

NEW DATA ON BETALOMONOSOVITE

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The new data on compositional variations, refined crystal structure, thermal properties, and formation conditions of betalomonosovite are discussed. The results obtained assert that betalomonosovite differs from lomonosovite with which the former is identified. It has individual chemical and structural features, and distinct geological and genetic setting, and should be rehabilitated as individual mineral species.

3 tables, 6 figures, 58 references.

Keywords: lomonosovite, betalomonosovite, murmanite, crystal structure, Khibiny massif, melteigite-urtite, juvite, rischorrite, hypergpaite minerals assemblage.

The aim of this study is comparison of new data on betalomonosovite, $\text{Na}_4\text{Ti}_4(\text{Si}_2\text{O}_7)_2(\text{O},\text{F})_4 \cdot \text{Na}_2\text{H}_4(\text{PO}_4)_2$ results of investigation of lomonosovite $\text{Na}_4\text{Ti}_4(\text{Si}_2\text{O}_7)_2(\text{O},\text{F})_4 \cdot \text{Na}_6(\text{PO}_4)_2$, with which betalomonosovite is identified according to recommendation of the Commission on new Minerals and Mineral Names International Mineralogical Association in 1988, and those of murmanite $\text{Na}_4\text{Ti}_4(\text{Si}_2\text{O}_7)_2\text{O}_4 \cdot (\text{H}_2\text{O})_4$ as final product of supergene alteration of lomonosovite, with which betalomonosovite is unreasonably attributed to the same solid solution series as intermediate species of similar alteration. We do not discuss other lomonosovite group minerals: vuonnemite and epistolite, Nb analogs of lomonosovite and murmanite, respectively, and quadruphite, sobolevite, and polyphite, Ca- and Mn-rich analogs of lomonosovite, although they are end-members of probable solid solution series for isomorphic admixtures typical of betalomonosovite and could be formed in similar geological environment.

Discovery

In 1890, Wilhelm Ramsay described new hydrous niobo-titano-silicate, mineral no. 3 (Ramsay, 1890) from the Lovozero tundras. In 1923, members of the Fersman expedition found this mineral in the same district and described it as violophillite. After detailed examination, Gutkova (1930) renamed it to murmanite with the refined composition $\text{Na}_4\text{Ti}_4\text{Si}_4\text{O}_{18} \cdot 4\text{H}_2\text{O}$ (Minerals..., 1937). Lomonosovite, anhydrous analog of murmanite, discovered from the same massif by Gerasimovsky

(1950) was studied in detail by Es'kova (1976), Vlasov *et al.* (1959), and Semenov *et al.* (1961). In contrast to murmanite, this mineral contained P and was anhydrous $\text{Na}_4\text{Ti}_4\text{Si}_4(\text{O},\text{F})_{18} \cdot 2\text{Na}_3\text{PO}_4$. In Khibiny, Dorfman (1962) found lomonosovite for the first time in the district of apatite deposits.

Betalomonosovite discussed in this article, was found and described as mineral no. 2 in 1938 by Gerasimovsky, but its detailed examination was started in 1960s (Gerasimovsky and Kazakova, 1962), when Semenov *et al.* (1961) found more representative material in the same district. In Khibiny, betalomonosovite was found at the Rasvumchorr deposit in 1958 (Sokolova, 1961; Sokolova *et al.*, 1971₂). In contrast to the previous findings, this mineral contained P and significant amount of water; betalomonosovite¹ was described by the following formulae: $\text{Na}_4\text{Ti}_4\text{Si}_4(\text{O},\text{F})_{18} \cdot (\text{Na},\text{H})_6(\text{PO}_4)_2$, $\text{Na}_4\text{Ti}_4\text{Si}_4(\text{O},\text{F})_{18} \cdot \text{Na}_2\text{HPO}_4 \cdot \text{NaH}_2\text{PO}_4$ or $\text{Na}_4\text{Ti}_4\text{Si}_4(\text{O},\text{F})_{18} \cdot \text{Na}_3[\text{PO}_4(\text{OH})\text{PO}_2(\text{OH})_2]$. To date, it is reasonably chemical, structural, and geological characterized in the context of its nature, abundance in alkaline rocks of agpaite nepheline syenite massifs and formation conditions to regard it as individual mineral species. Nevertheless, it was missinlcuded by CNMMN IMA into the list of discredited minerals (Nickel and Mandarino, 1988) that hampers its further detailed study. This forced us to carry out the new measurement of the chemical composition and crystal structure of betalomonosovite, as well as, its genetic relationship with lomonosovite and murmanite to additionally argue the reinstatement of this term.

¹ – Many researchers assumed that this name is poor because betalomonosovite is not structural modification of lomonosovite, i.e., β -species (β -lomonosovite), otherwise, term α -lomonosovite should be introduced.

Geological setting and formation conditions of murmanite, lomonosovite, and betalomonosovite

Murmanite. Murmanite is abundant accessory mineral of some peralkaline leucocratic rocks and hosted pegmatites in the Lovozero tundras. It was found at Mts. Punkaruai, Suoluai, Ninchurt, and Mannepahk; cirques Raslak, Sengischorr, and Angvundasschorr; and in the Chinglusuai, Motchisuai, and Muruai valleys (Minerals..., 1937). According to Bussen and Sakharov (1972) referring to Gutkova (1930) and Es'kova (1959), it occurs as lenticular clusters within layers I-1 and II-2 hosted in juvite, foyaite, and urtite of the differentiated lujavrite-foyaite-urtite complex (complex III); this mineral is common in leucocratic varieties of lujavrite complex (complex IV) where it forms phenocrysts in near-contact porphyry lujavrite (tinguaite) and always occurs in porphyry murmanite lujavrite (complex V). Through all rocks, murmanite is observed with lomonosovite typically associated with apgaitic minerals: K, Na feldspar, nepheline, sodalite, aegirine, lamprophyllite, and eudialyte. Pegmatite with murmanite and lomonosovite were also hosted in porphyritic and poikilitic nepheline-sodalite syenite and tavite (complex II) (Minerals..., 1937).

In contrast to Lovozero, in Khibiny, negligible amount of altered murmanite was found only on the surface (Gutkova, 1930; Kupletsky, 1930; 1932; Minerals..., 1937; Dorfman, 1962; Tikhonenkov, 1963). Fresh murmanite was identified in mines at the Rasvumchorr, Kukisvumchorr, and Yukspor apatite deposits in pegmatites hosted in coarse-grained urtite and rischorrite hosting ore sequence, as well as, in melteigite of the upper contact zone, where it replaces lomonosovite lamellae (Sokolova, 1965; Sokolova *et al.*, 1973). The freshest pinkish white fine-flake murmanite with nacreous luster that could be assumed as newly formed phase was found as thin (up to 1 mm in thickness) stringer cutting massive urtite at the Rasvumchorr deposit (Mineralogy..., 1978).

Murmanite (associated with lomonosovite) was found in the same situation from apgaitic rocks of the Ilmaussaq massif, South Greenland (Karup-Mueller, 1983; 1986).

Lomonosovite. Es'kova (1959) studied in detail the geological setting of lomonosovite in the Lovozero massif taking into account the data of Gerasimovsky (1950) and Borneman-Starynkevich (1946). Lomonosovite and mur-

manite were established to be common in the same rocks: leucocratic varieties of rocks from the differentiated complex (III) with greater amount in foyaite than urtite and lujavrite; leucocratic lujavrite of the lujavrite complex (IV), sodalite varieties of poikilitic nepheline-sodalite syenite (II), and pegmatites hosted in these rocks. Fresh lomonosovite was observed in drill core below 250–300 m, whereas at the depth of 100–200 m below surface it was followed by the yellow and violet-pink variety; at the surface murmanite is pink. Relics of altered lomonosovite retaining morphology and optical orientation were observed everywhere in murmanite. In other words, it was proved by direct methods that murmanite is secondary after lomonosovite.

Experiments in Na and P desalination from lomonosovite using hot and cold distilled water performed by Gerasimovsky and Borneman-Starynkevich (Borneman-Starynkevich, 1946) and specified by Zabavnikova (1967) and Sokolova *et al.* (1973) using chemical and thermal analysis, and X-ray diffraction supported the probable formation of murmanite by this manner. It was established that pink-lilac color of murmanite with characteristic absorption bands at 12650, 18850, and 20600 cm^{-1} is caused by Mn^{3+} (Platonov, 1976) that is also consistent with oxidative environment in murmanite formation.

By the further investigations of Khomyakov (1990), it has become clear that in addition to the lomonosovite – murmanite pair, there are some primary minerals, which are transformed to the secondary species due to Na desalination and hydration as a result of sharply evolved alkalinity of mineral-forming medium; these minerals common close to surface as rule are: vuonnemite, $\text{Na}_{11}\text{TiNb}_2\text{Si}_4\text{P}_2\text{O}_{25}\text{F} \rightarrow$ epistolite, $\text{Na}_5\text{TiNb}_2\text{Si}_4\text{O}_{17}\text{F}\cdot 4\text{H}_2\text{O}$, parakeldyshite, $\text{Na}_2\text{ZrSi}_2\text{O}_7 \rightarrow$ keldyshite, $\text{Na}_3\text{HZr}_2(\text{Si}_2\text{O}_7)_2$, zirsinalite, $\text{Na}_6\text{CaZrSi}_6\text{O}_{18} \rightarrow$ lovozerite, $\text{Na}_3\text{CaZrSi}_6\text{O}_{15}(\text{OH})_3$, kazakovite, $\text{Na}_6\text{MnTiSi}_6\text{O}_{18} \rightarrow$ tisinallite, $\text{Na}_3\text{MnTiSi}_6\text{O}_{15}(\text{OH})_3$. They are regarded as individual mineral species or varieties with prefix "hydro", for example, delhayelite, $\text{K}_3\text{Na}_2\text{Ca}_2\text{Si}_7\text{AlO}_{19}(\text{F},\text{Cl})_2 \rightarrow$ hydrodelhayelite, $\text{KCaSi}_7\text{AlO}_{17}(\text{OH})_2\cdot 6\text{H}_2\text{O}$.

Cogenetic minerals typically associated with lomonosovite and murmanite are the same: microcline, nepheline, arfvedsonite, and sodalite. Lomonosovite inclusions are observed in albite, sodalite, cancrinite, ussingite, and natrolite; however these inclusions are transformed to murmanite only in natrolite. This not contradicts the pseudomorphous origin of murmanite and it is clear that meteoric

water or low-hydrothermal fluid is required to form it. Villiaumite is a guide mineral for lomonosovite.

In Khibiny, lomonosovite found in slightly different environment from that in Lovozero (Dorfman, 1962; Dudkin, 1959; Dudkin *et al.*, 1959; Sokolova *et al.*, 1971₁, 1973; Mineralogy... 1978) was identified in pegmatites cutting fine-grained trachitoid ijolite-urtite-melteigite, but in the first place in pegmatites hosted in massive coarse-grained urtite, apatite-nepheline sequence, and rischorrite at the Yukspor, Kukisvumchorr, and Rasvumchorr deposits. Lomonosovite is the most typical of aegirine-diopside – feldspar (microcline, adularia-like orthoclase) pegmatite, where it is associated with nepheline, lamprophyllite, delhayelite, and villiaumite. It is unknown from aegirine-diopside – nepheline pegmatites depleted in feldspar or feldspar-free. Lomonosovite is associated with microcline, aegirine, lamprophyllite, shcherbakovite, and lovozerite in pegmatites hosted in rischorrite at the top of apatite body in the Apatite cirque of Mt. Rasvumchorr.

These pegmatites are opened by mines at the significant depth below surface and deep-seated weathering profiles that favors to retaining fresh lomonosovite. It is murmanitized only along fractures cutting plates. However, lomonosovite plates occurred in dumps for a long period or in pegmatites opened in open pit are altered to the greater extent up to pinkish violet murmanite. In contrast to Lovozero, lomonosovite or replacing murmanite were found only in melteigite-urtite of the Central Arc of the Khibiny massif; they were not identified in nepheline syenite (foyaite, khibinite) rimming the arc.

