

RARE-METAL MINERALIZATION CONNECTED WITH BITUMINOUS MATTERS IN LATE ASSEMBLAGES OF PEGMATITES OF THE KhibINY AND LOVOZERO MASSIFS

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The mineral composition and structure of microheterogeneous aggregates from the low-temperature assemblages, containing solid bituminous matters (SBM), from the Khibiny and Lovozero massifs have been studied. It is shown that thin intergrowths of SBM with the rare elements minerals are the typomorphic formations of hydrothermal zones of agpaitic pegmatites of these massifs. 4 types of such intergrowths are distinguished, which are characterized by different mineralogical composition, high content of rare elements, and extremely high degree of separation of Ce, La, Nd, Y, Sr, Th, U, Ti, Nb, and Ba between different phases, right up to the formation of proper minerals of these elements. Not only new mineral species for Khibiny and Lovozero but also a whole number of phases that do not have analogues among known minerals were found. The possible mechanisms of formation of microheterogeneous aggregates containing SBM and a role of complexes with organic compounds in the transportation of rare elements at low temperatures are discussed. 4 tables, 9 figures, 28 references.

Located at the Kola Peninsula, the Khibiny and Lovozero massifs of agpaitic alkaline rocks are characterized by a unique diversity of the rare-metal mineralization (Kostyleva-Labuntsova *et al.*, 1978; Semenov, 1972, 1997; Khomyakov, 1990; Yakovenchuk *et al.*, 1999, Pekov, 2001a). At present, within the bounds of these two massifs more than 570 mineral species are found, most of them contain rare elements (with clarks 0.1%) as the species-forming or important secondary components. The diversity of the Th, REE, U, Ti, Nb, Zr, Be, and Li minerals increases in the following series of stages: magmatic early pegmatite late pegmatite. This fact, which is in the obvious contradiction with the low mobility of many of mentioned elements at the low temperature (Dement'ev, Syromyatnikov, 1965; Semenov, 1972; Syromyatnikov *et al.*, 1976; Pekov *et al.*, 1997; Pekov, 1998, 2001b; Chukanov, 2002; Azarova *et al.*, 2002), in many cases can be explained by the formation of pseudomorphs after early minerals as a result of introduction or carrying-out of mobile components, whereas the less mobile components form the new phases. So-called transformation

mineral species are a special case of such pseudomorphs (Khomyakov, 1990). However, as we noted elsewhere (Chukanov *et al.*, 2006, in press; Ermolaeva *et al.*, in press), there is another, possibly, the not less important way of formation of the rare-metal mineralization in the late derivatives of alkaline rocks. This way is caused by increase of mobility of a number of high-valence elements (Th, REE, U, Ti, Nb, Zr) in presence of such water-soluble organic complexing agents as the oxygen-bearing aromatic compounds.

The microscopic aggregations of organic compounds, represented, as a rule, by the solid bituminous matters (SBM), are widespread in pegmatites of the Khibiny and Lovozero massifs (Antonov *et al.*, 1933; Labuntsov, 1937; Petersil'e, 1959, 1960, 1964; Linde, 1961; Sokolova, 1965; Zezin, Sokolova, 1967; Florovskaya *et al.*, 1968; Loskutov, Polezhaeva, 1968). One can observe the stable and clear connection of SBM with the regions, having the increased contents of zeolites and especially zeolite-like microporous hydrous titano-, niobo-, and zirconosilicates (elpidite, catapleiite, umbite, paraumbite, vino-gradovite, minerals of labuntsovite, hilairite,

lovozerite groups, etc.; Fig. 1), and directly with the aggregations of minerals of lanthanides, yttrium, and thorium, and also with the occurrences of carbonate and sulphide mineralization. In the previous work (Chukanov *et al.*, 2006, in press), we have discussed the possible catalysis role of microporous zeolite-like Ti, Nb, and Zr silicates in the formation of SBM from the low-molecular organic compounds in alkaline pegmatites.

In the Khibiny massif, the largest aggregations (to 5 mm in size) and abundant gatherings of SBM were observed in the feldspar-sodalite-natrolite pegmatite vein of the Kukisvumchorr deposit in close assemblage with natrolite, murmanite, nenadkevichite, etc. (Sokolova, 1965). The considerable aggregations of SBM were found in the mineralised cavities of pegmatite veins with villiaumite-carbonate mineralization, occurring among Khibinian ristschorrites and uncovered by the working of the Kirovskii underground mine at the Mt. Kukisvumchorr (Chukanov *et al.*, 2006, in press).

