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GENETIC MINERALOGY OF THE BURBANKITE GROUP

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The burbankite group consists of six mineral species with general formula $A_3B_3(\text{CO}_3)_5$ where $A = \text{Na} > \text{Ca}$, REE^{3+} , \square ; $B = \text{Sr}$, Ca , Ba , REE^{3+} , Na : burbankite, khanneshite, calcioburbankite, remondite-(Ce), remondite-(La), and petersenite-(Ce). The burbankite structural type (space group $P6_3mc$) is exclusively stable for chemical composition variations: khanneshite, calcioburbankite, remondite hexagonal analogue, and burbankite are isostructural and form the system of continuous solid solutions. All chemical compositions (94 analyses) of the burbankite group minerals can be described within the isomorphous system with end members: $(\text{Na}_2\text{Ca})\text{M}^{2+}_3(\text{CO}_3)_5$ and $\text{Na}_3(\text{REE}_2\text{Na})(\text{CO}_3)_5$, where $\text{M}^{2+} = \text{Sr}$, Ba , Ca . There are three genetic types of the burbankite mineralization: 1) in carbonatites where the minerals with the "most averaged" chemical composition and increased contents of Ba and Ca are formed; 2) in alkaline hydrothermalites where the range of chemical compositions of the burbankite-like phases is extremely wide; 3) in pectolite metasomatites where burbankite is strongly REE-depleted. In carbonatites the burbankite group minerals are early phases formed under high-temperature conditions, whereas in nepheline syenite massifs they are formed during hydrothermal stages under low temperatures, which is due to different regime of CO_2 . Under alkalinity decrease the burbankite group minerals are replaced by a whole series of secondary minerals, among which the alkali-free carbonates of REE, Sr, Ba, and Ca prevail.

5 tables, 3 figures, 50 references.

The burbankite group consists of six mineral species with general formula $A_3B_3(\text{CO}_3)_5$ where $A = \text{Na} > \text{Ca}$, REE^{3+} , \square ; $B = \text{Sr}$, Ca , Ba , REE^{3+} , Na : burbankite $(\text{Na}, \text{Ca}, \square)_3(\text{Sr}, \text{REE}, \text{Ba}, \text{Ca})_3(\text{CO}_3)_5$, khanneshite $(\text{Na}, \text{Ca})_3(\text{Ba}, \text{Sr}, \text{REE}, \text{Ca})_3(\text{CO}_3)_5$, calcioburbankite $(\text{Na}, \text{Ca}, \text{REE})_3(\text{Ca}, \text{REE}, \text{Sr})_3(\text{CO}_3)_5$, remondite-(Ce) $\text{Na}_3(\text{Ce}, \text{Ca}, \text{Na}, \text{Sr})_3(\text{CO}_3)_5$, remondite-(La) $\text{Na}_3(\text{La}, \text{Ce}, \text{Ca})_3(\text{CO}_3)_5$, and petersenite-(Ce) $(\text{Na}, \text{Ca})_4(\text{Ce}, \text{La}, \text{Sr})_2(\text{CO}_3)_5$. The first three minerals are hexagonal (space group $P6_3mc$), and others are pseudohexagonal monoclinic (sp. gr. $P2_1$, $\gamma = 119.8 - 120.5^\circ$).

In the crystal structures of hexagonal members of this group there are two independent cationic sites — A (Na и Ca) and B (REE, Sr, Ba и Ca), and three types of carbonate groups with different orientations. Ten-vertex B -polyhedra connected to CO_3 -groups by vertices form the layers of six-member rings parallel (001). Eight-vertex A -polyhedra form infinite zigzag columns where neighboring polyhedra are contacted by planes (Voronkov, Shumyatskaya, 1968; Effenberger *et al.*, 1985; Belovitskaya *et al.*, 2000, 2001, 2002). The crystal structure of remondite is quite similar to that of burbankite (Ginderow, 1989). In the crystal structure of petersenite atoms of Na occupy with order two B -polyhedra out of six, which results to doubling of a -parameter (Grice *et al.*, 1994).

Burbankite group carbonates form hexagonal prismatic crystals but occur more often as irregular grains and their aggregates. These minerals are transparent, without cleavage, have vitreous up to greasy luster and light

colours: yellow, green, pale-brown, pink. Frequently colorless and white, less often red, orange and gray varieties occur.

Burbankite is a widespread mineral, whereas other members of the group are rare. In one of types of «rare-earth carbonatites» (Khibiny, Vuoriyarvi, Gornoe Ozero *etc.*) burbankite and its alteration products will form huge accumulations, being the main potentially industrial component and easily enriched complex ore of REE, Sr, and Ba.

In spite of a semi-centennial history of research, significant number of the publications, and extensive geography of finds, generalizing papers on the burbankite group minerals are absent. We have attempted to systematize earlier published materials and having supplemented them with comparable volume of new data to show the connection of chemical composition and structural features of these minerals with conditions of their formation. We have studied 32 samples from eight alkaline complexes — Khibiny, Lovozero (Kola Peninsula), Vuoriyarvi (Northern Kareliya), Vishnevye Gory (Southern Urals), Gornoe Ozero, Murun (East Siberia), Mont Saint-Hilaire (Quebec, Canada), and Khanneshin (Afghanistan).

The cation composition of the minerals (Tables 1 – 3) was studied by electronmicroprobe method. All analyses including reference data were calculated on charge sum equal 10.00, i.e. equivalent $(\text{CO}_3)_5$. B -site was filled up to 3.00 atoms per formula unit (apfu) by atoms of Sr, Ba, REE, Th, K, in case of their deficiency

by atoms of Ca, and then atoms of Na was added. After that the rest of Na and Ca atoms was placed in A-site. If the A-cations sum appeared less 3.00, the missing value was attributed to vacancy according to the crystallochemical data (Effenberger *et al.*, 1985; Belovitskaya *et al.*, 2000). At calculation the atomic mass of Ce is conditionally taken for old analyses where the rare-earth elements were determined as a sum. The cation composition of the burbankite group minerals widely varies (Fig. 1, 2). In A-sites, sodium always prevails (1.3–3 *apfu*), but sometimes amounts of calcium is also essential (up to 1.25 *apfu*). The cation composition is more diverse in B-sites where atoms of Sr, Ba, Ce, La, and Ca can dominate.

We make the X-ray powder studies for 11 samples (Table 4) including five species with different chemical composition, which crystal structures was refined by Rietveld method: 1) REE-depleted burbankite (an. 92), its X-ray diffraction pattern contains distinct doublets; 2) burbankite with «typical» composition (an. 64) and nonsplit peaks on X-ray spectrum; 3) khanneshite (an. 21); 4) calcioburbankite (an. 12); 5) the mineral with chemical composition of remondite-(Ce) (an. 79), but according to its X-ray powder diagram identical to representatives of the burbankite structural type.

Burbankite group minerals form complex isomorphous system with end members: REE-free phases $(\text{Na}_2\text{Ca})\text{M}^{2+}_3(\text{CO}_3)_5$ where $\text{M}^{2+} = \text{Sr}, \text{Ba}, \text{Ca}$ and petersenite $\text{Na}_3(\text{REE}_2\text{Na})(\text{CO}_3)_5$, without divalent cations. All chemical compositions of the minerals are situated in interval between these two points forming extended field — Fig 1, and 2a, b. In spite of two structural transitions: from hexagonal members to monoclinic remondite and then to petersenite, essential mixable intermissions in this system aren't determined. These structural transitions are concerned to the second type, i.e. they are realized gradually, without break of chemical bonds.