Betalomonosovite. Betalomonosovite is less frequent mineral as compared with lomonosovite and murmanite. In the Lovozero massif, it was identified in association with microcline, aegirine, arfvedsonite, sodalite, zeolites, eudialyte, lorenzenite (ramsayite), lamprophyllite, neptunite, and steenstrupine in poikilitic nepheline-sodalite syenite and hosted pegmatites on the right bank of the Tulbn'yunuai river (Semenov *et al.*, 1961; Gerasimovsky and Kazakova, 1962). In the Khibiny massif, betalomonosovite was found in association with microcline, arfvedsonite, lamprophyllite, shcherbakovite, wadeite, lovozerite, and hisingerite as characteristic mineral of thin pegmatite veinlets cutting rischorrite at the top of apatite-nepheline body and in host rischorrite of the Apatite cirque at the Rasvumchorr deposit (Sokolova, 1961; Sokolova

et al., 1971₂). Sufficiently large well-shaped betalomonosovite crystals up to 5 mm in size measured with goniometer by T.A. Yakovlevskaya were recovered from gisengerite (Sokolova *et al.*, 1971₂; Mineralogy..., 1978).

Ageeva and Borutzky (1997) and Ageeva (1999, 2002) studied in detail the relationship between lomonosovite, betalomonosovite, and murmanite occurred as accessory minerals in the parental rocks of the Khibiny massif. It was established that accessory lomonosovite is common only in massive coarse-grained urtite, feldspar urtite, juvite, pyroxene rischorrite, and malignite, i.e., in the rocks of Central Arc of the massif and has different chemical composition and morphology. In urtite, it occurs as the largest (5–10 mm) grains enriched in Na, which are along with pyroxene, lamprophyllite, and aenigmatite forms poikilitic metacrysts enclosing euhedral nepheline grains (Fig. 1a). Clear smooth boundaries between lomonosovite and nepheline indicating simultaneous formation of these minerals attract attention. As K content increases from urtite to feldspar urtite, juvite, and rischorrite, lomonosovite is depleted in Na up to the composition typical of betalomonosovite and its forms resulted from orthoclase corrosion become more frequent (Fig. 1b).

In other words, as previously reported for pegmatites (Sokolova *et al.*, 1971₂), betalomonosovite is the most characteristic of rischorrite and could be resulted from the transformation of lomonosovite as primary mineral of massive coarse-grained urtite during rischorritization. It should be emphasized once more that in this process with partial removal of Na and dehydration, unlike murmanitization of lomonosovite, phosphorous is not removed and the Ti:Si:P ratio remains constant. Altered lomonosovite is observed in thin sections and attested by the electron microprobe measurement of Na and P. The alteration is usual in colorless crystal rims, whereas in the cores relict light brown-violet lomonosovite is retained (Fig. 1c).

Non-leached phosphorous indicates that this process differs from supergene or low-temperature hydrothermal transformation of lomonosovite to murmanite. The review of mineral assemblages containing betalomonosovite (K-rich adularia-like orthoclase, nepheline enriched in K, kalsilite, eudialyte enriched in K, wadeite, barium lamprophyllite, shcherbakovite) shows that it was most likely formed at one of the stages of melteigite-urtite fenitization under effect of fluids derived from nepheline syenite magma, i.e., K,Si metaso-

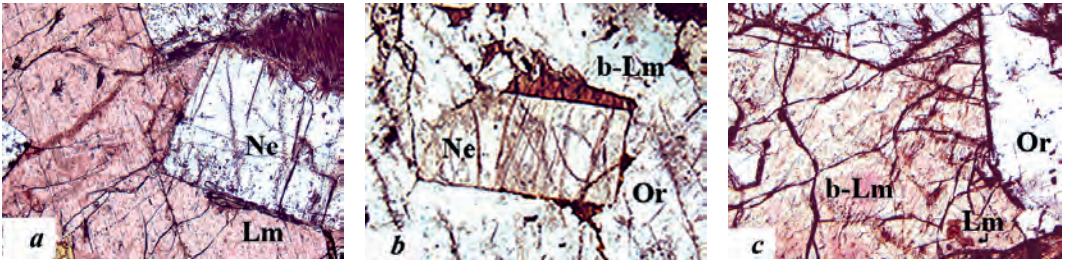


Fig. 1. Micrographs of accessory lomonosovite and betalomonosovite grains in the rocks of the urtite-juvite-rischorrite complex in the Khibiny massif: (a) poikilitic grains of lomonosovite (Lm) with euhedral nepheline phenocryst (Ne) in massive coarse-grained urtite, plane-polarized light, grain size 2×3 mm; (b) newly formed grain of betalomonosovite (b-Lm) corroded by adularia-like orthoclase (Or) on nepheline phenocryst (Ne) in rischorrite, plane-polarized light, grain size 0.4×0.8 mm; (c) lomonosovite relics (Lm) in betalomonosovite (b-Lm) in orthoclase form rischorrite, plane-polarized light, grain size 2×3 mm.

matic alteration affected primary relict rocks of Central Arc of the massif and causing the formation of high- and hyper-potassium rocks (juvite, rischorrite). The absence or low content of K in betalomonosovite is caused by that the incorporation of large K cations into the mineral crystal structure is impossible or strictly limited.

The metasomatic hypothesis of rischorrite (poikilitic nepheline syenite) origin in the Khibiny massif proposed and progressively advanced by Solodovnikova (1959), Tikhonenkov (1963), Rudenkov (1964), Titov *et al.* (1971), Mineralogy (1978), and Zotov (1989) is the most probable and elaborated because it is based on the additional results of detailed study of rock-forming and accessory minerals (Borutzky, 1988; Ageeva, 2002; Borutzky, 2010; 2012); however some details of this process remain unclear. Two conclusions are extremely important. In the first place, two types of newly formed minerals are formed: (1) replacement pseudomorphs with relics of primary minerals under conditions of non-equilibrium metasomatic process and (2) products of their recrystallization as metacrysts formed under equilibrium conditions. In the second place, the transformation of primary rocks of Central Arc of the massif urtite \rightarrow feldspar urtite \rightarrow juvite \rightarrow rischorrite started with fenitization (magmatic replacement) and as temperature and alkalinity of fluid decreased evolves to lower-temperature acidified aqueous solutions; Na minerals are replaced by Na,K minerals followed by K minerals to Na minerals again accompanied with dehydration.

Turning to betalomonosovite, we conclude that in addition to its pseudomorphs after lomonosovite forming at higher temperature than murmanite under effect of solution enriched in K in juvite, rischorrite, and pegmatites cutting these rocks, its newly formed more

perfect metacrysts overgrowing nepheline inclusions within adularia-orthoclase poikilitic crystals associated with potassium titanate and zirconosilicates: astrophyllite, wadeite, delhayelite, yuksporite, and phenacite (Fig. 2) are abundant. In contrast to pseudomorphous betalomonosovite, the crystals are colorless, optic angle decreases from $45-55^\circ$ to $27-36^\circ$ (Sokolova *et al.*, 1971₂; Ageeva, 1999). We believe that this undoubtedly indicates physicochemical equilibrium at the late stage of rischorritization, presence of individual stability field of betalomonosovite differed from that of lomonosovite that is basis for its definition as mineral species or equivalent variety.

Variation in chemical composition and typomorphism

The theoretical compositions (wt.%) are as follows: murmanite $\text{Na}_4\text{Ti}_4\text{Si}_4\text{O}_{18} \cdot 4\text{H}_2\text{O}$: $\text{Na}_2\text{O} - 16.40$, $\text{TiO}_2 - 42.28$, $\text{SiO}_2 - 31.79$, $\text{H}_2\text{O} - 9.53$, lomonosovite $\text{Na}_4\text{Ti}_4\text{Si}_4\text{O}_{18} \cdot 2\text{Na}_3\text{PO}_4$: $\text{Na}_2\text{O} - 30.63$, $\text{TiO}_2 - 31.59$, $\text{SiO}_2 - 23.75$, $\text{P}_2\text{O}_5 - 14.03$, betalomonosovite $\text{Na}_4\text{Ti}_4\text{Si}_4\text{O}_{18} \cdot \text{Na}_2\text{HPO}_4 \cdot \text{NaH}_2\text{PO}_4$: $\text{Na}_2\text{O} - 22.93$, $\text{TiO}_2 - 33.79$, $\text{SiO}_2 - 25.41$, $\text{P}_2\text{O}_5 - 15.01$, $\text{H}_2\text{O} - 2.86$, or $\text{Na}_4\text{Ti}_4\text{Si}_4\text{O}_{18} \cdot 2\text{NaH}_2\text{PO}_4$: $\text{Na}_2\text{O} - 20.02$, $\text{TiO}_2 - 34.64$, $\text{SiO}_2 - 26.05$, $\text{P}_2\text{O}_5 - 15.38$, $\text{H}_2\text{O} - 3.91$ (ignoring traces). The Si, Ti, P and O contents (O = 26 apfu) in lomonosovite and betalomonosovite are identical, whereas Na concentration decreases from lomonosovite to betalomonosovite as consistent with increasing content of H atoms from 10 Na at 0 H to 7 Na at 3 H apfu (first stage of transformation) to 6 Na at 4 H apfu (second stage). In murmanite with the same Si and Ti content, P is absent, H and O content is 8 and 22 apfu, respectively. Nb, Ta, Zr, Fe, Mn, Mg, Ca, K, and F are minor admixtures in these minerals.

The first researchers of the lomonosovite group minerals believed that lomonosovite

and murmanite are the products of magmatic crystallization and continuous solid solution series is between them, although murmanite containing 5.0 wt.% P_2O_5 was defined by Semenov *et al.* (1961) as betamurmanite. After pseudomorphic origin of murmanite being established, the presence of P in it was explained by relict lomonosovite. Betalomonosovite is behind this concept and variation in Na and H_2O content in its composition is determined by mineral-forming or mineral-retaining medium.

We have studied in detail using electron microprobe the chemical composition of accessory lomonosovite and betalomonosovite from the massive coarse-grained and feldspar urtite – juvite – pyroxene rischorrite selected from core of holes 1c, 2c, 4c, 1456, and 1494 drilled at the Rasvumchorr apatite deposit in Khibiny (Ageeva, 1992, 2002) and newly formed betalomonosovite from pegmatite vein hosted in rischorrite from the Apatite cirque of Mt. Rasvumchorr (specimen of M.N. Sokolova) previously examined with bulk chemical analysis (Sokolova *et al.*, 1971₂). The pegmatite sample was used for the crystal structure refinement. Electron microprobe data for lomonosovite and betalomonosovite are given in descending order of Na content in Table 1. The formulae are calculated on the basis of $Si + Al = 4$. The Na_2O content (wt.%) in the samples studied is substantially variable: 29.60–17.63 (Na 9.23–5.42 apfu; average 7.92 apfu) in feldspar urtite, 9.86–25.94 (9.69–7.99 apfu; 8.85 apfu) in juvite, and 28.98–13.57 (9.74–4.21 apfu; 6.96 apfu) in rischorrite, i.e., some features of the compositional distribution of the lomonosovite group minerals in the rocks of this complex are observed. However, overlapped compositions in the selected rock groups are established, for example, from the soda horizon within feldspar urtite (sample 61/2c, anal. 9, 38), in rischorrite (sample 50/2c, anal. 22, 35, 37, 39, 44 and sample 136/2c, anal. 5, 7, 25, 33) and malnigite (sample 502/1456, anal. 2, 19, 36). This testifies to different intensity of lomonosovite alteration, different rate of Na removal and hydration, and not achieved equilibrium during transformation of this rock complex. Accessory minerals with the most stable and closest to lomonosovite composition were observed in juvite, whereas in urtite and rischorrite, both lomonosovite (relict) and betalomonosovite (newly formed) are common, i.e., the formation of betalomonosovite corresponds to the early stage of feldspar alteration in the rocks of this complex.

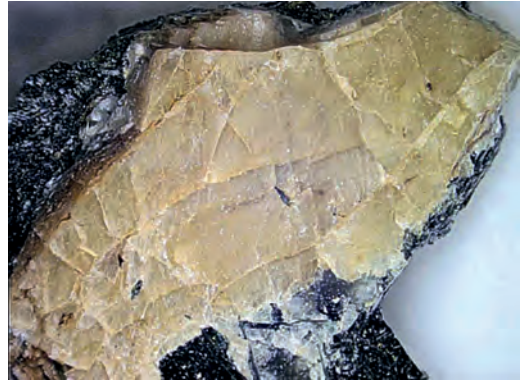


Fig. 2. Betalomonosovite from arfvedsonite-orthoclase pegmatite vein cutting rischorrite in the Apatite cirque of Mt. Rasvumchorr. Collection of M.N. Sokolova (no. 569). Grain size 3×5 mm.