In the Lovozero massive, the Shomiokitovoe pegmatite body should be mentioned as the most outstanding object, containing organic matters. The rich yttrium and oxalate mineralization, being unique for agpaitic rocks and accompanied by the abundant aggregations of SBM (numerous spherules up to some millime-

tres in size and films) and the microporous Ti, Nb, and Zr silicates (korobitsynite, nenadkevichite, elpidite, etc.), occurs here. Also in the Lovozero massif is the Elpiditovoe pegmatite body, in which black drop-like aggregations of SBM are associated with elpidite and the insignificantly studied hydrous silicate of Fe and Ti. The «oxalate mechanism» is seemed to be the most effective way of accumulation of Y and heavy Ln at the Shomiokitovoe pegmatite body (Pekov, 1998). The oxalate ions are able to form very strong complex compounds with yttrium and lanthanides, keeping these elements in the movable state to the latest stages. At a final stage of minerogenesis, the $C_2O_4^{2-}$ ions are removed from solution, they enter in the composition of oxalate minerals, natroxalate and whewellite.

Characteristic of studied samples

In pegmatites of the Khibiny and Lovozero massifs, at least four types of the microheterogeneous formations, containing organic matters, are known. Formations of the first type are the most characteristic for the hydrothermal paragenesis of the Khibinian pegmatites. These are **macroaggregations of SBM** with a high content of the oxygen-bearing aromatic compounds.

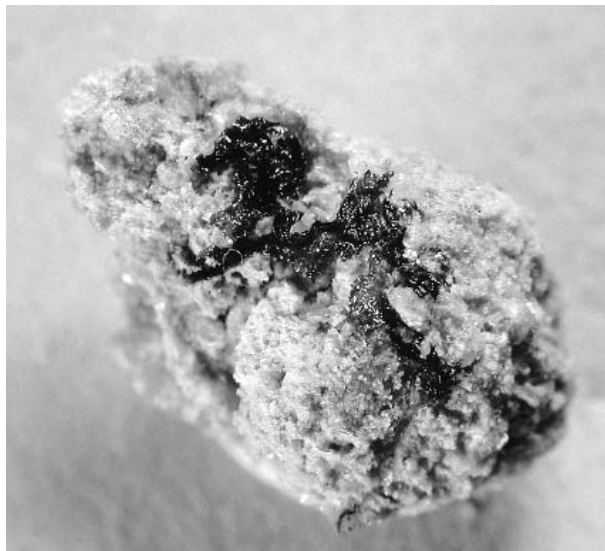
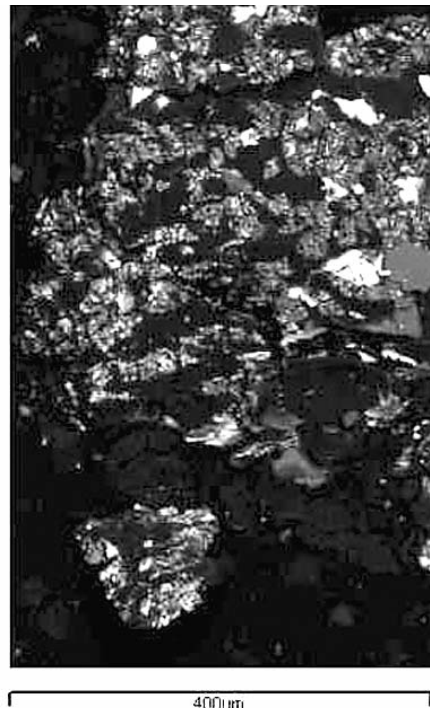


Fig. 1. Aggregations of SBM on the aggregate of paraumbite crystals (Mt. Koashva, Khibiny). Specimen max size is 8.5 mm

Fig. 2. Typical structure of decomposition of SBM (sample Kh3): black is organic phase without metals, grey is significantly organic phase with metals, white is mineral phase (thorite). Image in back-scattered electrons.



Almost always they include the abundant microscopic ingrowths of minerals, containing Th, REE, Ca, rarely U, Y, Nb, Ti, Ba, Sr. Formation of these microheterogeneous systems is connected with decomposition of the initially homogeneous phase into the purely organic (with predominance of hydrocarbons), mineral and organic phases with heavy elements (Ermolaeva *et al.*, in press; Fig. 2). The bituminous matters, in which the content the aliphatic hydrocarbons prevail, are usually poorly mineralised. Such formations are characteristic for hydrothermalites of the Lovozero massif.

The minerals of rare elements (most often Th and REE) belong to the second type, **they contain dispersed impregnation of SBM** and are easily detected by the IR spectroscopy method. Thus, in many cases, in the aggregations of thorium minerals from late assemblages in pegmatites of Lovozero, the large amounts of the oxidized aromatic compounds are found (Ermolaeva *et al.*, in press); obviously, they were captivated during crystallization.

The third type of heterogeneous aggregates with organic matters in alkaline pegmatites are represented by the **microheterogeneous crusts enriched by SBM** around large crystals of the Th and REE minerals: belovite-(Ce), karnasurtite-(Ce), Na-Th silicate (Fig. 3).