Occurrences and formation conditions

Generalizing an available material, it was possible to distinguish three main genetic types of burbankite mineralization. Each of them is connected to alkaline rocks. The largest burbankite concentrations occur in carbonatites. This genetic type is studied better than others. In alkaline hydrothermalites the widest variations of chemical compositions and, accordingly, the greatest species variety are observed at relatively small amounts. We have distinguished the third genetic type, accumulations of

REE-depleted burbankite, connected to specific pectolite metasomatites of Khibiny and Murun massifs. In each case the minerals are characterized by individual features of cation ratios (Fig. 1). Burbankite from soda-bearing sedimentary Green River Formation (USA) is in association with the majority of the same minerals as in carbonatites and alkaline hydrothermalites (Fitzpatrick, Pabst, 1977) and, probably, has low-temperature hydrothermal origin.

Occurrences of the burbankite group minerals with known chemical composition are briefly described in Table 5. They are grouped for genetic types. Localities connected to rocks enclosing carbonatites and also with products of hydrothermal activity in carbonatites are conditionally referred to carbonatite type. The finds made in late parageneses of pegmatite from nepheline syenite complex are referred to alkaline hydrothermalites.

Thus, burbankite group minerals are formed in alkali-carbonate systems connected to geological objects of different types. The temperature range these minerals crystallize in is extremely wide.

A number of massifs contain carbonatites where the burbankite group minerals are the main concentrators of strontium, barium, and rare-earth elements. Here burbankite and its analogs crystallize on early carbonatite formation stages under high temperatures (not below 500°C). That confirmed by the signs of joint growth with essential minerals of carbonatite rocks, the presence of the burbankite group minerals in primary inclusions, and the replacement of these minerals by products of later hydrothermal stages.

In alkaline hydrothermalites the burbankite group minerals are the late formations forming at essentially lower temperatures. Their crystals in cavities are frequently observed together with zeolites and hydrous soda minerals. Formation temperatures for these associations can be estimated as 100–250°C.

The difference in time of crystallization are first of all connected to different regime of carbon dioxide. The excess of CO_2 is present in carbonatite formation systems, and already at early stages burbankite and its analogs appear under sufficient activity of sodium. In nepheline syenite massifs, with which the burbankite-bearing hydrothermalites are in general connected, increase of potential of CO_2 and, accordingly, the development of carbonate mineralization take place mainly on a final stage of evolution

Typochemism and structural typomorphism

The wide variations of cation composition make the burbankite group minerals very in-

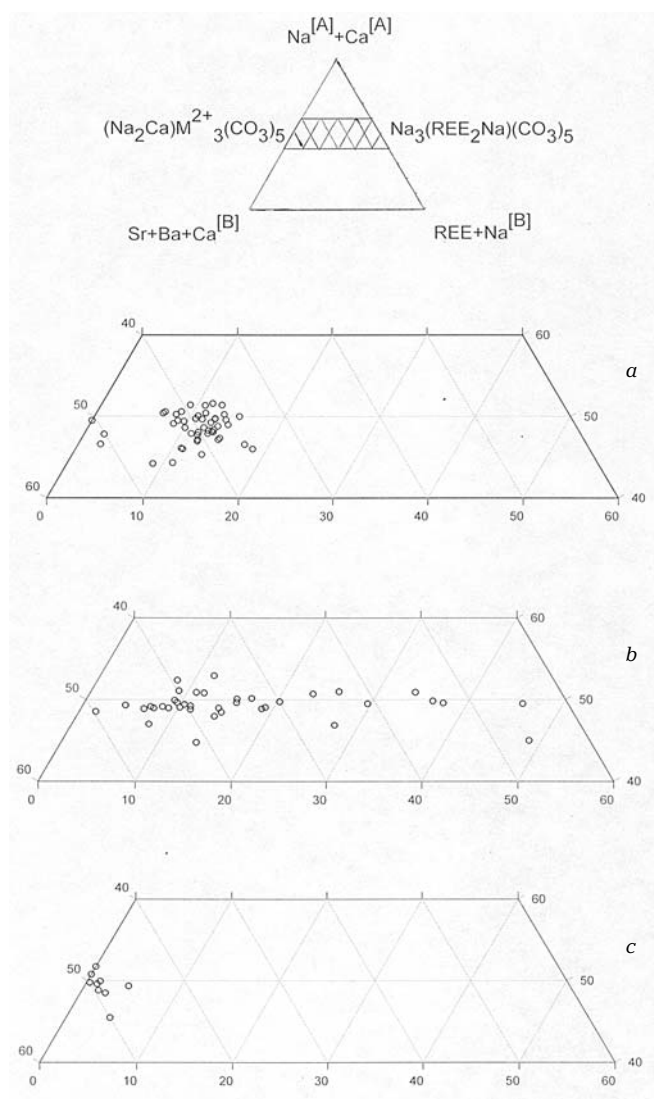


FIG. 1. Cation ratios in the burbankite group minerals: a — from carbonatites, b — from alkaline hydrothermalites, c — from pectolite metasomatites

formative in genetic relation.

In the system with end members $(\text{Na}_2\text{Ca})\text{M}^{2+}_3(\text{CO}_3)_5$ and $\text{Na}_3(\text{REE}_2\text{Na})(\text{CO}_3)_5$ (Fig. 1) samples from carbonatites occupy intermediate position making compact field. As a rule in the B-sites of these minerals atoms of Sr, rarely Ca and Ba prevail (Fig. 2a). Only in one sample from Vuoriayrvi domination of rare-earth elements is noted. The phases with «maximum averaged» chemical composition, often with comparable amounts of Sr (usually 0.7–1.5 apfu), Ba (on average 0.4–1.0 apfu), Ca (as a rule in B-site 0.3–1.0 apfu), and REE (usually 0.5–0.8 apfu), are typical for carbonatite complexes. Exactly in carbonatites the highest contents of barium for minerals of this group are fixed, and only here khan-

neshite is known (Khanneshin, Khibiny, Afrika-nda, Kovdor). Usually 0.3–0.7 apfu of calcium are present in A-sites (Table 1). «Averaged» chemical composition of these minerals from early carbonatite associations (Fig. 1) and high content of barium, the largest cation (Fig. 2a), is explained by high-temperature conditions of crystallization. High concentration of a certain cation as well as considerable depletion of it is not typical for the samples from carbonatites. The ratios of rare-earth elements in burbankite-like phases from carbonatites are sufficiently stable and in general typical for most other minerals from alkaline rocks: $\text{Ce} > \text{La} \gg \text{Nd}$. The increase of content of strontium from early generations to late ones is characteristic for the burbankite

Table 1. Chemical composition of burbankite group minerals from carbonatites (end)