The P_2O_5 content is weakly variable, wt.%: 15.15–11.59 (P 2.14–1.52 apfu; average 1.66 apfu) in feldspar urtite, 14.80–13.29 (2.07–1.79 apfu; 2.00) in juvite, and 16.95–11.91 (2.29–1.58 apfu; 1.96) in rischorrite. Assuming some uncertainty in determination of Na (elimination under beam) and P (Nb hampers its determination) we state the process differed from supergene mineralization. As is seen from Fig. 3, the lomonosovite and betalomonosovite compositions forms two different cluster close to theoretical compositions, but tend to the murmanite composition. However, parts of the same grain may correspond to both lomonosovite and betalomonosovite as illustrated by sample 87/1c from rischorrite shown as points 1 and 2 in Fig. 3 (Table 1, anal. 21, 29).

The elevated Nb_2O_5 content (wt.%) in some samples of both lomonosovite (3.76 – anal. 3, 5.18 – anal. 6, 9.00 – anal. 20) and betalomonosovite (3.82 – anal. 28) with low TiO_2

Fig. 3. A Na versus P plot for accessory minerals of the lomonosovite group in urtite-juvite-rischorrite complex in the Khibiny massif [(Lm) lomonosovite, (b-Lm) betalomonosovite, (Mmm) murmanite. (1) Core and (2) rim of the same grain (sample 87/1c) in rischorrite.

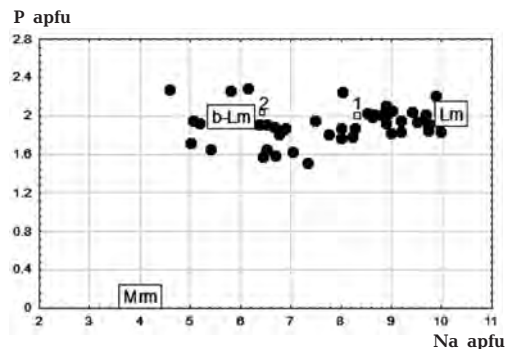


Table 1. Chemical composition (wt.%) of accessory lomonosovite and betalomonosovite in the rocks of the urtite-juvite-rischorrite complex (core samples from drill holes in the district of the Rasvumchorr apatite deposit)

No. anal.	Lomonosovite																						
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	
No. sample	80/ 2c	502/ 1456	319/ 1456	275/ 1456	136/ 2c	477/ 1456	136/ 2c	502/ 1456	61/ 1456	309/ 1456	142/ 1c	448/ 1456	80/ 2c	306/ 1456	318/ 1456	306/ 1456	275/ 1456	76/ 1c	502/ 1456	101/ 1494	87/ 1c	50/ 2c	
SiO ₂	23.57	21.92	23.08	23.79	23.02	23.96	23.55	23.91	23.45	23.68	22.82	23.27	23.38	24.75	23.32	23.94	23.92	23.79	24.06	24.79	23.96	24.73	23.96
TiO ₂	27.36	28.92	22.55	25.84	29.87	23.42	30.18	26.32	27.10	27.21	26.60	24.97	24.27	26.94	27.84	25.02	25.85	27.77	25.32	20.73	25.80	28.90	28.90
P ₂ O ₅	13.05	14.25	12.94	14.23	13.80	13.88	12.98	14.46	13.66	14.39	13.70	14.34	14.23	14.80	13.81	14.48	13.95	14.20	14.80	15.15	13.08	16.04	16.04
Nb ₂ O ₅	0.95	1.89	3.76	1.85	0.54	5.18	0.00	1.92	0.00	0.56	0.76	0.76	1.10	0.97	0.76	3.15	0.00	0.63	0.93	9.00	0.70	0.70	0.30
Al ₂ O ₃	0.00	0.08	—	0.09	0.06	0.00	0.39	0.08	1.71	0.00	0.06	—	0.00	0.00	0.00	0.28	0.00	0.00	0.06	0.02	0.00	0.06	0.06
Fe ₂ O ₃	4.07	2.50	1.86	1.97	1.91	3.34	2.41	2.55	3.32	2.79	3.24	2.79	4.44	3.09	3.04	3.64	2.86	2.56	2.63	2.47	2.86	2.13	2.13
MnO	0.62	0.57	0.41	0.23	0.22	0.70	0.22	0.57	0.40	0.39	0.28	0.26	0.67	0.50	0.21	0.68	0.00	0.49	0.46	2.20	0.92	0.93	0.93
MgO	—	0.38	0.25	0.38	0.07	0.58	0.15	0.38	0.00	0.27	0.30	0.08	0.00	0.36	0.13	0.66	0.95	0.18	0.83	0.46	0.38	0.43	0.43
CaO	3.07	1.93	1.75	1.55	1.32	2.95	1.58	1.94	3.35	2.49	2.66	2.10	3.65	2.49	2.24	3.15	2.90	2.18	2.43	1.69	2.13	2.01	2.01
Na ₂ O	30.28	28.13	28.98	29.86	28.09	28.50	28.36	27.94	29.60	27.43	27.10	26.69	26.78	28.25	26.47	27.51	26.96	26.99	27.49	26.31	26.30	24.80	24.80
K ₂ O	0.00	0.08	0.01	0.00	0.01	0.04	0.25	0.00	0.00	0.00	0.04	0.00	0.00	0.01	0.00	0.01	0.01	0.12	0.00	0.02	0.01	0.07	0.07
Σ	102.97	100.65	95.59	99.80	98.91	102.55	100.00	100.07	102.54	99.21	98.07	95.26	98.52	102.16	97.82	102.52	97.27	99.18	99.74	102.01	96.90	99.85	99.85
Formula calculated on the basis of Si + Al = 4 apfu																							
Si	4.00	3.98	4.00	3.98	4.00	4.00	3.92	3.98	3.68	4.00	3.88	4.00	4.00	4.00	4.00	4.00	3.95	4.00	4.00	3.99	4.00	3.99	3.99
Al	0.00	0.02	0.00	0.02	0.01	0.00	0.08	0.02	0.32	0.00	0.12	0.00	0.00	0.00	0.00	0.00	0.05	0.00	—	0.01	0.00	—	0.01
Ti	3.49	3.95	2.94	3.25	3.89	2.94	3.78	3.30	3.20	3.46	3.40	3.23	3.12	3.27	3.59	3.10	3.27	3.47	3.06	2.60	3.14	3.62	3.62
Nb	0.07	0.16	0.29	0.14	0.04	0.39	0.00	0.14	0.00	0.04	0.06	0.06	0.09	0.07	0.06	0.23	0.00	0.05	0.07	0.68	0.05	0.03	0.03
Fe	0.52	0.34	0.24	0.25	0.25	0.42	0.30	0.32	0.39	0.35	0.41	0.36	0.57	0.38	0.39	0.45	0.36	0.32	0.32	0.31	0.35	0.27	0.27
Σ(Ti+Nb+Fe)	4.08	4.45	3.52	3.65	4.18	3.75	4.08	3.77	3.59	3.85	3.87	3.75	3.78	3.72	4.10	3.79	3.63	3.84	3.45	3.59	3.54	3.92	3.92
Mn	0.09	0.09	0.06	0.03	0.03	0.10	0.03	0.08	0.05	0.06	0.04	0.04	0.10	0.07	0.03	0.09	0.00	0.07	0.06	0.31	0.13	0.13	0.13
Mg	0.00	0.10	0.06	0.09	0.02	0.14	0.04	0.09	0.00	0.07	0.08	0.02	0.00	0.09	0.03	0.16	0.24	0.04	0.20	0.11	0.09	0.11	0.11
P	1.87	2.19	1.90	2.02	2.02	1.96	1.83	2.04	1.81	2.06	1.97	2.07	2.06	2.02	2.00	2.02	1.99	2.00	2.02	2.14	1.79	2.26	2.26
Na	9.96	9.91	9.74	9.69	9.43	9.23	9.16	9.03	9.01	8.98	8.93	8.90	8.88	8.85	8.80	8.79	8.79	8.70	8.58	8.51	8.25	8.00	8.00
Ca	0.56	0.38	0.32	0.28	0.24	0.53	0.29	0.35	0.54	0.45	0.48	0.39	0.67	0.42	0.41	0.56	0.52	0.39	0.42	0.29	0.36	0.37	0.37
K	0.00	0.02	0.00	0.00	0.00	0.01	0.05	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.01	0.01
Σ(Na+Ca+K)	10.52	10.30	10.07	9.97	9.67	9.76	9.51	9.37	9.55	9.43	9.42	9.29	9.55	9.28	9.21	9.35	9.31	9.12	8.99	8.80	8.61	8.38	8.38
O	26.26	21.43	25.08	25.51	26.33	25.78	25.36	25.56	24.50	25.76	25.51	25.17	25.68	25.18	25.87	25.70	25.20	25.40	24.78	25.54	24.12	25.97	25.97