The predominance of the second and third types formations is depended on the peculiarities of crystallization. During crystallization, either the capture of metalloorganic complex by a growing crystal or the decomposition of this complex, being synchronic to the process of crystal growth, and the displacement of organic part to the periphery of a forming mineral individual can be the limiting stages. The second type formations are the most characteristic for

the hydrothermal assemblages of the thorium minerals. An example of the «through» minerals (thorite, Na-Th silicate, minerals of the steacyite-turkestanite series), which are stable in a wide interval of temperatures, is especially characteristic in this respect. By our numerous observations, the samples of these minerals from the hydrothermal assemblages almost always contain the SBM ingrowths, detected by the IR spectroscopy method; whereas in the same minerals from the earlier parageneses in alkaline rocks and pegmatites, the organic matter is absent.

At least, the fourth type is represented by the **polymictic pseudomorphs after steenstrupine**, which contain SBM. Such pseudomorphs are known in a whole number of pegmatites of the Lovozero massif, containing ussingite or apoussingite natrolite.

The samples studied in the present work are given in Table 1. All them, according to data of the IR spectroscopy, are characterized by high contents of the dispersed bituminous matters.

The IR spectroscopic studies

The IR spectra were obtained with the two-ray spectrophotometer Specord 75 IR in the range of wave numbers 400-4000 cm^{-1} . The samples were prepared by a standard method in pellets with KBr; the analogous pellet of pure KBr was placed in a reference beam.

The presence of numerous absorption bands in a range of 1210-1740 cm^{-1} is a characteristic feature of the presence of **aromatic compounds with oxygen-bearing groups**. In particular, a series of bands in the frequency range of 1370-1600 cm^{-1} belongs to the C-C stretching



Fig. 3. Crusts (black margins) enriched by SBM around aggregation of karnasurtite-(Ce) in natrolite, Mt. Karnasurt, Lovozero (a) and around the belovite-(Ce) crystal in albite, Mt. Alluaiv, Lovozero (b). Image size is 6 cm.

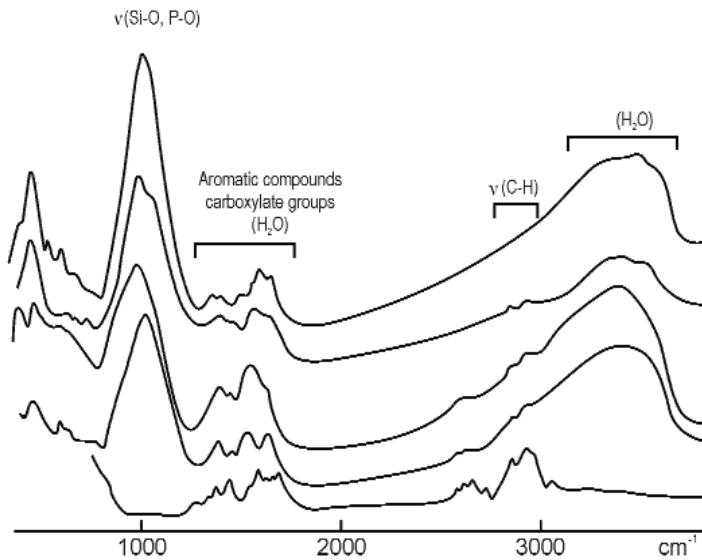


Fig. 4. The IR spectra of minerals of thorium from hydrothermalites of the Lovozero massif (1 – the Na-Ti-Th silicate with admixture of rhabdophane-(Ce), Mt. Alluaiv; 2 – the Na-Th silicate, Mt. Kedykverpakhk; 3 – thorite, Suluai River; 4 – the thorium phosphate, Mt. Malyi Punkaruiv; 5 – villiaumite from late-pegmatite assemblage, the Palitra pegmatite, Mt.

vibrations in aromatic rings. The CO₂ carboxylate groups absorb in the ranges of 1550-1670 cm⁻¹ (antisymmetric stretching vibrations) and 1280-1430 cm⁻¹ (symmetric stretching vibrations). The bands in these ranges are present in the IR spectra of the most SBM macroaggregations from Khibiny and, as a rule, in the IR spectra of samples with the dispersed SBM from Lovozero. Thus, one can conclude that salt (carboxylate) complexes are one of the main forms of occurrence of metals (mainly, alkaline-earth and rare-earth elements) in bituminous matters from agpaite pegmatites.

The C=O bonds (carbonyl and carboxyl groups, including two-dimensional forms of carbonic acids) have characteristic bands at 1690-1740 cm⁻¹; aromatic ethers have these bands in the range of 1210-1310 cm⁻¹ (antisymmetric stretching vibrations of the C-O-C bridges). In the mentioned range (1210-1740 cm⁻¹) also the bands of bending vibrations of the water molecules are present; they are characterized by a single or slightly split band in the relatively narrow range (usually 1600-1650 cm⁻¹).

For aromatic compounds, the bands of the C-H stretching vibrations in a range of 3000-3100 cm⁻¹ are characteristic, but at presence of a large amount of substitutes, especially for polycyclic aromatic compounds, these bands can be absent in the IR spectrum. A band with maximum of absorption nearly 2835 cm⁻¹ is characteristic for the O-CH₃ methoxy group connected with aromatic ring.