Constituents	Burbankite						
	Afri- k anda	Kalkfeld	Shaxio- ngdong	Chipman Lake			
	An. 41	an. 42	an. 43	an. 44	an. 45	an. 46	an. 47
	wt %						
Na ₂ O	7.47	10.6	13.1	6.03	7.38	7.20	6.70
K ₂ O	-	-	-	-	-	-	-
CaO	8.24	3.6	5.5	14.52	21.09	15.01	13.53
SrO	16.82	25.6	26.7	29.49	29.12	30.44	28.63
BaO	20.17	5.5	5.2	4.88	4.06	1.85	3.37
ΣREE ₂ O ₃	n.d.	n.d.	n.d.	12.53	n.d.	n.d.	n.d.
Y ₂ O ₃	-	-	-	n.d.	0.47	0.71	0.45
La ₂ O ₃	6.10	7.0	6.2	-	0.76	0.54	4.34
Ce ₂ O ₃	5.92	9.0	8.8	-	1.20	0.77	5.80
Pr ₂ O ₃	0.93	-	-	-	0.18	0.15	0.60
Nd ₂ O ₃	0.70	1.5	2.1	-	0.21	0.26	1.64
Sm ₂ O ₃	-	-	-	-	0.15	0.07	0.00
(CO ₂)	n.d.	(29.8)	(33.3)	32.58	n.d.	n.d.	n.d.
Sum	66.35	92.6	100.9	100.03	65.06*	60.54*	65.19*
	Formula						
Na ^[A]	1.76	2.51	2.79	1.24	1.43	1.62	1.37
Ca ^[A]	0.82	0.35	0.26	1.14	1.22	1.13	1.02
Σ[A]	2.57	2.86	3.05	2.38	2.62	2.75	2.39
K ^[B]	-	-	-	-	-	-	-
Ca ^[B]	0.25	0.13	0.39	0.51	1.03	0.75	0.52
Sr ^[B]	1.18	1.82	1.70	1.81	1.68	2.05	1.75
Ba ^[B]	0.96	0.26	0.22	0.20	0.16	0.08	0.14
ΣM ²⁺ [B]	2.39	2.21	2.31	2.52	2.87	2.88	2.41
Y ^[B]	-	-	-	n.d.	0.03	0.04	0.02
La ^[B]	0.27	0.32	0.25	-	0.03	0.02	0.17
Ce ^[B]	0.26	0.40	0.36	-	0.04	0.04	0.22
Pr ^[B]	0.04	-	-	-	0.01	0.01	0.02
Nd ^[B]	0.03	0.07	0.08	-	0.01	0.01	0.16
Sm ^[B]	-	-	-	-	0.01	-	-
ΣREE ^[B]	0.61	0.79	0.69	0.48	0.13	0.12	0.59
Σ[B]	3.00	3.00	3.00	3.00	3.00	3.00	3.00
(CO ₃)	5.00	5.00	5.00	5.00	5.00	5.00	5.00

Note.

1, 2 — samples №№ 65111 and 65105 accordingly from collection of Fersman Mineralogical Museum RAS; 3, 4 (Borodin, Kapustin, 1962); 5–7, 10 — samples from V.V. Subbotin collection; 8, 9 (Subbotin *et al.*, 1999); 11 (Kukharensko *et al.*, 1965); 12, 13 (Subbotin *et al.*, 1999); 14 — sample № 65503 from collection of Fersman Mineralogical Museum RAS; 15 (Zdorik, 1966); 16 — sample from A.P. Khomyakov collection (Pekov *et al.*, 1998); 17, 18 — sample № 81605 from collection of Fersman Mineralogical Museum RAS (Pekov *et al.*, 1998); 19, 20 (Eremenko, Vel'ko, 1982); 21, 22 (Pekov *et al.*, 1998); 24 (Tikhonenkova, 1974); 25 (Tikhonenkova *et al.*, 1977); 26 (Mineralogy..., 1978); 27 (Dudkin *et al.*, 1981); 28 (Zaitsev *et al.*, 1990); 29, 30 (Zaitsev *et al.*, 1997); 31, 32 (Zaitsev *et al.*, 1998); 33 (Zhabin *et al.*, 1971); 34 (Pozharitskaya, Samoilov, 1972); 35, 36 (Ivanyuk *et al.*, 2002); 37–40 (Zaitsev, Chakhmouradian, 2002); 41 (Zaitsev, Chakhmouradian, 2002); 42, 43 (Buhn *et al.*, 1999); 44 (Shi Li, Tong Wang, 1993); 45–47 (Platt, Woolley, 1990); №№ 1, 2, 5–7, 10, 14, 23 — data of present research.

* — The sum of analysis also contains (wt %): 3 — 0.35 MgO, 1.05 Al₂O₃, 0.48 Fe₂O₃, 0.19 SiO₂, 0.97 H₂O; 4 — 0.10 Fe₂O₃, 0.06 SiO₂, 2.60 H₂O; 11 — 0.03 Al₂O₃, 0.22 Fe₂O₃, 0.10 SiO₂, 0.25 H₂O; 15 — 0.14 MgO, 0.41 Al₂O₃, 0.24 Fe₂O₃, 0.16 SiO₂, 0.023 H₂O, 0.03 F; 19 — 1.59 H₂O; 20 — 1.32 H₂O; 25 — 0.93 Fe₂O₃; 26 — 0.10 MgO, 0.20 Al₂O₃, 0.10 Fe₂O₃, 0.22 SiO₂, 1.37 H₂O; 28 — 0.02 MgO, 0.07 MnO, 0.44 FeO, 0.20 SiO₂, 0.85 H₂O, 0.04 F, 0.02 -O=F₂; 32 — 0.16 ThO₂, 0.20 Gd₂O₃ (0.01 apfu); 33 — 0.05 MnO, 0.37 Fe₂O₃, 1.76 H₂O, 0.20 F, 0.08 -O=F₂; 34 — 0.93 Al₂O₃, 0.23 Fe₂O₃, 1.81 H₂O; 36 — 0.12 TiO₂; 45 — 0.25 FeO, 0.15 MnO, 0.04 MgO; 46 — 0.53 FeO, 0.13 MnO, 2.88 MgO; 47 — 0.13 FeO. n.d. — constituent was not determined, dash — the amount of constituent is below detection limit. ** — The mineral was described as «burbankite», but according to chemical composition, corresponds to calcioburbankite.

group minerals from carbonatites: burbankite replaces khanneshite in Khibiny (Pekov *et al.*, 1998) and calcioburbankite in Vuoriayrvi (Subbotin *et al.*, 1999), the high-strontian burbankite was found in the late association in Kovdor (Ivanyuk *et al.*, 2002).

In alkaline hydrothermalites all this group members are known except khanneshite. Here the range of their chemical composition is extremely wide (Fig. 1): from strongly REE-depleted burbankite (an. 73) to petersenite. Essential predominance of strontium (usually 1.6–2.3 apfu) over other B-cations (Fig. 2b) is observed in burbankite from alkaline hydrothermalites almost of all geological objects. High content of barium in burbankite-like phases is not typical for this genetic type (rarely more than 0.6 apfu), which is explained by that with temperature decrease the tendency of very large Ba²⁺ to isolation intensifies, and it will form own phases practically without strontium: zeolites, BaTi-silicates, BaREE-fluorcarbonates, and others. Almost all finds of high-sodium members of the burbankite group are made in alkaline hydrothermalites. The maximum contents of sodium are reached here, which is a necessary condition for origin of remondite and petersenite. The specimens of the burbankite group in alkaline hydrothermalites are characterized by increased part of strontium and a little one of neodymium in spectrum of REE.

Burbankite from pectolite metasomatites approaches in its chemical composition to REE-free end member (Na₂Ca)M²⁺₃(CO₃)₅ (Fig. 1). It is strongly Sr-enriched (usually 2.1–2.5 apfu, Table 3). All samples from both Khibiny and Murun are characterized by predominance of lanthanum over cerium together with insignificant contents of praseodymium and neodymium.

The widest prevalence of burbankite forming very large accumulations among other members of the group is evidence of maximum stability of this structural type exactly under predominance of strontium in B-site. Also that can be confirmed by sharply Sr-enriched chemical compositions of burbankite from alkaline hydrothermalites. Here crystallization proceeds from water solutions under sufficiently low-temperature conditions, consequently, the fractionating of similar in properties chemical elements is accomplished by the best way, and affinity of different structural types to certain components is realized as much as possible. In high-alkaline hydrothermal systems the separation of strontium from more widespread calcium, which caused by the crystallochemical reasons, is clear demonstrated by stable paragenesis of high-strontian burbankite with shortite Na₂Ca₂(CO₃)₃ almost non-containing strontium.