Table 1. Continuation

Lomonosovite				Betalomonosovite																				
No. anal.	23	24	25	26*	27*	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	
No. sample	58/ 2c	279/ 1456	123/ 2c	69/ 2c	142/ 1456	142/ 1456	87/ 1c	142/ 1456	142/ 1456	307/ 4c	123/ 1c	136/ 2c	142/ 1456	50/ 2c	502/ 1456	50/ 2c	61/ 2c	50/ 2c	43/ 1c	17/ 1c	Pegm. 1c	50/ 2c	43/ 1c	
SiO ₂	26.34	24.28	26.88	25.00	25.81	24.43	25.22	25.72	24.90	23.44	25.49	25.00	24.26	25.13	24.23	25.21	26.57	25.35	24.86	26.52	25.41	25.05	24.86	25.05
TiO ₂	27.26	26.04	28.29	25.20	28.52	25.24	26.30	25.72	27.66	27.60	28.61	24.60	27.50	27.26	28.20	27.32	26.64	15.05	27.50	29.22	20.03	29.60	26.60	26.60
P ₂ O ₅	14.55	13.29	14.30	14.41	11.59	13.38	13.56	14.20	11.69	13.29	11.91	14.11	16.50	14.57	16.38	12.34	15.12	13.95	14.36	13.43	15.28	16.95	14.02	14.02
Nb ₂ O ₅	0.76	3.62	1.12	1.43	0.79	3.82	0.73	3.43	1.07	0.41	1.26	2.10	0.50	0.92	0.60	0.78	1.04	15.26	2.07	0.94	12.69	0.34	0.77	0.77
Al ₂ O ₃	0.09	0.77	0.00	0.04	0.00	0.11	0.00	0.00	0.13	0.00	0.13	0.00	0.11	0.06	0.23	0.01	0.00	0.00	0.00	0.00	0.00	0.11	0.11	0.11
Fe ₂ O ₃	3.02	2.70	2.77	5.09	2.95	3.16	2.74	3.19	3.22	4.33	3.50	3.84	2.59	2.64	2.27	3.69	2.74	3.11	2.87	2.82	2.30	1.81	1.70	1.70
MnO	0.46	0.36	0.40	0.58	0.27	3.16	0.97	0.12	0.46	0.32	0.33	0.18	1.37	0.46	0.88	0.48	0.94	2.32	0.48	0.46	0.52	0.90	0.49	0.49
MgO	0.23	0.40	0.08	0.22	0.26	0.33	0.33	0.58	0.25	0.00	0.22	0.58	0.48	0.78	0.40	0.46	0.73	—	0.13	0.35	0.58	0.38	5.65	5.65
CaO	2.38	2.59	1.79	3.15	2.36	3.04	2.34	3.25	2.56	3.18	2.52	3.33	2.60	2.42	2.25	3.04	2.59	1.15	2.11	2.88	2.25	2.00	3.05	3.05
Na ₂ O	27.26	25.94	26.88	24.20	24.40	21.80	22.2	22.28	21.54	19.90	21.34	20.68	19.20	19.06	18.40	17.63	17.82	16.98	16.20	17.17	15.38	14.90	13.57	13.57
K ₂ O	0.07	0.05	0.01	0.06	0.03	0.04	0.06	0.04	0.03	0.13	0.03	0.05	0.06	0.02	0.07	0.04	0.17	0.86	0.02	0.37	1.85	0.11	0.02	0.02
Σ	102.42	100.04	102.52	99.42	96.97	95.48	94.43	98.53	93.37	92.71	95.21	94.47	95.18	93.32	93.95	91.00	94.36	94.03	90.65	94.16	97.92	92.15	90.84	90.84
Formula calculated on the basis of Si + Al = 4 apfu																								
Si	3.98	3.86	4.00	3.99	4.00	3.98	4.00	4.00	4.00	3.97	4.00	4.00	3.98	3.99	3.96	4.00	4.00	4.00	4.00	4.00	4.00	4.00	3.98	3.98
Al	0.02	0.14	0.00	0.01	0.00	0.02	—	0.00	0.00	0.03	0.00	0.00	0.02	0.01	0.04	0.00	0.00	0.00	—	—	0.00	0.02	0.02	0.02
Ti	3.10	3.11	3.17	3.03	3.32	3.09	3.14	3.01	3.34	3.52	3.37	2.96	3.39	3.25	3.46	3.26	3.02	1.79	3.33	3.31	2.37	3.54	3.20	3.20
Nb	0.05	0.26	0.08	0.10	0.06	0.28	0.05	0.24	0.08	0.03	0.09	0.15	0.04	0.07	0.04	0.06	0.07	1.09	0.15	0.06	0.90	0.02	0.06	0.06
Fe	0.34	0.32	0.31	0.61	0.34	0.39	0.33	0.37	0.39	0.55	0.41	0.46	0.32	0.32	0.28	0.44	0.31	0.37	0.35	0.32	0.27	0.22	0.20	0.20
Σ(Ti+Nb+Fe)	3.40	3.70	3.56	3.74	3.66	3.76	3.52	3.62	3.81	4.10	3.87	3.58	3.75	3.64	3.78	3.80	3.40	3.24	3.83	3.69	3.54	3.78	3.46	3.46
Mn	0.06	0.05	0.05	0.08	0.04	0.02	0.13	0.02	0.06	0.05	0.04	0.02	0.19	0.06	0.12	0.06	0.12	0.31	0.07	0.06	0.28	0.01	0.07	0.07
Mg	0.05	0.09	0.02	0.05	0.06	0.08	0.08	0.13	0.06	0.00	0.05	0.14	0.12	0.18	0.10	0.11	0.16	0.00	0.03	0.08	0.14	0.09	1.35	1.35
P	1.86	1.79	1.80	1.95	1.52	1.84	1.82	1.87	1.59	1.91	1.58	1.91	2.29	1.96	2.26	1.66	1.93	1.86	1.96	1.71	2.04	2.28	1.90	1.90
Na	7.99	7.99	7.76	7.49	7.33	6.88	6.83	6.72	6.71	6.54	6.49	6.42	6.11	5.87	5.82	5.42	5.20	5.19	5.05	5.02	4.69	4.59	4.21	4.21
Ca	0.39	0.44	0.33	0.57	0.40	0.53	0.40	0.56	0.36	0.58	0.42	0.57	0.46	0.43	0.40	0.52	0.42	0.19	0.36	0.47	0.38	0.32	0.52	0.52
K	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.03	0.17	0.00	0.07	0.37	0.02	0.04	0.04
Σ(Na+Ca+K)	8.39	8.44	8.09	8.07	7.74	7.42	7.24	7.28	7.07	7.15	6.92	7.00	6.58	6.30	6.23	5.95	5.65	5.56	5.41	5.56	5.44	4.93	4.77	4.77
O	24.00	24.33	23.72	24.21	23.07	24.14	23.47	23.72	23.36	24.61	23.32	23.72	24.90	23.63	24.48	22.87	22.81	22.69	23.26	22.71	23.83	23.89	23.63	23.63

Notes: Analyses 9, 11, 20, 27, 31, 33, and 38 were obtained on Camebax SX-50 electron microprobe at ICGEM RAS, analyst V.V. Khangulov; analyses 1, 35, 37, 39, 40, 44 were obtained on JSM-5300 Link ISIS SEM at ICGEM RAS, analyst N.V. Trubkin; other analyses were obtained on a Cameca MS-46 at ICGEM RAS, analyst O.A. Ageeva. Host rocks: subore massive coarse-grained urtite (soda horizon) (anal. 20); feldspar urtite; with areas of fresh urtite (anal. 23), with soda horizons (anal. 9, 27, 38), with areas of juvite (anal. 6); juvite; with areas of urtite (anal. 4, 14–17, 24), with areas of rischorrite (anal. 10, 12); rischorrite; anal. 3, 5, 7, 13, 21, 22, 25, 28–30, 32–35, 37, 39, 41, 44–45, the same rock with soda horizon; anal. 1, 26; malignite; anal. 2, 8, 19, 36, the same rock with zones of rischorrite; anal. 31; pegmatites in rischorrite and malignite; anal. 11, 40, 42–43. Dash denotes that the data are absent. In number of sample, sampling depth over number of drill hole.

content comes to our attention. It is interesting that Na is partially substituted by K with high-level substitution Ti for Nb. For example, some betalomonosovites from the Mt. Yukspor pegmatite are K-Nb varieties (Nb₂O₅ 12.69 wt.%, Nb 0.90 apfu and K₂O 1.85 wt.%, K 0.37 apfu – anal. 50; Nb₂O₅ 15.26 wt.%, Nb 1.09 apfu and K₂O 0.86 wt.%, K 0.17 apfu – anal. 40).

Betalomonosovite from arfvedsonite-feldspar pegmatite vein (collection of M.N. Sokolova, sample no. 569) in the Apatite cirque of Rasvumchorr was studied in detail. Electron microprobe data together with bulk data of Sokolova *et al.* (1971) are given in Table 2. As these compositions (anal. 1–5) had been normalized to 16 cations, we recalculated them on the basis of Si + Al = 4. As is seen from Table 2, the chemical composition of betalomonosovite is more or less constant: total alkali constituents is about 6 apfu; amount of Ti and isomorphous admixtures is about 4; Si = 4; and proportion of P is about 2 apfu, but O and

H concentration ranges from 24 to 26 and 1 to 2 apfu (exceptional holotype sample from Lovozero), respectively. In general, this supports that the chemical composition of the Khibiny lomonosovite is consistent with formula: Na₄Ti₄Si₄O₁₈•2NaH₂PO₄.

Crystal structures of lomonosovite and betalomonosovite: similarity and differences

The crystal structure of lomonosovite was determined by Rastsvetaeva *et al.* (1971) and was refined by Belov *et al.* (1977). It was discussed in detail in light of the murmanite structure determined by Khalilov *et al.* (1965₁, 1965₂), Khalilov (1989), and Rastsvetaeva and Andrianov (1986), general problems of crystal chemistry and structural topology, and genetic singularities of murmanite (Belov and Organova, 1962; Belov, 1965; Khalilov and Makarov, 1966). The crystal structure of betalomonosovite was solved on samples from Lo-

Table 2. Chemical composition (wt.%) of betalomonosovite from pegmatites of various geological setting

No. anal.	1	2	3	4	5	6
SiO ₂	25.18	25.51	25.05	26.07	25.22	25.27
TiO ₂	25.01	28.80	28.58	28.77	27.64	30.43
ZrO ₂	1.89	1.00	0.52	0.71	0.54	–
P ₂ O ₅	16.12	15.12	14.31	14.55	14.86	14.49
Nb ₂ O ₅		1.10	1.70	1.16	1.17	1.01
Ta ₂ O ₅	4.78	–	0.037	0.02	0.012	–
Al ₂ O ₃	0.69	0.30	0.21	0.30	0.12	0.01
Fe ₂ O ₃	2.38	3.27	3.37	2.75	3.87	3.04
FeO	Bdl	–	0.28	–	0.16	–
MnO	1.40	0.37	0.03	0.35	0.78	0.48
MgO	0.22	0.20	0.34	0.35	0.22	0.33
CaO	0.62	2.01	2.88	2.68	3.04	3.19
Na ₂ O	17.13	18.28	17.68	17.63	16.19	19.90
K ₂ O	0.88	0.34	0.45	0.40	0.35	0.32
H ₂ O ⁺		3.90	3.83	3.80	4.95	–
H ₂ O ⁻	4.60	Bdl	Bdl	0.70	Bdl	–
F	–	0.59	0.50	0.43	0.64	0.53
-O = F ₂	–	-0.25	-0.21	-0.19	-0.27	-0.22
Total	100.90	100.54	99.55	100.49	99.67	92.48

Empirical formula calculated on the basis Si + Al = 4 apfu

1. (Na_{5.11}K_{0.17}Ca_{0.10})_{Σ=5.38}(Ti_{2.89}Nb_{0.33}Zr_{0.14}Fe_{0.28}Mn_{0.18}Mg_{0.05})_{Σ=3.87}(Si_{3.88}Al_{0.12})_{Σ=4}P_{2.10}O_{25.84}H_{4.72}
2. (Na_{5.48}K_{0.07}Ca_{0.33})_{Σ=5.88}(Ti_{3.35}Nb_{0.08}Zr_{0.08}Fe_{0.38}Mn_{0.05}Mg_{0.05})_{Σ=3.99}(Si_{3.95}Al_{0.05})_{Σ=4}P_{1.98}O_{24.74}H_{2.01}F_{0.29}
3. (Na_{5.42}K_{0.09}Ca_{0.49})_{Σ=6.00}(Ti_{3.40}Nb_{0.12}Zr_{0.04}Fe_{0.45}Mn_{0.00}Mg_{0.07})_{Σ=4.08}(Si_{3.96}Al_{0.04})_{Σ=4}P_{1.92}O_{24.83}H_{1.83}F_{0.25}
4. (Na_{5.17}K_{0.08}Ca_{0.45})_{Σ=5.70}(Ti_{3.28}Nb_{0.08}Zr_{0.05}Fe_{0.31}Mn_{0.05}Mg_{0.08})_{Σ=3.85}(Si_{3.95}Al_{0.05})_{Σ=4}P_{1.86}O_{23.59}H_{1.19}F_{0.21}
5. (Na_{4.95}K_{0.07}Ca_{0.51})_{Σ=5.53}(Ti_{3.28}Nb_{0.08}Zr_{0.04}Fe_{0.48}Mn_{0.10}Mg_{0.05})_{Σ=4.03}(Si_{3.96}Al_{0.02})_{Σ=4}P_{1.98}O_{24.31}H_{1.24}F_{0.32}
6. (Na_{4.26}K_{0.06}Ca_{0.54})_{Σ=4.86}(Ti_{3.62}Nb_{0.07}Fe_{0.36}Mn_{0.06}Mg_{0.08})_{Σ=4.10}(Si_{4.00}Al_{0.00})_{Σ=4}P_{1.94}O_{23.77}F_{0.27}

Notes: (1) Lovozero massif, Tulbn'yunai river, pegmatite hosted in nepheline-sodalite poikilitic syenite, analyst M.E. Kazakova (Gerasimovskiy and Kazakova, 1962); (2–6) Khibiny massif, Apatite cirque of the Rasvumchorr deposit: (2) rischorrite, (3–5) arfvedsonite-feldspar pegmatite veins cutting rischorrite, analyst N.I. Zabavnikova (Sokolova *et al.*, 1971₃), (6) the same, sample no. 569, collection of M.N. Sokolova, structurally refined in this study, electron-microprobe analysis. Total of anal. 3 includes 0.024 wt. % SrO; total of anal. 5 includes, wt. %: 0.018 Li₂O, 0.013 Rb₂O, 0.0007 Cs₂O, 0.007 % SrO, analyst G.Ye. Kalenchuk. No water was analyzed in anal. 6.

vozero by Khalilov and Makarov (1966), Khalilov (1990), and Rastsvetaeva (1986, 1988, 1989) as well as sample from Khibiny (Rastsvetaeva *et al.*, 1975).

As the data on the discussed structures were obtained long enough and some new members of the lomonosovite group were discovered to date, these structures should be refined with the state methods and revision of crystal chemical features. Cámara *et al.* (2008) performed this study for the lomonosovite and murmanite structures, but the structure of betalomonosovite attributed to discredited minerals was not refined. Yakubovich *et al.* (2014) refined it and below it is compared with the structure of lomonosovite.