The bands in the range of 2843-2972 cm⁻¹ in the spectrum (often there is a doublet belong-

ing to CH₂ or CH₃ groups) are the most effective characteristic of the presence of aliphatic hydrocarbons or **aliphatic** hydrocarbon groups. The large aggregations of bituminous matters, in which composition the aliphatic components prevail, are especially characteristic for alkaline hydrothermalites of Lovozero. As a rule, SBM of this type are characterized by very low contents of the oxygen-bearing groups.

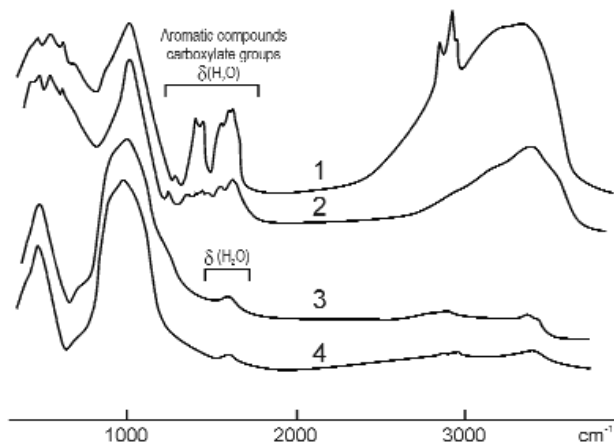
As a result of systematic study of the low-temperature minerals of thorium from hydrothermalites of the Lovozero massif, it has been ascertained that all studied samples contain the dispersed admixture of organic matters, which can be easily detected by the IR spectroscopy method. Some examples are given on Figure 4. Also the IR spectrum of villiaumite of the third generation (late pegmatite stage), enriched by dispersed organic matter, is given at the same figure; this mineral is associated with the Na-Th silicate in the Palitra pegmatite (Lovozero).

The dispersed organic matter is quite often found also in the REE minerals from hydrothermal zones of alkaline massifs. Both in accompanying minerals without Th and REE (for example, in zeolites) and in earlier minerals of Th and REE (for example, in umbozerite or unaltered steenstrupine from paragenesis with ussingite), organic matter is contained in significantly lower concentrations and, as a rule, is not observed in the IR spectra obtained by a standard method. In the IR spectra of steenstrupine from the association with natrolite weak bands of the C-H stretching vibrations in a range of 2800-3000 cm⁻¹ are present (curves 3 and 4 on