Table 2. Chemical composition of burbankite group minerals from alkaline hydrothermalites (continuation)

Constituents	Burbankite	Remondite-(Ce)	Remondite-(La)		Petersenite-(Ce)	Burbankite	Calcioburbankite	Petersenite-(Ce)		
	Khibiny					Mont Saint-Hilaire				
	an. 68	an. 69	an. 70	an. 71	an. 72	an. 73	an. 74	an. 75	an. 76	an. 77
	wt %									
Na ₂ O	10.80	15.3	12.84	15.48	17.51	8.30	15.17	13.81	17.38	16.77
K ₂ O	-	-	1.54	0.58	-	-	-	-	-	-
CaO	4.74	4.9	2.33	5.13	5.52	12.03	11.81	12.48	1.32	5.07
SrO	22.98	7.8	14.66	2.93	4.10	32.35	7.65	7.90	1.70	2.37
BaO	14.45	3.1	6.34	0.18	0.42	11.02	0.46	6.00	0.32	0.54
ΣREE ₂ O ₃	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Y ₂ O ₃	0.36	-	-	-	0.04	-	-	-	-	-
La ₂ O ₃	5.61	11.3	18.01	19.75	11.97	-	9.30	12.51	14.49	12.14
Ce ₂ O ₃	5.31	17.8	12.22	16.67	17.80	2.12	14.38	10.89	23.66	21.29
Pr ₂ O ₃	0.24	1.4	-	0.99	1.54	-	1.26	-	2.00	2.10
Nd ₂ O ₃	0.71	3.7	0.86	2.27	5.20	0.13	3.76	0.74	5.82	5.04
Sm ₂ O ₃	-	0.22	-	0.37	0.39	-	0.48	-	0.60	0.66
ThO ₂	-	-	-	1.34	0.78	-	-	-	-	-
CO ₂	n.d.	(32.7)	n.d.	n.d.	n.d.	(33.17)	(35.13)	(34.98)	(32.92)	(34.07)
Total	65.20	98.22	68.80	65.69	65.27	99.30*	99.40	99.31	100.21	100.05
	Formula									
Na ^[A]	2.53	2.94	2.78	2.87	3.09	1.76	2.97	2.86	2.94	2.95
Ca ^[A]	0.46	-	0.07	-	-	1.07	-	0.10	-	-
Σ[A]	2.99	2.94	2.85	2.87	3.09	2.83	2.97	2.96	2.94	2.95
Na ^[B]	-	0.35	-	0.47	0.60	-	0.09	-	0.83	0.59
K ^[B]	-	-	0.23	0.08	-	-	-	-	-	-
Ca ^[B]	0.15	0.59	0.21	0.60	0.64	0.35	1.31	1.32	0.16	0.60
Sr ^[B]	1.61	0.51	0.97	0.19	0.26	2.07	0.46	0.49	0.11	0.15
Ba ^[B]	0.68	0.14	0.28	0.01	0.02	0.48	0.02	0.25	0.01	0.02
ΣM ²⁺ [B]	2.45	1.24	1.46	0.80	0.92	2.90	1.79	2.06	0.28	0.77
Y ^[B]	0.02	-	-	-	-	-	-	-	-	-
La ^[B]	0.25	0.47	0.76	0.80	0.48	-	0.36	0.49	0.59	0.49
Ce ^[B]	0.24	0.72	0.51	0.68	0.71	0.09	0.55	0.42	0.97	0.85
Pr ^[B]	0.01	0.06	-	0.04	0.06	-	0.05	-	0.08	0.08
Nd ^[B]	0.03	0.15	0.04	0.09	0.20	0.01	0.14	0.03	0.23	0.20
Sm ^[B]	-	0.01	-	0.01	0.01	-	0.02	-	0.02	0.02
ΣREE ^[B]	0.55	1.41	1.31	1.62	1.46	0.10	1.12	0.94	1.89	1.64
Th ^[B]	-	-	-	0.03	0.02	-	-	-	-	-
Σ ^[B]	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
(CO ₃)	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00

Table 2. Chemical composition of burbankite group minerals from alkaline hydrothermalites (continuation)

Constituents	Remondite-(Ce)		Burbankite				Remondite-(Ce)	
	Mont Saint-Hilaire		Rocky Boy		Ridge Moskal	Pokrovo-Kireevskoe		Ebounja
	an. 78	an. 79**	an. 80	an. 81	an. 82	an. 83	an. 84	
	wt %							
Na ₂ O	13.09	12.60	9.69	8.34	9.81	7.33	17.16	-
K ₂ O	0.22	0.24	0.15	-	2.35	-	-	-
CaO	1.68	3.89	13.46	11.47	6.76	6.62	10.54	-
SrO	1.67	14.63	19.42	25.08	18.45	30.87	3.98	-
BaO	0.50	0.85	13.56	11.47	9.97	4.51	-	-
ΣREE ₂ O ₃	n.d.	n.d.	9.48	n.d.	14.81	n.d.	n.d.	-
Y ₂ O ₃	-	-	n.d.	-	n.d.	-	0.24	-
La ₂ O ₃	11.69	16.13	-	3.37	-	10.00	11.60	-
Ce ₂ O ₃	25.50	17.27	-	5.39	-	7.74	14.99	-
Pr ₂ O ₃	2.72	0.96	-	0.46	-	0.36	1.49	-
Nd ₂ O ₃	9.00	2.57	-	1.26	-	0.24	3.34	-
Sm ₂ O ₃	1.13	0.33	-	0.14	-	0.08	0.50	-
ThO ₂	-	-	-	-	0.50	-	-	-
CO ₂	n.d.	n.d.	32.55	33.24	32.55	(32.26)	(35.24)	-
Sum	67.20	69.47	99.31*	100.68*	100.02*	100.09*	99.554*	-
	Formula							
Na ^[A]	2.42	2.61	2.06	1.77	2.23	1.62	3.11	-
Ca ^[A]	-	-	0.79	0.89	0.64	0.81	-	-
Σ[A]	2.42	2.61	2.85	2.66	2.87	2.43	3.11	-
Na ^[B]	0.50	0.05	-	-	-	-	0.35	-
K ^[B]	0.04	0.04	0.02	-	0.35	-	-	-
Ca ^[B]	0.21	0.46	0.79	0.46	0.20	0.01	1.17	-
Sr ^[B]	0.11	0.93	1.23	1.60	1.25	2.03	0.24	-
Ba ^[B]	0.02	0.04	0.58	0.49	0.46	0.20	-	-
ΣM ²⁺ [B]	0.34	1.43	2.60	2.55	1.91	2.24	1.41	-
Y ^[B]	-	-	n.d.	-	n.d.	-	0.01	-
La ^[B]	0.50	0.64	-	0.13	-	0.42	0.45	-
Ce ^[B]	1.08	0.69	-	0.22	-	0.32	0.57	-
Pr ^[B]	0.12	0.04	-	0.02	-	0.01	0.06	-
Nd ^[B]	0.37	0.10	-	0.05	-	0.01	0.12	-
Sm ^[B]	0.05	0.01	-	0.01	-	-	0.02	-
ΣREE ^[B]	2.12	1.48	0.38	0.45	0.64	0.76	1.23	-
Th ^[B]	-	-	-	-	0.10	-	-	-
Σ ^[B]	3.00	3.00	3.00	3.00	3.00	3.00	3.00	-
(CO ₃)	5.00	5.00	5.00	5.00	5.00	5.00	5.00	-

Note.