Unfortunately, the sample refined by Cámara *et al.* (2008) cannot be regarded as typical lomonosovite, because it was selected from fine fraction of the Lovozero bornemanite that is secondary mineral replacing lomonosovite, i.e., it is originated from different geological environment than the Khibiny lomonosovite genetically related to the discussed betalomonosovite. However, our examination of this uncommon and deficient material showed the power of modern structural methods and allowed justification of sites, their occupancies by trace elements, and determination of iron valence with the Mössbauer method. By the way, the $\text{Fe}^{2+}/\text{Fe}^{3+} = 58/42$ value of 58/42 indicates long transition from reductive to oxidative formation conditions, whereas the Lovozero murmanite was formed under oxidative conditions (iron is completely trivalent).

The empirical formula of lomonosovite with refined structure $(\text{Na}_{9.50}\text{Mn}_{0.16}\text{Ca}_{0.11})_{\Sigma 9.77}(\text{Ti}_{2.83}\text{Nb}_{0.51}\text{Mn}_{0.27}\text{Zr}_{0.11}\text{Mg}_{0.11}\text{Fe}_{0.10}^{2+}\text{Fe}_{0.06}^{3+}\text{Ta}_{0.01})_{\Sigma 4.00}(\text{Si}_{2.02}\text{O}_7)_2(\text{P}_{0.98}\text{O}_4)_2(\text{O}_{3.50}\text{F}_{0.50})_{\Sigma 2}$, calculated on the basis of 26 (O + F) anions from the composition determined on a Cameca SX100 electron microprobe is consistent with the structural formula $\text{Na}_{10}\text{Ti}_4(\text{Si}_2\text{O}_7)_2(\text{PO}_4)_2\text{O}_4$ ($Z = 1$). The unit cell dimensions are $a = 5.4170(7)$, $b = 7.1190(9)$, $c = 14.487(2)\text{Å}$, $\alpha = 99.957(3)^\circ$, $\beta = 96.711(3)^\circ$, $\gamma = 90.360(3)^\circ$, $V = 546.28(4)\text{Å}^3$, $D_{\text{calc.}} = 3.175\text{ g/cm}^3$. Space group is $P\bar{1}$ (Cámara *et al.*, 2008).

We refined the crystal structure of the Khibiny betalomonosovite on the material from pegmatite in the Apatite cirque of Mt. Rasvumchorr. The chemical composition determined on a JEOL JXA-8200 electron microprobe (Table 2) are normalized on the basis of 4 (Si + Al) atoms to formula $(\text{Na}_{4.26}\text{Ca}_{0.54}\text{K}_{0.07})_{\Sigma 4.87}(\text{Ti}_{3.66}\text{Nb}_{0.07}\text{Fe}_{0.36}\text{Mn}_{0.07}\text{Mg}_{0.08})_{\Sigma 4.24}\text{Si}_4\text{P}_{1.96}\text{O}_{23.54}\text{F}_{0.27}$, corresponding to the crystal chemical formula

$(\text{Na}_{4.42}\text{Mn}_{0.11}\text{Ca}_{0.71}\text{K}_{0.07})_{\Sigma 5.31}(\text{Ti}_{3.63}\text{Nb}_{0.03}\text{Fe}_{0.34}^{3+})_{\Sigma 4.00}\text{O}_2[(\text{O},\text{OH})_{0.79}\text{F}_{0.21}]_2[\text{Si}_2\text{O}_7]_2[\text{H}_2\text{PO}_4]_2$. The unit cell dimensions are $a = 5.3184(3)$, $b = 7.0869(5)$, $c = 14.4490(10)\text{Å}$, $\alpha = 102.944(7)^\circ$, $\beta = 96.367(7)^\circ$, $\gamma = 90.331(6)^\circ$, $V = 527.22(6)\text{Å}^3$, $D_{\text{calc.}} = 2.91\text{ g/cm}^3$. Space group is $P\bar{1}$.

The comparison of the structures indicates.

Lomonosovite is disilicate. According to Cámara *et al.* (2008), its structure is based on the **TS** titanosilicate blocks with formula $A^p_2M^h_2M^o_4(\text{Si}_2\text{O}_7)_2X_4$, alternated along axis c with intermediate blocks **I** corresponding in composition to $\text{Na}_6(\text{PO}_4)_2$ (Fig. 4a). The **TS** block consists of octahedral layer **O** composed of close packed octahedra $M^o(2) - {}^{16}\text{Ti}^o(2)$ and ${}^{16}\text{Na}^o(2)$ as brookite-type chains $(\text{Ti}_2\text{O}_8)^{8-}$ linked with Na octahedra in similar configuration in ratio $\text{Ti}:\text{Na} = 1:1$ (Na_2Ti_2 per cell) (Fig. 5a), and heteropolyhedral layer **H** composed of M^h polyhedra $- {}^{16}\text{Ti}^h(1)$ octahedra bonded with Si_2O_7 groups and eight-fold polyhedra ${}^{18}\text{Na}^h(1)$ (Fig. 5b). Connecting **P** layer is conditionally determined because two Si_2O_7 groups are linked with the nearest ${}^{16}\text{Ti}^o(2)$ octahedra of the brookite chains via oxygen atoms (Fig. 5c) while ${}^{16}\text{Ti}^h(1)$ octahedron shares apex occupied by oxygen $X^o_M = \text{O}(8)$ with two ${}^{16}\text{Na}^o(2)$ and one ${}^{16}\text{Ti}^o(2)$ octahedra of the **O** layer (Figs. 5b, 5c). Tetrahedrally coordinated **P** bonded with Na polyhedra of three types ${}^{16}\text{Na}(3)$, ${}^{14}\text{Na}(4)$ and ${}^{15}\text{Na}(5)$ occurs in block **I** (Fig. 4a).

As aforementioned, the ideal structural formula of lomonosovite regardless isomorphic admixtures is $\text{Na}_{10}\text{Ti}_4(\text{Si}_2\text{O}_7)_2(\text{PO}_4)_2\text{O}_4$ ($Z = 1$). The both Ti sites contain Nb, Fe, Mn, and Mg admixtures, but ${}^{16}\text{Ti}^h(1)$ octahedron is dominated by Ti. Small portion of vacancy $\square_{0.05}$ per cell occurs in eight-fold polyhedron ${}^{18}\text{Na}^h(1)$ and octahedron ${}^{16}\text{Na}^o(2)$; octahedron ${}^{16}\text{Na}(3)$ of the **I** layer contains 0.11 apfu Ca, and tetrahedron ${}^{14}\text{Na}(4)$ contains 1.71 Na + 0.16 Mn^{2+} + 0.13 \square . The calculated valence force at site $X^o_A = \text{O}(9)$ bonded with two atoms Ti(2) and atom Na(2) in the **O** layer and atom Na(1) in the **H** layer is lesser than that at site X^o_M , occupied only by O atoms and linked with Ti(1) in the **H** layer and Ti(2) and two Na(2) in the **O** layer (Fig. 5c) (1.84 against 2.05 v.u.) that is consistent with the partial substitution of F for O according to the reaction: $\text{Ti}^{4+} + \text{O}(9)^{2-} \rightarrow \text{M}^{2+} + \text{F}^-$ with the substitution of Ti at site $\text{Ti}^o(2)$ with divalent elements $\text{Mn}_{0.22}\text{Mg}_{0.11}\text{Fe}_{0.05}^{2+}$ (0.38 apfu).

The refined crystal structure of betalomonosovite (Yakubovich *et al.*, 2014) is distinguished by some features (Table 3). In the **O**

layers of the **TS** blocks, Ti sites $M2^{[6]}$ corresponding to $M^{\circ}(1) = {}^{16}\text{Ti}^{\circ}(2)$ in lomonosovite (Fig. 4b) are also completely occupied, but with Fe admixture only, whereas all-Na octahedra $M^{\circ}(2) = {}^{16}\text{Na}(2)$ of lomonosovite are transformed to seven-fold polyhedra $M5^{[7]}$ in betalomonosovite and are half occupied by Na with Ca admixture, whereas another half is vacant (Fig. 5d). In the *H* layers of the **TS** blocks the Ti dominated $M1^{[6]}$ octahedra corresponding to octahedra $M^{\text{H}} = {}^{16}\text{Ti}^{\text{H}}(1)$ in lomonosovite are also completely occupied, but only with Ti and Nb; Ca incorporates into all-Na eight-fold polyhedra $A^{\text{P}} = {}^{18}\text{Na}(1)$ depicted as $M4^{[8]}$, and nearly half polyhedra is vacant (Fig. 5e).

Therefore, Ti content in the **TS** blocks of betalomonosovite is elevated; Na is partly substituted by Ca; and nearly half Na is removed. However, the crystal chemical analysis should be careful because isomorphous admixtures in the minerals from different geological environment are compared. The additional comparison with the structure of murmanite from Lovozero (Cámara *et al.*, 2008) shows that the greatest occupancy of $\text{Ti}^{\circ}(2)$ octahedral in brookite chains with various isomorphous admixtures is common in the discussed minerals of the lomonosovite group, whereas octahedron $\text{Ti}^{\text{H}}(1)$, linked with disilicate groups Si_2O_7

is always Ti dominated. The elevated content of trace elements is observed at Na sites linked with Ti; in this case, $\text{Na}^{\circ}(2)$ contains not only Ca, but Mn, and in eight-fold $\text{Na}^{\text{P}}(1)$ polyhedra, where Cámara *et al.* (2008) found K in murmanite, Mn could be incorporated into the structures of the Khibiny lomonosovite and betalomonosovite, where elevated K and Nb contents were found (Table 1). Few vacancies are typical of these Na sites in lomonosovite and betalomonosovite. However, their amount is disparate with vacancies in the structure of betalomonosovite from Rasvumchorr that is the *most important feature* of the mineral studied here.

The differences in the structure of the intermediate **I** block in the structure of betalomonosovite as compared with lomonosovite highlight this feature (Table 3). All-Na five-fold polyhedron ${}^{15}\text{Na}(5)$ in lomonosovite corresponds to $M3^{[6]}$ octahedron less than half occupied and contaminated by Mn ($0.762 \text{ Na} + 0.118 \text{ Mn} + 1.12 \square$) in betalomonosovite. Tetrahedron ${}^{14}\text{Na}(4)$ ($1.71 \text{ Na} + 0.16 \text{ Mn} + 0.13 \square$) with similar occupancy and small vacancy was such polyhedron in lomonosovite. The ${}^{14}\text{Na}(2)$, polyhedron occupied with Na only for eight ($0.24 \text{ Na} + 1.76 \square$) corresponds to it in betalomonosovite. Eight-fold ${}^{18}\text{Na}(1)$ polyhedron that was octahedron and contained

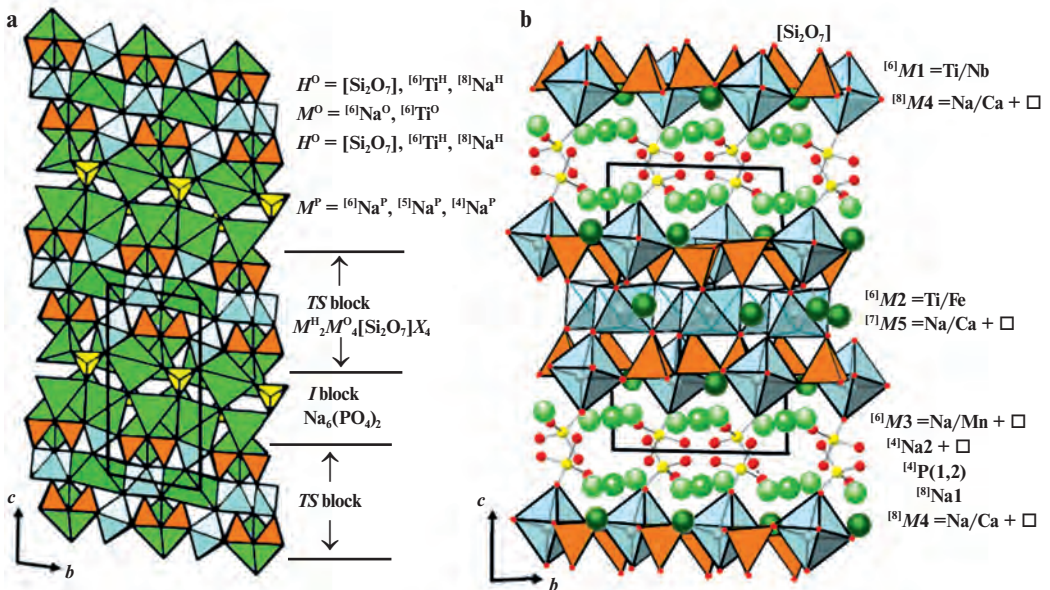


Fig. 4. Comparison of crystal structures of lomonosovite (Cámara *et al.*, 2008), and betalomonosovite (Yakubovich *et al.*, 2014): (a) structure of lomonosovite projected onto (100), titanosilicate (**TS**), heteropolyhedral (**I**), and Na-P $\text{Na}_6(\text{PO}_3)_2$ blocks alternated along axis *c*;

(b) structure of betalomonosovite, view along diagonal of the *ab* face, alternation of the same blocks along axis *c*; the unit cells are shown as rectangles; disilicate groups Si_2O_7 are red-orange; Ti-octahedra are blue; differently coordinated Na polyhedra are green; P tetrahedra are yellow; and oxygen atoms are red circles.