Table 1. The studied samples

Sample	Occurrence	Description
Minerals of Th and REE with high contents of the dispersed SBM (by the IRS data)		
Na-Th silicate, $\text{Na}_5\text{Th}_3\text{Si}_8\text{O}_{24}$ (OH) $n\text{H}_2\text{O}$	The Palitra pegmatite (Mt. Kedykverpakhk, Lovozero)	Colourless and grey grains up to 5 mm in size, ingrowing in manaksite, sometimes with margins of SBM; crystals in cavities filled up by late villiaumite (Pekov, in press). It is associated with ussingite, natrosilite, serandite, the nordite group minerals, bario-oligite, chkalovite, phosinaite-(Ce), vitusite-(Ce), belovite-(Ce), steenstrupine-(Ce), thoros teenstrupine, etc
Thorite, ThSiO_4	Valley of the Suluai River, Mt. Kuamdespakhk, Lovozero	Brown-black tetragonal-dipyramidal crystals ingrown in natrolite; crystals size is 0.5-3 mm; fracture is conchoidal; lustre is pitchy
Na-Ti-Th silicate, $\text{Na}_{6-x}\text{ThTiSi}_8$ (O,OH) $_{24}n\text{H}_2\text{O}$	The Shkatulka pegmatite, Mt. Alluauiv, Lovozero	Metamictic; it forms pseudomorphs with reddish-brown colour (up to 1 cm in size) after steenstrupine grains, in ussingite (Ermolaeva <i>et al.</i> , in press)
Thorium , phosphate $(\text{Th},\text{Na})(\text{P},\text{Si})\text{O}_4$ $n\text{H}_2\text{O}$	Ussingite pegmatite # 71 (Th,Na)(P,Si) $\text{O}_4n\text{H}_2\text{O}$ Malyi Punkaruauiv, Lovozero	Grains with hexagonal section, size is nearly 2 mm. Empirical formula (by data of electron microprobe analysis) is $(\text{Th}_{0.88}\text{Na}_{0.07}\text{K}_{0.02}\text{Ca}_{0.02}\text{U}_{0.01}\text{Ba}_{0.01}\text{Sr}_{0.01})\Sigma_{1.01}(\text{P}_{0.71}\text{Si}_{0.15}\text{Al}_{0.14})\Sigma_{1.00}\text{O}_{4.15}n\text{H}_2\text{O}$. It is associated with mangan-neptunite and belovite-(Ce)
High-thorium or ussingite (formula is after Pekov <i>et al.</i> , 1997)	Natrolite and natrolite-ussingite veins, Mt. Kedykverpakhk, Lovozero	Isometric grains up to 1 cm in size, in natrolite steenstrupine, $\text{Na}_{0.5}\text{Ca}_{1-3}(\text{REE},\text{Th})_6(\text{Mn},\text{Fe},\text{Al},\text{Ti})_{4-5}[\text{Si}_6\text{O}_{18}]_2[(\text{Si},\text{P})\text{O}_4]_6(\text{OH},\text{F},\text{O})_x n\text{H}_2\text{O}$
Karnasurtite-(Ce), $(\text{Ce},\text{La},\text{Th})(\text{Ti},\text{Nb})$ $\text{Al},\text{Fe}^{3+}(\text{Si},\text{P})_2\text{O}_7$ (OH) $_4;3\text{H}_2\text{O}$	Pegmatite # 62 (Semenov, 1972), Mt. Karnasurt, Lovozero	Yellow fine-grained aggregations up to 10 cm in size, in coarse-grained natrolite; rarely isometric grains up to 2 cm in size, with orange-brown colour, coarse jointing in one direction, and black margin enriched by the SBM inclusions (Fig. 3a).
Belovite-(Ce), $\text{Sr}_3\text{NaCe}(\text{PO}_4)_3\text{F}$	The Shomiokitovoe pegmatite body, Mt. Alluauiv, Lovozero	Large crystals with black margin composed by burbankite and remondite-(Ce) and containing abundant small inclusions of bituminous matters (see Fig. 3b). It is associated with albite, korobitsynite, elpidite, sidorenkite, etc.
Microaggregations of SBM		
Kh1	Lovchorrite-apatite vein, Mt. Apatitovaya, Khibiny	Aggregations of irregular and spherical form, size up to 4-5 mm, brittle, black, with lustreless surface of fracture. They contain abundant inclusions of thorite (detected by chemical composition and the X-ray powder pattern). Collection of A.N. Labuntsov (Antonov <i>et al.</i> , 1933; Labuntsov, 1937; Loskutov, Polezhaeva, 1968). Sample # 40749 from the Fersman Mineralogical Museum RAS («carbocere»).
Kh2	The same	The same; sample # 41156 from the Fersman Mineralogical Museum RAS.
Kh3	The same	The same; sample # 44322 from the Fersman Mineralogical Museum RAS.
Kh4	The Kirovskii mine, Khibiny	Roundish aggregations of SBM with dark brown colour, up to 3 mm in diameter, from cavity of rinkite-nepheline-aegirine-microcline pegmatite. It contains abundant microgrowths of steacyite (detected by chemical composition and the IRS). It is associated with crystals of microporous titanocillate pyatenkoite-(Y), $\text{Na}_3(\text{Y},\text{HREE})\text{TiSi}_6\text{O}_{18}6\text{H}_2\text{O}$.

Kh5	Pegmatite at the contact of urtites with apatite ore, Mt. Koashva, Khibiny	Abundant roundish aggregations of SBM with black colour (up to 5 mm in diameter), included in natrolite. They are associated with Sr- <i>REE</i> phosphates (belovite-(Ce), fluorcaphite), microporous Zr, Ti, and Nb silicates (sazykinaite-(Y), catapleiite, sitinakite, lemmleinite-K).
Kh6	Natrolite vein, cutting ijolite-urtites, Mt. Kukisvumchorr, Khibiny	Roundish brown-black aggregations of SBM (up 1.5 mm in size) from cavity in natrolite.
Kh7	Feldspar-sodalite-natrolite vein, laying in melteigites of the Kukisvumchorr apatite deposit	Drop-like aggregation of SBM with shining surface (in fracture it is lustreless, black), size is 2.4x1.4 mm, it was extracted from aggregate of altered nenadkevichite. Detailed description see in following articles: Sokolova, 1965; Zezin, Sokolova, 1967.
Kh8	The Natrolite vein, Mt. Eveslogchorr, Khibiny	Spherical aggregation of SBM with diameter 5 mm (in fracture it is lustreless with dark grey colour), included in coarse-tabular aggregate of natrolite. It is associated with thorite and the labuntsovite group minerals (vuoriyarvite-K, kuzmenkoite-Zn, paratsepinite-Ba, tsepinite-Ca).
Kh9	The Ileritovoe pegmatite body, Mt. Kukisvumchorr, Khibiny.	Dark brown roundish aggregations up to 1 mm in size among cavernous natrolite. Aggregations of SBM are accompanied by exceptional diversity of rare-metal mineralization, connected mainly with hydrothermal stage.
L1	The Shkatulka pegmatite, Mt. Alluaiv, Lovozero	Nests (up to 1 mm in size) of black SBM in ussingite and serandite.
Polymictic pseudomorphs after steenstrupine, containing SBM		
L2	The Shkatulka pegmatite, Mt. Alluaiv, Lovozero	Friable polymictic margins with grey-brown colour, replacing isometric and tabular grains of steenstrupine (up to 2 cm in size), composing by silicates and phosphates of <i>REE</i> , Th, U, Ti, and containing dispersed microscopic ingrowths of SBM (detected by the IR spectra).
L3	The same	The same
L4	The same	The same
L5	The same	Incomplete polymictic pseudomorphs after steenstrupine, mainly composed by rhabdophane-(Nd), in which mass the ingrowths of SBM, Na-Th silicate, Na-Mn-Y silicate, and high-barium variety of belovite-(Ce) are dispersed. After some grains the X-ray amorphous phase with grey-brown colour is developed, it corresponds by chemical composition to Nd-dominated analogue of abenakiite-(Ce), it is closely associated with sodium-uranium silicates. In edge zones of these pseudomorphs, the aggregations (up to 2-3 mm in size) of Na-U silicates are noted.
L6	The same	Compact polymictic pseudomorph after steenstrupine