48 — sample from S.N. Nikandrov collection (Pekov *et al.*, 1996); 49 (Tikhonenkova, Kazakova, 1964); 50, 51 (Khomyakov, 1990); 52–55 — samples from A.P. Khomyakov collection (Pekov, 2001); 56 (Shlyukova *et al.*, 1972); 57 (Tikhonenkova *et al.*, 1977); 58 (Tikhonenkova *et al.*, 1977); 59 (Khomyakov, 1990); 60–63 (Yakovenchuk, 1995); 64 (Belovitskaya *et al.*, 2000); 68 — sample from A.P. Khomyakov collection; 69 (Khomyakov, 1990); 70 (Yakovenchuk *et al.*, 1999); 71 (Pekov *et al.*, 2000); 72 (Pekov *et al.*, 1998); 73 (Chen, Chao, 1974); 74, 75 (Van Velthuizen *et al.*, 1995); 76 (Grice *et al.*, 1994); 77 (Van Velthuizen *et al.*, 1995); 80 (Pecora, Kerr, 1953); 81 (Effenberger *et al.*, 1985); 82 (Efimov *et al.*, 1969); 83 (Litvin *et al.*, 1998); 84 (Cesbron *et al.*, 1988); 65–68, 78, 79 — data of present research. * — The sum of analysis also contains (wt %): 50 — 1.2 Gd₂O₃ (0.05 apfu), 0.5 Dy₂O₃ (0.02 apfu), 0.5 Er₂O₃ (0.02 apfu); 56 — 0.19 Fe₂O₃, 0.9 SiO₂; 73 — 0.08 Dy₂O₃, 0.10 Yb₂O₃; 79 — 0.14 MgO, 0.25 Al₂O₃, 0.03 Fe₂O₃, 0.16 SiO₂, 0.18 H₂O, 0.12 P₂O₅, 0.24 S, 0.12 -O=S; 81 — 0.41 Gd₂O₃ (0.02 apfu), 0.05 Tb₂O₃; 82 — 0.32 MgO, 0.37 Al₂O₃, 0.19 Fe₂O₃, 3.94 H₂O; 83 — 0.08 Gd₂O₃; 84 — 0.09 Eu₂O₃, 0.24 Gd₂O₃ (0.01 apfu), 0.07 Dy₂O₃, 0.01 Ho₂O₃, 0.03 Er₂O₃, 0.03 Yb₂O₃, 0.004 Lu₂O₃. n.d. — constituent was not determined, dash — the amount of constituent is below detection limit. ** — According to structural refinement by Rietveld method, this mineral is a hexagonal (sp. gr. P63mc) analogue of remondite (Gobetchiya *et al.*, 2001).

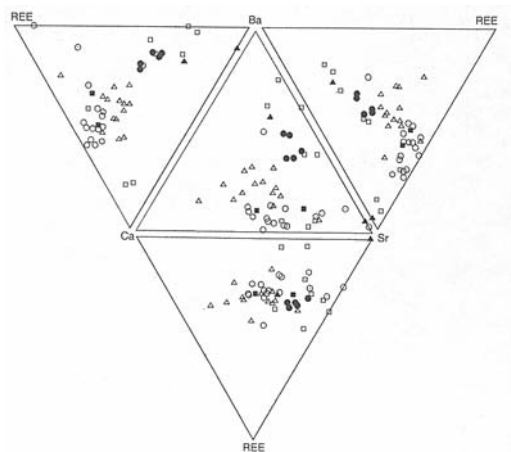


FIG. 2a. Ratios of Sr, Ca, Ba, and REE in B-site of the burbankite group minerals from carbonatites:

● — Afrikanda, ○ — Arbarastakh, △ — Vuoriyarvi, ■ — Gornoe Ozero, ⊙ — Kalkfeld, ▲ — Kovdor, △ — Srednyaya Zima, □ — Khaneshin, ○ — Khibiny, ⊠ — Chipman Lake, ⊕ — Shaxiongdong

Location of calcium in A-site, than in B-site is more typical for burbankite-like phases from low-temperature formations, i.e. isomorphism of calcium with sodium is preferable than with strontium. Probably, relative rarity of Ca-, Ba-, and REE-dominant members of the burbankite group is connected to their ability to crystallize only in strontium deficiency conditions, which is untypical for alkaline complexes as a whole.

The rare-earth elements in burbankite occupy ten-vertex B-polyhedra where the large ion Sr^{2+} with radius 1.32 Å (Shannon, Prewitt, 1969) predominates. As a rule the more widespread in nature ion Ce^{3+} (radius 1.26 Å) prevails in spectrum of REE of burbankite-like phases. However, La^{3+} (1.28 Å), largest ion of REE^{3+} , is closer in size to Sr^{2+} that is the reason of its presence in significant amount. The degree of fractionating of rare-earth elements increases with temperature lowering, which results in increase of lanthanum role that is turned out especially significant than more strontium is contained by the mineral. The ratios of lanthanides in burbankite of different genetic types from Khibiny massif are the evident example of that. High-strontian burbankite from relatively low-temperature differentiates (hydrothermalites of Mt. Kukisvumchorr and metasomatites of Mt. Ni'orkpahk) is also sharply enriched by La (up to 85% from sum of REE), whereas the high-temperature burbankite from carbonatites of Khibiny has «averaged» chemical composition which is typical for these minerals from other carbonatite objects: Ce — 45–50, La — 35–45, Nd — 5–10% from the sum of REE.

X-ray powder diffraction diagrams of hexagonal burbankite-like minerals are divided into two groups. The first group contains spectra of the

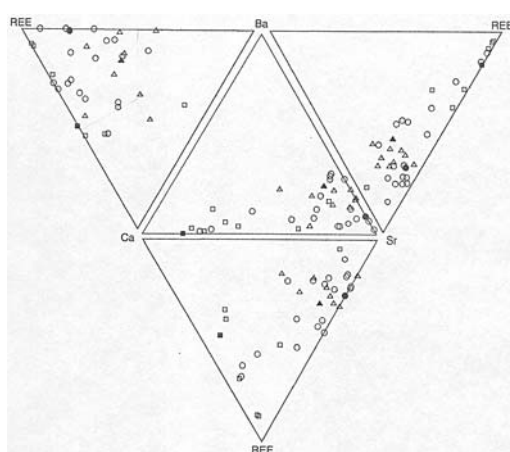


FIG. 2b. Ratios of Sr, Ca, Ba, and REE in B-site of the burbankite group minerals from alkaline hydrothermalites:

○ — Vishnevye Gory, ● — Pokrovo-Kireevskoe, △ — Lovozero, ▲ — Ridge Moska, — Rocky Boy, □ — Mont Saint-Hilaire, ○ — Khibiny, ■ — Ebounja

samples from carbonatites and hydrothermalites. The spectra of REE-depleted burbankite from pectolite metasomatites make the second group. The most of peaks on the latter are split (Fig. 3). This splitting is most strongly displayed on reflections in areas 2.74–2.77 Å (*hkl* 112, 301) and 2.62–2.65 Å (*hkl* 202, 220): burbankites from carbonatites and alkaline hydrothermalites give single peaks, while burbankite from pectolite metasomatites gives clear distinguished doublets (Fig. 3). All that together with stability of value of ratio $\text{Na}:\text{Ca} \approx 2:1$ in A-site of REE-depleted burbankite has caused the assumption about order of A-cations in this mineral. However, it isn't confirmed: all studied samples proved to be isostructural with sp. gr. $P6_3mc$ and disordered distribution of sodium and calcium in A-sites (Belovitskaya *et al.*, 2000, 2001, 2002; Gobetchiya *et al.*, 2001). The cause of reflection splitting is only ratio of unit cell parameters: $c/a = 0.621$ for REE-depleted burbankite and $c/a \approx 0.615$ for burbankite with «typical» composition (Table 4). The closing in values of interplaner distances in many pairs of reflections takes place with decrease of c/a . Thus, full coincidence for pairs (112)-(301) and (202)-(220) will occur at $c/a = 0.61237$.