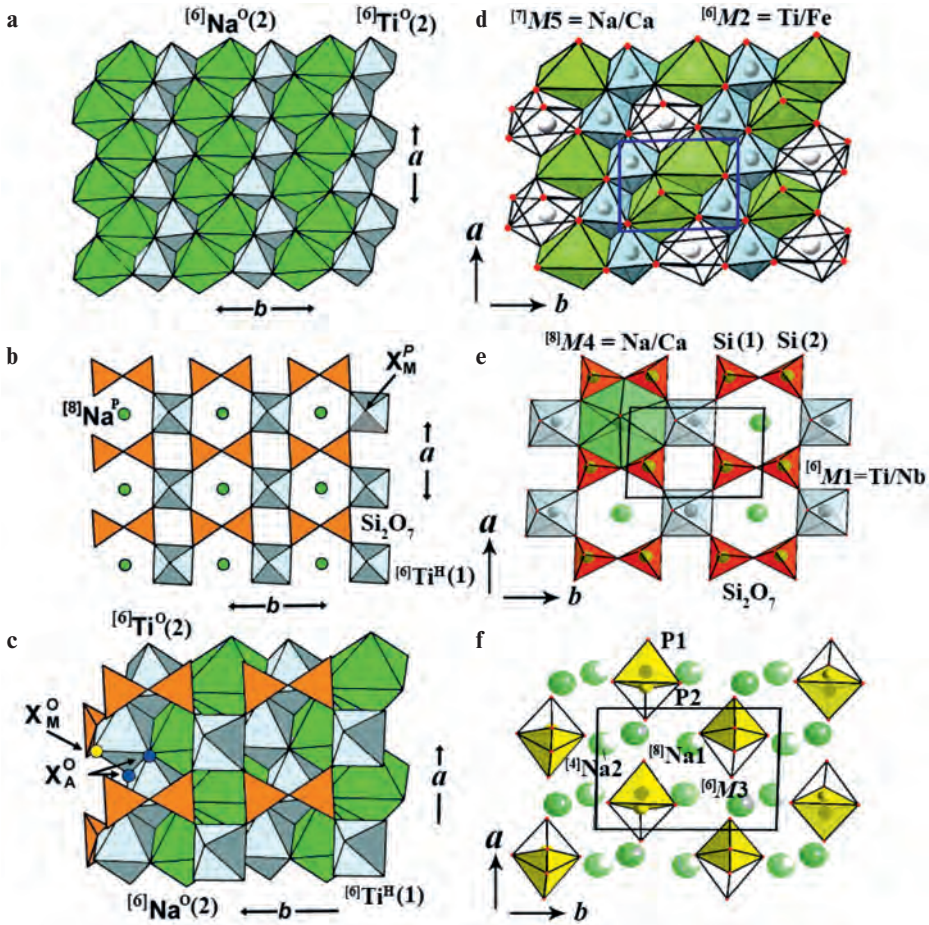


Fig. 5. Comparison of crystal structures of lomonosovite (a–c) (Cámara *et al.*, 2008) and betalomonosovite (d–f) (Yakubovich *et al.*, 2014) projected perpendicular to axis [001]:

- (a) close packed Ti and Na octahedra of octahedral O layer from TS block in lomonosovite;
 (b) disilicate groups Si_2O_7 , Ti octahedral, and Na eight-fold polyhedral of heteropolyhedral H layer from TS block;
 (c) junction of octahedral and heteropolyhedral layers in TS block, main oxygen atoms in Ti and Na polyhedra X_M^P , X_M^O and X_A^O (see text) are shown;
 (d) probable distribution of vacancies in Na polyhedra of octahedral O layer from the TS block in betalomonosovite; (e) titanosilicate "maille" of heteropolyhedral H layer from the TS block with Na eight-fold polyhedra in cavities;
 (f) defect Na-P layer $[\text{Na}_{3.00}\text{Mn}_{7.11}(\text{H}_2\text{PO}_4)_2]$ in betalomonosovite with oxocomplexes $[\text{P}_2\text{O}_4]_{0.5}\text{O}_2$ composed of two phosphate tetrahedra with different filling put into each other.

Ca ($^{[6]}\text{Na}(3) = 1.89 \text{ Na} + 0.11 \text{ Ca}$) in lomonosovite becomes all-Na. In other words, Na polyhedra are substantially reorganized: tetrahedra are retained ($\text{Na}(4) \rightarrow \text{Na}2$), whereas lomonosovite five-fold Na(5) polyhedron and octahedron Na(3) are modified to octahedron M3 and Na1 eight-fold polyhedron, respectively (Fig. 5f). According to Rastsvetaeva *et al.* (1975), two couples of Na_6 and Na_7 eight-fold polyhedra and nonpaired octahedron Na_5 disturbing centrosymmetric structure occur in this block. Thus, in I block of betalomonosovite, Na polyhedra (determined by various investigators in different ways) are signifi-

cantly rearranged and degree of their occupancy substantially decreases (proportion of vacancy increases = 2.88 □).

The split of P site is also substantial that was previously reported by Rastsvetaeva *et al.* (1975). According to their data, position of P_2 corresponded to that in lomonosovite, whereas the second P_1 was turned around that resulted in the P–O chain. Our version of the structure shows that phosphorus site is split to P_1 and P_2 at inadmissible short distance of 0.53 Å, and therefore there is a 50% chance that these positions will be occupied, as well as, two of four apices occupied by oxygen atoms

Table 3. Comparison of cation sites in the crystal structures of lomonosovite (Cámara *et al.*, 2008) and betalomonosovite (our data) as indicated by various authors and their occupancy

	Lomonosovite (Cámara <i>et al.</i> , 2008)	Betalomonosovite (Yakubovich <i>et al.</i> , 2014)
$M^O(1) = {}^{60}\text{Ti}^O(2)$	1.31 Ti + 0.22 Mn ²⁺ + 0.20 Nb + 0.11 Zr + 0.05 Fe ²⁺ + 0.11 Mg = 2.00	M2 ⁶⁰ 1.66 Ti + 0.34 Fe = 2.00
$M^O(2) = {}^{60}\text{Na}^O(2)$	1.95 Na + 0.05 □ = 2.00	M5 ⁷⁰ 0.63 Na + 0.37 Ca + 1.00 □ = 2.00
$M^H = {}^{60}\text{Ti}^H(1)$	1.52 Ti + 0.05 Mn ²⁺ + 0.31 Nb + 0.01 Ta + 0.06 Fe ³⁺ + 0.05 Fe ²⁺ = 2.00	M1 ⁶⁰ 1.97 Ti + 0.03 Nb = 2.00
$A^P = {}^{60}\text{Na}(1)$	1.95 Na + 0.05 □ = 2.00	M4 ⁸⁰ 0.78 Na + 0.34 Ca + 0.88 □ = 2.00
${}^{40}\text{P}$	2.00 P	P1 ⁴⁰ 1.00 P
		P2 ⁴⁰ 1.00 P
${}^{60}\text{Na}(5)$	2.00 Na	M3 ⁶⁰ 0.76 Na + 0.12 Mn + 1.12 □ = 2.00
${}^{60}\text{Na}(3)$	1.89 Na + 0.11 Ca = 2.00	Na1 ⁶⁰ 2.00 Na
${}^{40}\text{Na}(4)$	1.71 Na + 0.16 Mn ²⁺ + 0.13 □ = 2.00	Na2 ⁴⁰ 0.24 Na + 1.76 □ = 2.00

Notes: The site occupancy in betalomonosovite is shown for complete cell to compare with lomonosovite, i.e. it is duplicated; in this case, vacancies in its structure are better displayed.

O12 and O12A, and O13 and O13A in phosphate tetrahedra input into each other that leads to the formation of orthocomplexes $[(\text{P}_2\text{O}_4)_{0.5}\text{O}_2]$ in average structure (Fig. 5f). The deficient valence force and overestimated O–P distance for these oxygen atoms (0.66–1.00 v.u. and 1.513–1.547Å) relative to other atoms O11 and O4 in P tetrahedral (1.61 and 1.96 v.u. and 1.497–1.508Å, respectively) suggest that they are transformed to OH groups and are donors of hydrogen bonds linking orthocomplexes and Na polyhedra.

Thus, betalomonosovite substantially differs from both lomonosovite and murmanite in the arrangement of H atoms in the structure. According to (Cámara *et al.*, 2008) in murmanite, blocks **TS** are linked through outer anions X^P_M of titanium $M^H = \text{Ti}(1)$ octahedra and anions X^P_A of sodium $A^P = \text{Na}(1)$ eight-fold polyhedral, in which oxygen atoms O(10) and O(11) are substituted by H₂O groups and donor-acceptor hydrogen bond arises between oxygen atoms of different oppositely oriented H₂O groups or with non-substituted oxygen atoms O(2)a and O(4)a. Hydroxyl groups are absent in the structure of murmanite.

Hydration of lomonosovite and water in the structure. Thermal analysis

The hypothesis of the secondary origin of murmanite, its formation as a result of Na leaching and hydration, was proposed for the first time by Borneman-Starynkevich (1946) and experimentally confirmed by Zabaynikova (1967); in the course of experiments, milled lomonosovite was treated by water at room temperature during one year; Na and P released from mineral as Na orthophosphate

Na₃PO₄ to complete loose of Na-phosphate constituent. The degree of replacement of lomonosovite by murmanite depended on the degree of bucking and time of water treatment. The scheme proposed by I.D. Borneman-Starynkevich and N.I. Zabaynikova is used in literature to explain pseudomorphic nature of murmanite.

Recently, Selivanova *et al.* (2008) and Selivanova (2102) performed experiments on lomonosovite hydrolysis and cation exchange, but worse carefully (the samples were soaked only 0.5–48 hours at room temperature or 1–100 hours at 74–80°C). It is surprisingly that any result has been obtained, especially when the dependence of dehydration degree on the trace element content in the structure of lomonosovite has been established. Nevertheless, Selivanova's objection of classic concept of pseudomorphic nature of murmanite as a supergene alteration product of lomonosovite caused a discussion in literature.

Lykova *et al.* (2012) repeated runs in distilled water at room temperature for 1000 hours for lomonosovite and betalomonosovite samples of 75 mg in weight crushed to 0.5–1.5 mm in size. These experiments showed that alteration is very slow in distilled water at room temperature and geological time is required to obtain the expected result. The rate of Na and P leaching from the intermediate layer in the structure of lomonosovite increases at 90°C: Na and P contents decrease from 9.5 to 5.4–3.0 apfu and from 2.0 to 0.7–0.6 apfu, respectively, i.e., the rate of Na removal is much higher than that P with d_{001} changing from 14.2 to 12.7Å in final phase.

It is important that in the first place, the rate of Na and P leaching from betalomonosovite is half of that from lomonosovite: only 0.4% P₂O₅ and 0.5% Na₂O were leached from

fraction -0.25 to $+0.1$ mm during 6 months at room temperature, whereas from lomonosovite 2.0 and 3.3%, respectively, i.e., betalomonosovite is more persistent to affecting neutral solutions than hyperagpaitic lomonosovite. In the second place, Na is leached only from the Na-P intermediate layer of the lomonosovite structure at room temperature, but it does not remove from titanosilicate layer as established by Selivanova *et al.* (2008). The data of Lykova *et al.* (2012) support the classic conclusion that murmanitization of lomonosovite is resulted from the effect of neutral of weakly acidic low-temperature solutions although a long time is required. More stable linkage of Na-P clusters in betalomonosovite than that in lomonosovite was explained by hydrogen bonds, which are typical of acidic salts Na_2HPO_4 or NaH_2PO_4 (Sokolova *et al.*, 1971; Rastsvetaeva *et al.*, 1975). In contrast to murmanitization, lomonosovite is replaced by betalomonosovite at higher temperature in strongly alkaline medium with substantial Na removal. Our data indicate that Na is leached from both intermediate *I* layer and titanosilicate *TS* layer.