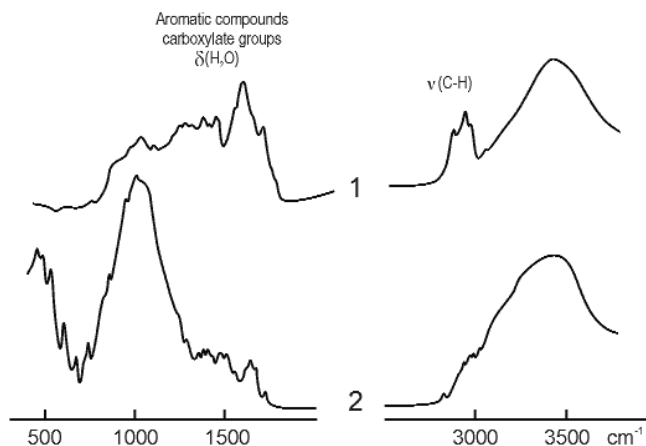
Kedykverpakhk.

Fig. 5. The IR spectra of karnasurtite-(Ce) from the Mt. Karnasurt, Lovozero (1 – orange-brown compact variety, see Fig. 3a; 2 – yellow powdery variety) and steenstrupine-(Ce) from assemblage with natrolite from the Mt. Kedykverpakhk, Lovozero (3 – the Kedykverpakhk-21 vein; 4 – the

Fig. 5). The hydrothermal alteration of steenstrupine leading to the formation of polymictic pseudomorphs after it (see below) is accompanied by introduction of thorium, titanium, and also a large amount of organic matter (curve 2 on Fig. 6). Another phosphatosilicate of Th and REE, karnasurtite from paragenesis with natrolite, is characterized by high contents of aromatic compounds, both in combination with aliphatic hydrocarbon groups (curve 1 on Fig. 5) and purely aromatic compounds (curve 2 on Fig. 5).

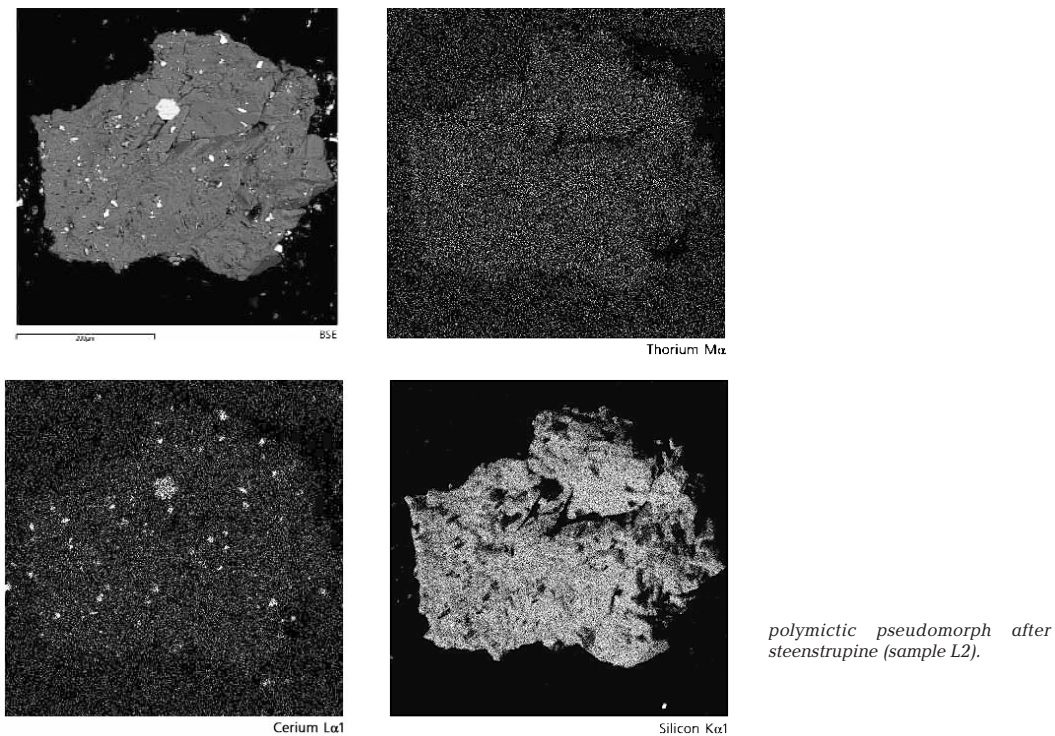
E. Makovicky and S. Karup-Moller (1981) have described steenstrupine from sodalite-natrolite-aegirine veins in naujaite of the Ilimaussaq massif in Greenland. In the IR spectra of the mineral is a series of bands in a range of 1270-1780 cm^{-1} , the most part of which is concerned by the authors of the cited work to the bending vibrations of the water molecules, although these bands (to the exclusion of a wide band at 1655 cm^{-1}) are more typical for

