A_{\alpha 0.01} = 1.06$; $C_{\alpha 0.05} = 0.89$ and $c_{\alpha 0.01} = 0.91$; $F_{0.05} = 2.28$ and $F_{0.01} = 3.25$; $t_{0.05} = 1.69$ and $t_{0.01} = 2.44$, n — number of samples. Underlined are the values greater than the critical values $t_{0.01}$ and $F_{0.01}$.

Table 5

Comparison of Country Rocks (CR), Remote (RH) and Near-Contact (NH) Hornfelses According to Various Criteria

Parameter, rock	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O
RH ($n = 14$)									
$\overline{X}$	60.85	1.10	20.16	10.30	0.37	2.07	0.54	1.25	3.01
σ	0.67	0.06	0.31	0.52	0.05	0.17	0.11	0.13	0.17
NH ($n = 4$)									
$\overline{X}$	60.68	1.09	20.15	10.37	0.38	2.09	0.55	1.29	2.97
σ	0.41	0.07	0.28	0.34	0.04	0.14	0.10	0.12	0.19
t_α									
CR-NH	0.72	0.81	0.25	0.80	$\underline{6.32}$	0.51	0.81	0.15	0.39
CR-RH	0.08	1.48	0.26	1.17	$\underline{8.44}$	1.03	1.28	0.68	1.37
RH-NH	0.62	0.26	0.06	0.32	0.42	0.24	0.17	0.58	0.38
F_α									
CR-NH	2.75	2.25	1.30	2.31	4	1.15	2.25	1.19	1.60
CR-RH	1.03	2.25	1.07	1.20	$\underline{6.25}$	1.28	1.86	1.40	1.28
RH-NH	2.67	1.36	1.23	2.34	1.56	1.47	1.21	1.17	1.25

Note. Critical values of statistical parameters: CR-NH — $F_{0.05} = 3.24$ and $F_{0.01} = 5.29$, $t_{0.05} = 1.73$ and $t_{0.01} = 2.54$; CR-RH — $F_{0.05} = 2.40$ and $F_{0.01} = 3.50$; $t_{0.05} = 1.70$ and $t_{0.01} = 2.46$; RH-NH — $F_{0.05} = 3.41$ and $F_{0.01} = 5.74$; $t_{0.05} = 1.75$ and $t_{0.01} = 2.58$. For mean and standard deviations for CR see Table 5.

the chemical compositions of hornfelses and country rocks shows that they differ only in MnO content (Table 5), which indicates the absence of the supply into the inner zones of the contact aureole during the formation of hornfels.

Thus, special petrochemical studies have shown the isochemical character of mineral transformations in metapelites. The evolution of the chemical composition of minerals during the contact metamorphism was determined by the *PT*-conditions of the initial country rocks.

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