We obtained the new data on thermal behavior of the lomonosovite group minerals. Thermograms were obtained on a Q-1500D derivatograph, Hungary equipped with an Ecohrom complex for the data recording and processing within the range from 25 to 1000°C. The samples were placed into platinum crucibles and heated in air with rate of 15 degree/min; the Al_2O_3 sample of 200 mg in weight was used as reference material.

The lomonosovite thermogram (Fig. 6a) was recorded for the sample of 228 mg in weight. The DSC curve of lomonosovite exhibits one pronounced high-temperature endothermic peak at 871°C corresponding to the melting of mineral and two weak endothermic effects at 941 and 992°C not accompanied with weight loss and reflecting energy input for the processes in the lomonosovite melt. This energy was probably to be consumed for rebuilding of crystalline clusters composed of the SiO_4 and PO_4 tetrahedra. In the low-temperature region of the curve, two insignificant bends are exhibited at 248 and 250°C accompanied with insignificant weight loss of 0.68 and 0.48 wt.%. They are evidently caused by the evaporation of water and NaF.

The thermogram of betalomonosovite recorded for the sample of 227 mg in weight differs fundamentally from that of lomonosovite (Fig. 6b). The DSC curve exhibits triple endothermic effect in the range of 237 to 550° with

the bend at 271°C and minimums at 382 and 406°C followed by clear exothermic effect at 625°C corresponding to rebuilding of the mineral structure and two symmetric endothermic effects with maximum at 761 and 852°C not accompanied with weight loss and corresponding to two stage of the minerals melting. The DTG curve shows that most weight (11.01 wt.%) is lost during three stages (1.86, 3.65, and 5.50 wt.%) within the range 235–720°C. As is seen from the TG curve, at high temperature the weight is lost evenly and is not related to the high-temperature endothermic peaks on the DSC curve.

The thermogram of murmanite (Fig. 6c) recorded for the sample of 190 mg in weight differs enormously from that of lomonosovite and betalomonosovite in both shape and weight loss (27.16 wt.%). The DSC curve of murmanite exhibits strong symmetric endothermic effect at 275°C corresponding to a weight loss of 17.88 wt.% related to water removal from the mineral. This effect is followed by a pronounced curve bend at 450°C corresponding to the major stage of weight loss. The clear symmetric endothermic peak at 726°C corresponds to the mineral melting accompanied with loss of residual water (1.94 wt.%) that is exhibited as small peak at 733°C on the DTG curve. This peak is followed by a clear bend at 993°C on the DSC caused by energy consumption for the structure rebuilding in the murmanite melt. The analysis of the DTG curve reveals two types of water in the structure of murmanite: weakly bound (17.88 wt.%) quickly removed in the narrow temperature range up to 275°C with maximum at 177°C and tightly bound (7.34 wt.%) gradually released up to the mineral melting.

Thus, the minerals studied here are dramatically different in thermal curves. Total weight loss with heating increases from lomonosovite through betalomonosovite to murmanite (2.65, 14.10, and 27.16 wt.%, respectively). However, the review of thermograms does not allow consideration of betalomonosovite as an intermediate product of transformation of lomonosovite to murmanite with Na leaching and hydration. In the first place, it is indicated by the exothermic effect on the DSC curve of betalomonosovite corresponding to the rebuilding of the mineral structure accompanied with the substantial energy release. If betalomonosovite was intermediate member of the lomonosovite-murmanite series then we could observe comparable or more pronounced energy outbreak related to the end member recrystallization. However, it was obser-

ved neither in our experiments nor on the previously published DCS curves of lomonosovite and murmanite. In general, our results supplement the data of previous investigators, who terminated sample heating before mineral melting.

Status of betalomonosovite

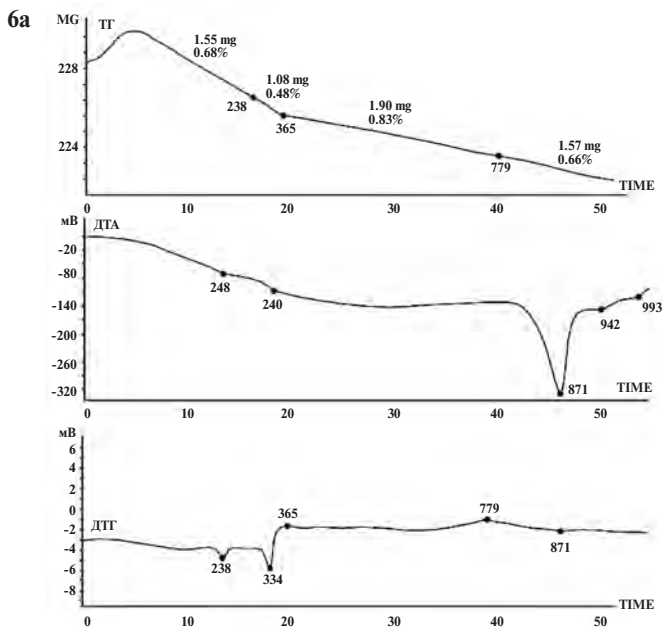
The history of the betalomonosovite discreditation is tortuous. Having acted on behalf of the Commission on New Minerals and Mineral Names of International Mineralogical Association formed in 1959 with the revision of minerals discovered in 1959–1960 and not approved by the Commission Villarroel and Joel (1967) were quite delicate in this question. They evidently understood the importance of the terms β -lomonosovite and metamurmanite and remained them with a significance of 60% or higher; however, they discredited notions metalomonosovite (= β -lomonosovite) and ortholomonosovite (= lomonosovite). In the similar publication, Nickel and Mandarino (1988) put dogmatically betalomonosovite into the list of already discredited mineral name that is surprisingly because, in the first place, this mineral was studied in detail meanwhile and this term was used in literature concerned with mineralogy of alkaline complexes; in the second place, its discreditation was argued by the references to the aforementioned article published in 1967, in which, as we know, discreditation was not discussed.

It does not matter if betalomonosovite is approved by the Commission as individual mineral species or variety of lomonosovite. It is necessary that this term should not be lost with nomenclature changes. However, we think that betalomonosovite has more reasons to be approved as mineral species than many "new minerals" recently approved by the Commission using only recommended formal chemical and crystal chemical criteria regardless genesis, i.e., analysis of formation conditions, stability field of a described mineral, and its importance for geology.

Unfortunately, well-known story of data generalization and formalization in determination of mineral species was about lomonosovite and betalomonosovite, as a result of which mineral is separated away from the parent geological system and is transformed from the real chemical compound to abstract divorced from formation conditions and field of stability within which its chemical composition, structure, and physical properties evolve during geological time in accordance with the evolution of physicochemical parameters of mineral-forming and mineral-retaining medium.

Conclusions

The novel data obtained and detailed review of this problem support necessary rehabilitation of indefinitely discredited term betalomonosovite. This mineral substantially differs in the chemical composition, structural



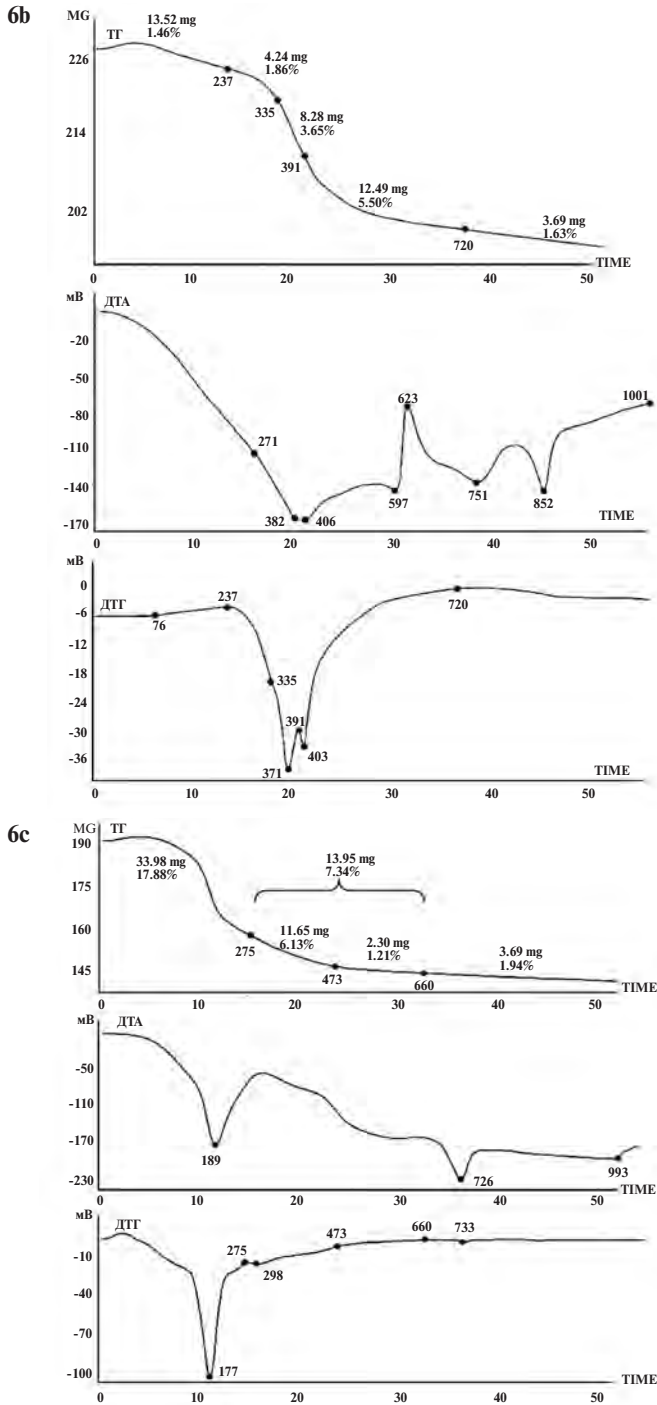


Fig. 6. Thermograms of the lomonosovite group minerals, our data:

(a) lomonosovite (weight 228 mg, weight loss 6.04 mg, 2.65 %);

(b) betalomonosovite (weight 227 mg, weight loss 32.04 mg, 14.10 %);

(c) murmanite (weight 190 mg, weight loss 57.62 mg, 27.16 %).

A Q-1500D derivatograph (MOM, Hungary), 25–1000°C, platinum crucibles, heating rate 15 degree/min, 200 mg Al₂O₃, as reference sample; measurement at air. Analyst P.M. Kartashov.

singularities, and physical properties from both lomonosovite, with which the researchers who do not know enough with nuances of mineralogy of alkaline complexes formally attempt to associate it in the recent mineralogical nomenclature, and murmanite with which it is frequently associated in the lomonosovite-murmanite solid solution, where betalomonosovite is not end-member. It is really genetically related to lomonosovite, but is a product of metasomatic alteration of lomonosovite, recrystallization and crystallization at high-temperature fenitization of rocks of alkaline magmatic complexes with variable basicity of mineral-forming fluids rather than supergene alteration like murmanite. In other words, this mineral could be defined reasonably as individual mineral species characterized by discrete chemical composition and structural singularities, with certain field of stability and studied compositional variations resulted from variable character of mineral-forming and mineral-retaining medium.