combination C-H of bending and C=C stretching vibrations of aromatic organic matters. A band at 1740 cm^{-1} is characteristic for stretching vibrations of C=O (carbonyl groups in composition of organic matters). The wide structured bands in the range of 2500-3700 cm^{-1} are interpreted as the stretching vibrations of the water molecules (Makovicky, Karup-Moller, 1981). The most intensive and broad band within the limits of this range (3380-3400 cm^{-1}) really corresponds to vibrations of the weakly joined water molecules, but rather narrow bands at 2830 and 2950 cm^{-1} , obviously, correspond to the C-H stretching vibrations of aliphatic hydrocarbons. A doublet in the range of 2800-3000 cm^{-1} is so characteristic for aliphatic hydrocarbons that it is a test on their presence; for assignment of these bands to other types of vibrations the weighty reasons are necessary, but they are absent in the cited work.



Kedykverpakhk-19 vein, see (Pekov, 2001)).

Fig. 6. The IR spectra: 1 – SBM, containing aromatic and aliphatic components (sample Kh5); 2 –



polymictic pseudomorph after steenstrupine (sample L2).

Study of samples by the X-ray analysis method

The electron microscopy study, including the obtaining of image of studied object in secondary electrons, back-scattered and reflected electrons, and also the local X-ray spectral (electron microprobe) analysis were made on a digital electron scanning microscope instrument CamScan MV2300 (Tescan Vega TS5130MM), equipped with the YAG detectors of secondary and reflected electrons and the energy-dispersed X-ray microanalysis instrument with a semi-conductor Si(Li) detector instrument Link INCA Energy. The calculations of results of the X-ray spectral microanalysis were made with a program INCA Energy 200 with subsequent recalculation of the obtained data by a packet of programs elaborated in the IEM RAS.

The studies were made at accelerating voltage of 20 kV. The absorbed electrons current was 540 pA on a standard sample of cobalt (Co) and 565-615 pA on the studied silicate samples. A size of the electron microprobe beam on the surface of a sample was 0.2 μm.

The spatial distribution of SBM in microaggregations of organic matters from pegmatites of the Khibiny massif has quite often a form of typical structures of decomposition: in purely organic matrix there are the lamellar ingrowths of

essentially organic matter with total contents of heavy elements (with atomic numbers above 10) from 3 to 11 wt %. Mainly these are the alkaline-earth and rare-earth elements, lead and thorium. Judging by the IR spectra, heavy elements are here predominantly in the form of carboxylate salts (see above). These phases in their turn contain microingrowths of inorganic phases. The latter are usually represented by minerals of rare elements and also calcite. The typical sizes of the mineral inclusions in SBM are from several units to several tens of microns. As a rule, they do not form well-shaped crystals. Only carbonates, including carbonates of rare-earth elements (Fig. 7) and calcite, sometimes form perfect crystals in the SBM mass.

In detail the microheterogeneous formations of this type are described in a separate publication (Chukanov *et al.*, 2006, in press), an example of their typical structure is given on Figure 2. In present work, the main attention is paid to their mineral components. Chemical compositions of some mineral microphases from SBM are given in Table 2. In a number of cases, diagnostics of minerals can be made exactly on the basis of chemical composition. Steacyite was also identified by the IR spectrum, and thorite was also confirmed by the X-ray powder pattern. At the same time, in SBM the inclusions of the rare-metal microphases with a stable chemical composition are often