We shall especially note the detection of earlier unknown hexagonal modification of remondite-(Ce) established in the sample from Mont Saint-Hilaire (Gobetchiya *et al.*, 2001).

Thus, the burbankite structural type is very stable. It is maintained in wide interval of cationic ratios: from REE-free end member $(\text{Na}_2\text{Ca})(\text{Sr},\text{Ca},\text{Ba})_3(\text{CO}_3)_5$ at least to chemical composition $\text{Na}_{2.6}(\text{REE}_{1.5}\text{Sr}_{0.9}\text{Ca}_{0.5}\text{Na}_{0.1})_{\Sigma 3.0}(\text{CO}_3)_5$ which hexagonal analog of remondite corresponds to. The representatives of this

Table 3. Chemical composition of burbankite from pectolite metasomatites and Green River Formation

Constituents	Pectolite metasomatites									Green River Formation
	Murun				Khibiny					
	an. 85	an. 86	an. 87	an. 88	an. 89	an. 90	an. 91	an. 92	an. 93	
wt %										
Na ₂ O	9.83	5.64	8.44	8.04	9.92	8.84	8.51	8.29	9.72	10.47
K ₂ O	-	-	1.06	0.82	-	-	-	-	-	-
CaO	12.30	10.27	12.04	13.59	11.22	7.85	10.04	10.32	8.59	8.00
SrO	42.18	32.00	34.60	33.10	37.88	26.10	36.28	36.94	34.00	15.61
BaO	2.72	13.38	1.79	1.83	10.21	21.05	9.91	6.61	6.83	5.73
Y ₂ O ₃	0.33	-	-	-	-	-	0.48	0.49	-	0.19
La ₂ O ₃	-	3.04	-	-	1.58	1.16	1.32	2.06	3.58	3.73
Ce ₂ O ₃	-	2.90	-	-	0.33	0.40	0.44	0.90	2.65	8.65
Pr ₂ O ₃	-	-	-	-	-	-	-	-	-	1.57
Nd ₂ O ₃	-	0.02	-	-	-	0.34	-	-	0.17	4.60
Sm ₂ O ₃	-	-	-	-	-	-	-	-	-	0.55
CO ₂	n.d.	31.08	30.86	29.19	n.d.	n.d.	n.d.	n.d.	n.d.	(29.73)
Sum	67.36	98.31	90.94*	93.71*	71.14	65.73	66.98	65.59	65.54	88.83
Formula										
Na ^[A]	1.96	1.26	1.92	1.82	1.98	2.07	1.82	1.78	2.11	2.50
Ca ^[A]	1.01	1.25	1.12	1.15	0.98	0.92	1.04	1.04	0.81	0.32
Σ[A]	2.97	2.50	3.04	2.97	2.96	2.99	2.86	2.82	2.92	2.82
K ^[B]	-	-	0.16	0.12	-	-	-	-	-	-
Ca ^[B]	0.35	0.02	0.40	0.55	0.26	0.09	0.15	0.19	0.22	0.75
Sr ^[B]	2.52	2.13	2.36	2.24	2.26	1.83	2.32	2.37	2.21	1.11
Ba ^[B]	0.11	0.60	0.08	0.08	0.41	1.00	0.43	0.29	0.30	0.28
ΣM ^[2+]	2.98	2.75	2.84	2.88	2.93	2.92	2.90	2.85	2.73	2.14
Y ^[B]	0.02	-	-	-	-	-	0.03	0.03	-	0.01
La ^[B]	-	0.13	-	-	0.06	0.05	0.05	0.08	0.15	0.17
Ce ^[B]	-	0.12	-	-	0.01	0.02	0.02	0.04	0.11	0.39
Pr ^[B]	-	-	-	-	-	-	-	-	-	0.07
Nd ^[B]	-	-	-	-	-	0.01	-	-	0.01	0.20
Sm ^[B]	-	-	-	-	-	-	-	-	-	0.02
ΣREE ^[B]	0.02	0.25	-	-	0.07	0.08	0.10	0.15	0.27	0.86
Σ[B]	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
(CO ₃)	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00

Note.

85 — sample № 82976 from collection of Fersman Mineralogical Museum RAS; 86-88 (Konev *et al.*, 1996); 92 (Belovitskaya *et al.*, 2000); 93 (Yakovenchuk *et al.*, 1999); 94 (Fitzpatrick, Pabst, 1977); 85, 89–91 — data of present research.* — The sum of analysis also contains (wt %): 87 — 0.01 MgO, 0.01 MnO, 0.05 TiO₂, 0.08 H₂O, 0.10 F; 88 — 0.04 MgO, 0.02 MnO, 0.08 TiO₂, 0.01 H₂O, 0.05 F.

Table 4. Symmetry and unit cell parameters of burbankite group minerals

	Sp. gr.	a, Å	b, Å	c, Å	γ, gradus	V, Å ³	c/a	Reference
REE-depleted burbankite								
an. 85	<i>P6₃mc</i>	10.525(1)	10.525(1)	6.492(1)	120	619.64(1)	0.6168	The authors' data
an. 92	<i>P6₃mc</i>	10.5263(1)	10.5263(1)	6.5392(1)	120	627.49(1)	0.6212	Belovitskaya <i>et al.</i> , 2000
Burbankite								
an. 2	<i>P6₃mc</i>	10.494(1)	10.494(1)	6.498(1)	120	622.82(1)	0.6192	The authors' data
an. 23	<i>P6₃mc</i>	10.458(1)	10.458(1)	6.381(3)	120	604(1)	0.6102	The authors' data
an. 64	<i>P6₃mc</i>	10.5313(1)	10.5313(1)	6.4829(1)	120	622.68(1)	0.6156	Belovitskaya <i>et al.</i> , 2000
an. 65	<i>P6₃mc</i>	10.516(2)	10.516(2)	6.482(4)	120	620(1)	0.6164	The authors' data
an. 66	<i>P6₃mc</i>	10.54(1)	10.54(1)	6.48(1)	120	623(1)	0.615	The authors' data
without chemical data	<i>P6₃mc</i>	10.52(4)	10.52(4)	6.51(2)	120	624(2)	0.619	Voronkov, Shumyats-kaya, 1968
an. 81	<i>P6₃mc</i>	10.512(2)	10.512(2)	6.492(2)	120	621.3	0.6176	Effenberg <i>et al.</i> , 1985
Calcioburbankite								
an. 12	<i>P6₃mc</i>	10.4974(1)	10.4974(1)	6.4309(1)	120	613.72(1)	0.6126	Belovitskaya <i>et al.</i> , 2001
Khanneshite								
an. 21	<i>P6₃mc</i>	10.5790(1)	10.5790(1)	6.5446(1)	120	634.31(1)	0.6186	Belovitskaya <i>et al.</i> , 2002
Hexagonal analogue of remondite								
an. 79	<i>P6₃mc</i>	10.4889(1)	10.4889(1)	6.3869(1)	120	608.53(6)	0.6089	Gobetchiya <i>et al.</i> , 2001
Remondite-(Ce)								
an. 84	<i>P2₁</i>	10.412(4)	10.414(4)	6.291(3)	119.80(5)	591.9	0.6042	Ginderow, 1989
Remondite-(La)								
an. 71	<i>P2₁</i>	10.49(1)	10.50(1)	6.417(4)	119.80(1)	613(1)	0.6117	Pekov <i>et al.</i> , 2000
Petersenite-(Ce)								
an. 76	<i>P2₁</i>	20.872(4)	10.601(2)	6.367(1)	120.50(1)*	1213.9(4)	0.6006**	Grice <i>et al.</i> , 1994

Note.