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References

- Ageeva O.A. Typomorphism of accessory lomonosovite from the rocks of the Khibiny massif // *Zap. Ross. Mineral. O-va.* **1999.** Vol. 128. No. 2. P. 99–104 (in Russian).
- Ageeva O.A. Typomorphism of Accessory Minerals and Evolution of Mineral Formation in the Rocks of Rischorrite Complex, Khibiny Massif // *Diss. Cand. Geol.-Min. Sci. Moscow: IGEM RAS.* **2002.** 180 p. (in Russian).
- Ageeva O.A., Borutzky B.Ye. To typomorphism of the lomonosovite group minerals // *Mineralogy at the Turn of XIX Century. Abstract. vol. Moscow: VIMS.* **1997.** P. 4 (in Russian).
- Belov N.V. Essays of structural mineralogy. XVI. Murmanite // *Mineral. Proc. Lvov Geol. Soc.* **1965.** Vol. 19. No. 3. P. 295–305 (in Russian).
- Belov N.V., Gavrilova G.S., Solov'eva L.P., Khalilov A.D. The refined structure of lomonosovite // *Dokl. AN SSSR.* **1977.** Vol. 235. No. 5. P. 1064–1067 (in Russian).
- Belov N.V., Organova N.I. Crystal chemistry and mineralogy of the lomonosovite group in terms of the crystal structure of lomonosovite // *Geokhimiya.* **1962.** No. 1. P. 6–14 (in Russian).
- Borneman-Starynkevich I.D. On the chemical nature of murmanite // *Problems of Mineralogy, Geochemistry, and Petrography, Moscow: AN SSSR.* **1946.** P. 66–74 (in Russian).
- Borutzky B.Ye. Rock-forming mineral of peralkaline complexes. Moscow: Nauka. **1988.** 212 p. (in Russian).
- Borutzky B.Ye. Recent concept of nature and geological history of rocks of the Khibiny massif (Critical comparison of proposed hypotheses and comments) // *Unique Objects of the Kola Peninsula: Khibiny. Proc. All-Russia Conf. 80 Anniv. Kola Sci. Center Russian Academy of Sciences, Apatity.* **2010.** P. 7–30 (in Russian).
- Borutzky B.Ye. The essays on fundamental genetic mineralogy: 6. Experience of using detail mineralogical investigation to resolve problems of rock and ore formation: case of study Khibiny massif // *New Data on Minerals.* **2012.** Vol. 47. P. 128–157.
- Bussen I.V., Sakharov A.S. Petrology of the Lovozero Alkaline Massif. Leningrad: Nauka. **1972.** 296 p. (in Russian).
- Cámara F., Sokolova E., Hawthorne F.C., Abdu Y. From structure topology to chemical composition. IX. Titanium silicates: revision of the crystal chemistry of lomonosovite and murmanite, Group-IV minerals // *Miner. Mag.* **2008.** V. 72. № 6. P. 1207–1228.
- Dorfman M.D. Mineralogy of Pegmatites and Weathering Profiles in Ijolite-Urtite of Mt. Yukspor, Khibiny Massif. Moscow-Leningrad: AN SSSR. **1962.** 168 p. (in Russian).
- Dudkin O.B. Structural features of giant pegmatite body in ijolite-urtite of Mt. Yukspor, Khibiny // *Proc. Mineralogy of the Kola Peninsula. Kirovsk: Kola Branch AN SSSR.* **1959.** No. 1. P. 14–19 (in Russian).
- Dudkin O.B., Kozyreva L.V., Pomerantseva N.G. Mineralogy of Apatite Deposits of the Khibiny Tundra Moscow-Leningrad: Nauka. **1964.** 236 p. (in Russian).
- Es'kova E.M. On the lomonosovite-murmanite group minerals // *Tr. IMGRE AN SSSR.* **1959.** No. 2. P. 110–123 (in Russian).
- Gerasimovsky V.I. Lomonosovite, a new mineral // *Dokl. AN SSSR.* **1950.** Vol. 70. No. 1. P. 83–86 (in Russian).
- Gerasimovsky V.I., Kozakova M.E. Betalomonosovite // *Dokl. AN SSSR.* **1962.** Vol. 142. No. 3. P. 670–673 (in Russian).
- Gutkova N.N. Murmanite, a new titanosilicate from the Lovozero tundra // *Dokl. AN SSSR, ser. A.* **1930.** No. 27. P. 731–736 (in Russian).

- Karup-Møller S.* Lomonosovite from the Ilimussaq intrusion, South Greenland // Neues Jahrb. Miner., Abh. **1983**. Bd. 148. H. 1. S. 83–96.
- Karup-Møller S.* Murmanite from the Ilimussaq alkaline complex, South Greenland // Neues Jahrb. Miner., Abh. **1986**. Bd. 155. H. 1. S. 67–88.
- Khalilov A.D.* Refined crystal structure of murmanite and new data for its crystal chemical properties // Mineral Zh. **1989**. Vol. 11. No. 5. P. 19–27 (in Russian).
- Khalilov A.D.* Refined crystal structure of betalomonosovite from the Lovozero alkaline massif // Mineral. Zh. **1990**. Vol. 12. No. 1. P. 10–18 (in Russian).
- Khalilov A.D., Makarov E.S.* Crystal chemistry of the murmanite-lomonosovite group minerals // Geokhimiya. **1966**. No. 3. P. 259–280 (in Russian).
- Khalilov A.D., Makarov E.S., Mamedov Kh.S., P'yanzina L.Ya.* About crystal structure of the murmanite-lomonosovite group minerals // Dokl. AN SSSR. **1965**₁. Vol. 162. No. 1. P. 179–182 (in Russian).
- Khalilov A.D., Mamedov Kh.S., Makarov E.S., P'yanzina L.Ya.* Crystal structure of murmanite // Dokl. AN SSSR. **1965**₂. Vol. 161. No. 6. P. 1409–1411 (in Russian).
- Khomyakov A.P.* Mineralogy of Hyperagpaitic Alkaline Rocks. Moscow: Nauka. **1990**. 196 p. (in Russian) (see also: Oxford: Oxford Univ. Press. **1995**).
- Kupletsky B.M.* To mineralogy of the Khibiny tundras // Dokl. AN SSSR, Ser. A. **1930**. No. 13. P. 331–336 (in Russian).
- Kupletsky B.M.* Kukisvumchorr and adjacent massifs of the central Khibiny tundras by survey in 1929 and 1930 // Tr. SOMPS. **1932**. No. 2. P. 5–62 (in Russian).
- Lykova I.S., Chukanov N.V., Pekov I.V., Chervonnaya N.A., Yapaskurt V.O.* Hydration of the lomonosovite family phosphosilicates // Crystalline and Solid Non-Crystalline State of Mineral Matter: Problems of Structuring, Ordering, and Evolution of Structure. Proc. Mineral. Workshop. Syktyvkar: Geoprint. **2012**. P. 140–141 (in Russian).
- Mineralogy of the Khibiny Massif. Vol. 2. Minerals / Ed. F.V. Chukhrov. Moscow: Nauka. **1978**. 586 p. (in Russian).
- Minerals of the Khibiny and Lovozero Tundras / Eds. A.T. Fersman, N.A. Smol'yani-nov, E.M. Bonshtedt. Moscow-Leningrad: AN SSSR. **1937**. 563 p. (in Russian).
- Nickel E.H., Mandarino J.A.* Procedures involving the IMA Commission on New Minerals and Mineral Names, and guidelines on mineral nomenclature. Appendix 1: Discredited mineral names // Miner. Mag. **1988**. Vol. 52. Pt. 2. № 365. P. 275–292.
- Platonov A.N.* The Nature of Color of Minerals. Kiev: Naukova Dumka. **1976**. 264 p. (in Russian).
- Ramsay W.* Geologische Beobachtungen auf der Halbinsel Kola. Nebst einem Anhang. Petrographische Beschreibung der Gesteine des Lujavurrut // Fennia. **1890**. Vol. 3. No 7. S. 1–52 (in German).
- Rastsvetaeva R.K.* Crystal structure of the Lovozero betalomonosovite // Kristallografiya. **1986**. Vol. 31. No. 6. P. 1070–1075 (in Russian).
- Rastsvetaeva R.K.* Crystal structure of disordered modification of betalomonosovite // Zap. Vses. Mineral. O-va. **1988**. Vol. 117. No. 6. P. 696–705 (in Russian).
- Rastsvetaeva R.K.* On the structural transformations of betalomonosovite // Kristallografiya. **1989**. Vol. 34. No. 4. P. 880–884 (in Russian).
- Rastsvetaeva R.K., Andrianov. V.I.* The new data for the crystal structure of murmanite // Kristallografiya. **1986**. Vol. 31. No. 1. P. 82–87 (in Russian).
- Rastsvetaeva R.K., Simonov V.I., Belov N.V.* Crystal structure of lomonosovite Na₅Ti₂[Si₂O₇][PO₄]O₂ // Dokl. AN SSSR. **1971**. Vol. 197. No. 1. P. 81–84 (in Russian).
- Rastsvetaeva R.K., Sirota M.I., Belov N.V.* Crystal structure of betalomonosovite // Kristallografiya. **1975**. Vol. 20. P. 259–264 (in Russian).
- Rudenko S.A.* To the genesis of apatite deposits in the Khibiny massif // Zap. Leningrad Mining Inst. **1964**. Vol. 47. No. 2. P. 49–70 (in Russian).
- Selivanova E.A.* Exchange Processes and Evolution of Titanosilicates in the Khibiny and Lovozero Alkaline Massifs // Abstract Cand. Diss. Geol.-Min. Sci. St.-Petersburg: St.-Petersburg State Mining Univ. **2012**. 19 p. (in Russian).
- Selivanova E.A., Yakovenchuk V.N., Pakhomovsky Ya.A., Ivanyuk G. Yu.* Features of low-temperature alteration of Ti- and Nb-phyllsilicates under laboratory condition // Minerals as Advanced Materials I / Ed. S. Krivovichev / Berlin, Heidelberg: Springer-Verlag. **2008**. P. 143–151.
- Semenov E.I., Organova N.I., Kukharchik M.V.* New data on the lomonosovite-murmanite group minerals // Kristallografiya. **1961**. Vol. 6. No. 6. P. 925–932 (in Russian).
- Sokolova M.N.* Mineralogical study of pegmatites from economic apatite deposits in

- Khibiny // Abstracts of research papers of IGEM AN SSSR in 1958–1959. Moscow: IGEM. **1961**. 263 p. (in Russian).
- Sokolova M.N.* To mineralogy of deep levels of the Kukisvumchorr apatite deposit in the Khibiny tundras // Dokl. AN SSSR. **1965**. Vol. 160. No. 1. P. 193–195 (in Russian).
- Sokolova M.N., Zabavnikova N.I., Rudnitskaya E.S.* New data for the composition of lomonosovite and murmanite // New Data on Minerals of the USSR, Tr. Fersman Mineral. Museum. **1973**. No. 22. P. 129–142 (in Russian).
- Sokolova M.N., Zabavnikova N.I., Rudnitskaya E.S., Organova N.I.* On the chemical features and homogeneity of the lomonosovite group minerals from the Khibiny massif // Problems of Homogeneity and Heterogeneity of Minerals. Moscow: Nauka. **1971**₁. P. 174–187 (in Russian).
- Sokolova M.N., Zabavnikova N.I., Yakovlevskaya T.A., Rudnitskaya E.S.* Betalomonosovite from the Khibiny massif // Izv. AN SSSR, ser Geol. **1971**₂. No. 3. P. 77–84 (in Russian).
- Solodovnikova L.L.* Feldspars of the Kukisvumchorr deposit // Mineralogy of Postmagmatic Processes. Leningrad: Leningrad State Univ. **1959**. P. 7–72 (in Russian).
- Tikhonenkov I.P.* Nepheline Syenites and Pegmatites of the Khibiny Massif and Importance of Postmagmatic Phenomena in Their Formation. Moscow: AN SSSR. **1963**. 247 p. (in Russian).
- Titov V.N., Rudenko S.A., Kozlovsky A.D., Kuznetsov Zh.M.* Origin of urtitite of the Khibiny alkaline massif // Zap. Leningrad Mining Inst. **1971**. Vol. 60. No. 2. P. 19–25 (in Russian).
- Villarroel H., Joel N.* International Mineralogical Association: Commission on New Minerals and Mineral Names // Miner. Mag. **1967**. Vol. 36. No. 277. P. 131–136.
- Vlasov K.A., Kuzmenko M.V., Es'kova E.M.* The Lovozero Alkaline Massif. Moscow: AN SSSR. **1959**. 623 p. (in Russian).
- Yakubovich O.V., Karimova O.V., Ageeva O.A., Borutzky B.Ye.* Crystal structure of betalomonosovite: new data // Zap. Ross. Mineral. O-va. **2014**. Vol. 143. No. 6. P. 88–103 (in Russian).
- Zabavnikova N.I.* Water treatment of the lomonosovite group minerals // Methods of Chemical Analysis and Chemical Composition of Minerals. Moscow: Nauka. **1967**. P. 69–78 (in Russian).
- Zotov I.A.* Transmagmatic fluids in magmatism and ore formation. Moscow: Nauka. **1989**. 214 p. (in Russian).