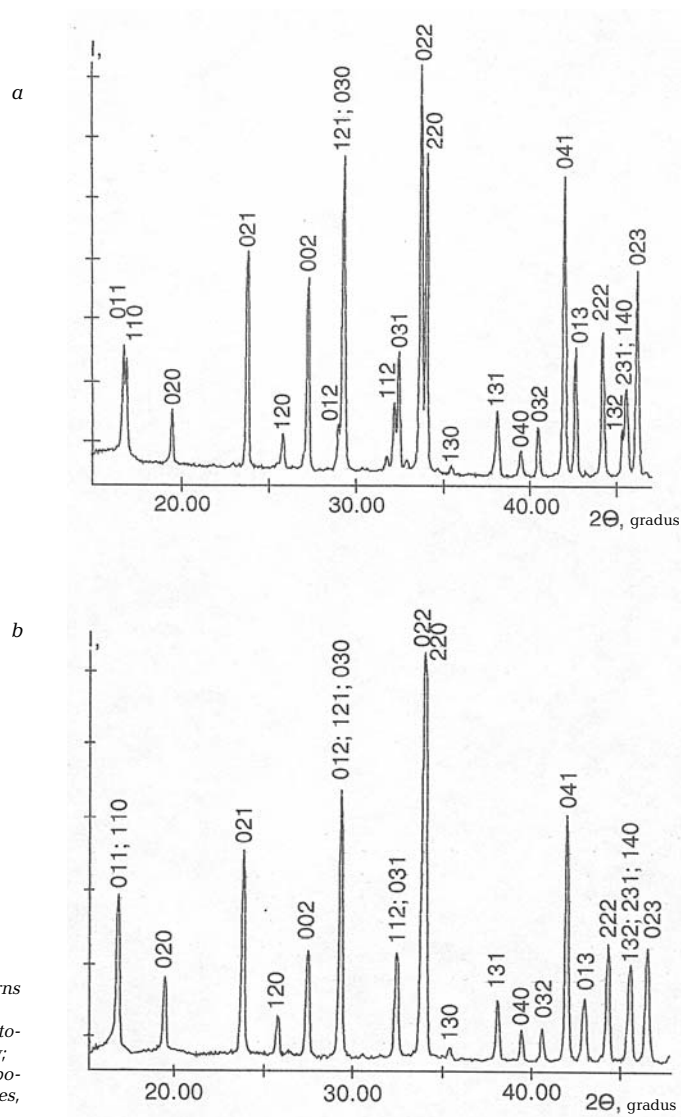
The numbers of analyses correspond to tables 1–3. * — In original publication b and c are changed. ** — c/b.

Table 5. Localities and occurrence conditions of burbankite group minerals

Localities	Minerals	Occurrence conditions and typical satellites	Sources
<i>Localities connected with carbonatites</i>			
Vuoriyarvi, Northern Kareliya	Burbankite Calcioburbankite Remondite-(Ce)	Calcite carbonatites: pyrrhotite, phlogopite, barytocalcite, norsethite, ewaldite, donnayite, vaterite, strontianite, olekminskite, ancylite, pyrochlore, franconite; dolomite carbonatites: calcite, siderite, ancylite, barite, amphibole, chlorite, serpentine, sulphides	Borodin, Kapustin, 1962; Kukhareenko et al., 1965; Subbotin <i>et al.</i> , 1999; the authors' data
Gornoe Ozero, East Siberia	Burbankite	Amphibole- and aegirine-dolomite, amphibole-calcite and ankerite carbonatites	Zdorik, 1966
Khanneshin, Afghanistan	Khanneshite Burbankite	Hydrothermally altered volcanic dolomite and dolomite-ankerite carbonatites: barite, calkingsite, carbocernaite, mckelveyite, chlorite	Eemenko, Vel'ko, 1982; Pekov <i>et al.</i> , 1998
Khibiny, Kola Peninsula	Burbankite Khanneshite Calcioburbankite	Calcite carbonatites: biotite, apatite, carbocernaite, fluorite, sulphides, dawsonite	Kirnarskii, Kozyreva, 1974; ; Zaitsev <i>et al.</i> , 1997 Pekov <i>et al.</i> , 1998; the authors' data
Arbarastakh, Yakutiya	Calcioburbankite	Dolomite-ankerite carbonatites: witherite, strontianite, bastnasite, huanghoite, magnetite, sphalerite, galena; calcite carbonatites: fluorite	Zhabin <i>et al.</i> , 1971
Srednyaya Zima, Siberia	Calcioburbankite	Calcite carbonatites: ankerite	Pozharitskaya, Samoilov, 1972
Kovdor, Kola Peninsula	Burbankite Khanneshite	Cavities in dolomite carbonatites: bakhchisaraitsevite (for burbankite) Calcite-shortite carbonatites: phlogopite, bonshtedtite (for khanneshite)	Ivanjuk <i>et al.</i> , 2002
Afrikanda, Kola Peninsula	Burbankite Khanneshite	Calcite-amphibole-clinopyroxene rock: inclusions in apatite	Zaitsev, Chakhmouradian, 2002
Kalkfeld, Namibia	Burbankite	Inclusions in quarts from quartzites containing carbonatites: nahcolite, halite, sylvite, fluorite, calcite, cryolite, sulphides, phosphates	Buhn <i>et al.</i> , 1999
Chipman Lake, Ontario, Canada	Burbankite	Dolomite carbonatites: apatite, magnetite, sulphides, pyrochlore, barite, monazite, calcite, magnesite, siderite, norsethite, strontianite, REE-fluorcarbonates, albite, orthoclase	Platt, Wooley, 1990
<i>Localities connected with alkaline hydrothermalites</i>			
Vishnevy Gory, South Urals	Burbankite	Cracks in miaskites: microcline, albite, chlorite, muscovite, ilmenorutile, calcite, siderite, strontianite, ancylite, donnayite, nenadkevichite, korobitsynite, franconite	Pekov <i>et al.</i> , 1996
Lovozero, Kola Peninsula	Burbankite	Hyperalkaline pegmatites: common potassic feldspar, aegirine, sidorenkite, nahcolite, shortite, catapleiite, kogarkoite, neighborite, belovite; microcline veins of contact zone	Tikhonenkova, Kazakova, 1964; Khomyakov, 1990; Pekov, 2001
Khibiny, Kola Peninsula	Burbankite Remondite-(Ce) Remondite-(La) Petersenite-(Ce)	Hyperalkaline pegmatites: microcline, aegirine, sodalite, biotite, natrolite, pectolite, cancrisiliite, villiaumite, shortite, pirssonite, trona, bonshtedtite, vinogradovite, lamprophyllite, rasvumite, mackinawite, vitusite-(Ce), nacaphite, lomonosovite, sazykinaite-(Y); aegirine and feldspar-fluorite veinlets	Shlyukova <i>et al.</i> , 1972; Tikhonenkova <i>et al.</i> , 1972; Khomyakov, 1990; Pekov <i>et al.</i> , 1998, 2000; Yakovenchuk <i>et al.</i> , 1999; Belovitskaya <i>et al.</i> , 2000; the authors' data
Mont Saint-Hilaire, Quebec, Canada	Burbankite Calcioburbankite Remondite-(Ce) Petersenite-(Ce)	High-alkaline pegmatites: microcline, albite, aegirine, analcime, natrolite, chlorite, apatite, rhodochrosite, biotite, catapleiite, epididymite, eudialyte, serandite, shomiokite-(Y), rutile, cryolite, siderite, sabinaite. Xenoliths of marbles: calcite, fluorite, leucophanite, narsarsukite, schairerite, shortite, thermonatrite; miaroles in nepheline-syenites	Chen, Chao, 1974; Horvath, Gault, 1990; Grice <i>et al.</i> , 1994; Van Velthuisen <i>et al.</i> , 1995; Horvath, Pfenninger- Horvath, 2000; the authors' data
Rocky Boy, Montana, USA	Burbankite	Calcite veinlets: aegirine, barite, calkingsite, lanthanite, ancylite, sulphides	Pecora, Kerr, 1953
Ridge Moskal, South Urals	Burbankite	Sodalite-analcime-cancrinite veinlets in alkaline metasomatites: neighborite	Efimov <i>et al.</i> , 1969
Pokrovo-Kire- evskoe, Ukraine	Burbankite	Hydrothermalites of nepheline-syenites: calcite, fluorite, natrolite	Litvin <i>et al.</i> , 1998

Table 5. Localities and occurrence conditions of burbankite group minerals (continuation)

Localities	Minerals	Occurrence conditions and typical satellites	Sources
Ebounja, Cameroon	Remondite-(Ce) Burbankite	Veinlets in nepheline-syenites: calcite, aegirine	Cesbron <i>et al.</i> , 1988
Green River Formation, Utah and Wyoming, USA	Burbankite	Hydrothermally altered soda-bearing sediments: nahcolite, trona, mckelveyite	Fitzpatrick, Pabst, 1977
Localities connected with pectolite metasomatites			
Murun, East Siberia	Burbankite	Veins in microclinites and fenites: pectolite, charoite, magnesio-arfvedsonite	Konev <i>et al.</i> , 1996; the authors' data
Khibiny, Kola Peninsula	Burbankite	Lenses and veins in ijolite-urtites: pectolite, fluorite, biotite, sphalerite, galena	The authors' data

FIG. 3. Fragments of X-ray diffraction patterns ($\lambda\text{CuK}\alpha$) of burbankite:

a) REE-depleted burbankite (an. 92) from pectolite metasomatites, Mt. Ni'orkpakhk, Khibiny;
 b) burbankite with «typical» chemical composition (an. 64) from alkaline hydrothermalites, Mt. Kukisvumchorr, Khibiny

high-symmetrical structural type can crystallize in wide range of conditions and in nature greatly prevail over monoclinic members of this group. The latter are typomorphic for low-temperature alkaline hydrothermalites and are extremely rare.

Secondary alterations

Burbankite group minerals become unstable at decrease of alkalinity and easily alter, being replaced by a whole number of secondary products. As components of pseudomorphs after burbankite almost two tens (!) of the minerals of REE, Sr, Ba, and Ca are known. Above all that are the alkali-free carbonates. Burbankite and its analogues from early carbonatite parageneses are exposed to alteration most frequently. Their replacement takes place at hydrothermal stages.

In carbonatites of Vuoriyarvi burbankite is usually replaced by aggregates of barite, strontianite, and ancylite or carbocernaite. Less often here there are the partial pseudomorphs after burbankite, which consist of lanthanite, aragonite, and celestine, but sometimes of calkingsite, barite, strontianite, and pyrite (Kapustin, 1971). At dolomitization of calcite carbonatites of Vuoriyarvi the mixes of calcite, ancylite-(Ce), olekminskite, strontianite, and barite develop after calcioburbankite and burbankite; less often in the alteration products there are carbocernaite, witherite, alstonite, kukharenkoite-(Ce), Ce-ewaldite, Nd-mckelveyite (Subbotin *et al.*, 1999). In aegirine-dolomite carbonatites of Gornoe Ozero massif carbocernaite and ancylite develop after burbankite, and in ankerite carbonatites the burbankite completely replaced by aggregates of strontianite (70–80%), bastnä site (20–30%), calcite, barite, and allanite (Zdorik, 1966). In carbonatites of Khibiny the burbankite sometimes wholly replaced by ancylite-(Ce), synchysite-(Ce), strontianite, and barite (Zaitsev *et al.*, 1998). In Khanneshin, formation of barite (Eremenko, Vel'ko, 1982) and mckelveyite (Pekov *et al.*, 1998) after khannesite is mentioned. In hydrothermally altered carbonatites of Sebl'yavr (Kola Peninsula) the primary plentiful burbankite is entirely replaced by ancylite-(Ce) (N.V. Sorokhtina data).

In alkaline hydrothermalites the alteration processes of burbankite group minerals are developed much poorly. In Rocky Boy calkingsite grows after burbankite (Pecora, Kerr, 1953). In Mont Saint-Hilaire remondite-(Ce) and petersenite-(Ce) are replaced by alkali-free carbonates of REE: synchysite-(Ce), calico-ancylite-(Ce), bastnä site-(Ce) (Horvath, Pfenninger-Horvath, 2000; the authors' data), at the latest stages. In Kirovskii

mine in Khibiny the development of ancylite-(Ce) after burbankite is observed. Probably, exactly burbankite was the protomineral of cellular ancylite pseudomorphs after hexagonal prisms of undetermined mineral that are widely spread in hydrothermally altered pegmatites of Khibiny.

Conclusions

The crystal structures of all hexagonal members of the burbankite group were studied (Belovitskaya *et al.*, 2000, 2001, 2002; Gobetchiya *et al.*, 2001). The results of this research have allowed ascertaining that the burbankite structural type (sp. gr. $P6_3mc$) is exceptionally steady to variations of cationic composition in *B*-polyhedra: all these minerals are isostructural and form system of continuous solid solutions. Judging by relative prevalence of these minerals in nature and by parageneses, this crystal structure is most steady at predominance of strontium in *B*-site.

All chemical compositions of the burbankite group minerals are described within the limits of system with end members: $(Na_2Ca)M^{2+}_3(CO_3)_5$ and $Na_3(REE_2Na)(CO_3)_5$, where $M^{2+} = Sr, Ba, Ca$. Three groups of chemical compositions are distinguished, they correspond to three genetic types of burbankite mineralization which connected to alkaline rocks. The first of them is confined to carbonatites where the minerals with «maximum averaged» chemical composition containing increased amounts of barium and calcium will be formed. The industrial accumulations of burbankite occur here. The second type is allocated in alkaline hydrothermalites where the range of chemical compositions of burbankite-like phases is extremely wide. The third type is connected to pectolite metasomatites of Khibiny and Murun massifs where strongly REE-depleted burbankite is present in considerable amounts. In carbonatites the burbankite group minerals for rare exception are the early high-temperature formations, and vice versa in agpaitic massifs they are formed at late stages under low temperatures that is connected to various regimes of carbon dioxide.

At alkalinity decrease the burbankite group minerals become unstable and at hydrothermal conditions they are easily replaced by a whole series of secondary minerals, among which alkali-free carbonates of REE, Sr, Ba, and Ca prevail.

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