Table 2. Chemical composition of minerals, forming inclusions in SBM

Mineral	Thorite	Thorite	Steacyite	Silicate of Th and REE		Silicate of Ti and Th		Silicate of Na and U
No. of sample	Kh2	Kh3	Kh4	Kh5		Kh6		L1
No. of analysis	1	2	3	4	5	6	7	8
Contents of components, wt %								
Na ₂ O	bdl	bdl	4.41	bdl	bdl	bdl	bdl	2.20
K ₂ O	bdl	bdl	3.93	0.60	0.71	bdl	bdl	bdl
CaO	2.85	3.60	5.41	1.94	1.77	2.08	2.21	0.18
SrO	bdl	bdl	bdl	bdl	bdl	0.95	1.52	bdl
FeO	bdl	bdl	0.77	bdl	bdl	0.54	0.71	bdl
MnO	bdl	bdl	bdl	0.81	bdl	0.87	0.96	bdl
ZnO	bdl	bdl	bdl	2.08	0.64	bdl	bdl	bdl
Al ₂ O ₃	bdl	bdl	bdl	1.32	0.79	0.96	0.80	bdl
La ₂ O ₃	bdl	bdl	bdl	1.04	bdl	2.86	2.11	bdl
Ce ₂ O ₃	0.95	1.99	bdl	5.41	2.55	3.37	2.12	bdl
Pr ₂ O ₃	bdl	bdl	bdl	1.46	1.13	bdl	bdl	bdl
Nd ₂ O ₃	0.85	1.76	bdl	2.36	3.06	bdl	bdl	bdl
ThO ₂	66.00	59.72	30.69	48.15	57.18	38.31	41.01	0.46
UO ₂	bdl	bdl	bdl	bdl	bdl	bdl	bdl	27.83
TiO ₂	bdl	bdl	bdl	bdl	bdl	12.20	12.25	bdl
SiO ₂	15.45	15.79	53.62	24.16	21.59	13.57	14.84	34.78
Nb ₂ O ₅	bdl	bdl	bdl	bdl	bdl	7.16	7.06	bdl
P ₂ O ₅	bdl	bdl	bdl	1.36	0.91	0.75	0.57	bdl
SO ₃	2.15	2.07	bdl	bdl	bdl	bdl	bdl	bdl
Total	88.25	84.93	99.79	96.40	95.29	88.12	90.64	66.21
Formula coefficients								
Na	—	—	1.28	—	—	—	—	0.73
K	—	—	0.74	0.03	0.04	—	—	—
Ca	0.20	0.24	0.86	0.08	0.09	0.16	0.15	—
Sr	—	—	—	—	—	0.04	0.06	—
Fe	—	—	0.09	—	—	0.03	0.04	—
Mn	—	—	—	0.03	—	0.05	0.05	—
Zn	—	—	—	0.06	0.02	—	—	—
Al	—	—	—	0.06	0.04	0.08	0.06	—
La	—	—	—	0.02	—	0.08	0.05	—
Ce	0.02	0.05	—	0.08	0.04	0.09	0.05	—
Pr	—	—	—	0.02	0.02	—	—	—
Nd	0.02	0.04	—	0.03	0.05	—	—	—
Th	0.97	0.92	1.04	0.43	0.58	0.61	0.61	0.02
U	—	—	—	—	—	—	—	1.07
Ti	—	—	—	—	—	0.65	0.60	—
Si	1.00	1.00	8.00	0.96	0.97	0.96	0.97	6.00
Nb	—	—	—	—	—	0.23	0.21	—
P	—	—	—	0.04	0.03	0.04	0.03	—
S	0.10	0.10	—	—	—	—	—	—
Method of calculation, f. c.	Si = 1.00	Si = 1.00	Si = 8.00	(Si + P) = 1.00	(Si + P) = 1.00	(Si + P) = 1.00	(Si + P) = 1.00	Si = 6.00

Table 2 (end).

Mineral	Nb silicate		Thin intergrowths of Sr-barite, thorite, and calcite		REE carbonate
	Kh7	Kh8	Kh8	Kh9	Kh9
No. of sample	9	10	11	12	13
No. of analysis	9	10	11	12	13
	wt %				
Na ₂ O	3.68	3.71	bdl	bdl	11.57
K ₂ O	1.89	1.34	bdl	bdl	0.28
CaO	9.57	12.40	5.64	6.47	1.56
SrO	1.16	0.33	5.83	9.61	3.05
BaO	bdl	bdl	15.45	16.09	10.61
FeO	1.09	0.39	bdl	bdl	0.96
MnO	1.81	1.69	bdl	bdl	bdl
Al ₂ O ₃	1.66	1.00	bdl	bdl	bdl
La ₂ O ₃	bdl	bdl	bdl	bdl	5.95
Ce ₂ O ₃	0.47	bdl	bdl	bdl	9.75
Nd ₂ O ₃	bdl	bdl	1.06	bdl	1.84
ThO ₂	0.63	0.74	36.12	27.27	1.45
UO ₂	0.96	0.26	bdl	bdl	bdl
TiO ₂	10.78	11.07	bdl	bdl	bdl
SiO ₂	13.95	15.57	10.63	6.69	1.12
Nb ₂ O ₅	30.68	40.17	bdl	bdl	bdl
SO ₃	2.12	0.90	12.69	15.92	1.27
Total	81.82	91.18	87.42	82.05	49.95

Note: bdl means that content of this component is below detection limits.

The total also includes (numbers of analyses, wt %): 3 – Y₂O₃ 0.96; 4 – PbO 1.97, Sm₂O₃ 1.49, Gd₂O₃ 0.83, Y₂O₃ 0.56, Lu₂O₃ 0.86; 5 – Y₂O₃ 0.82, Sm₂O₃ 0.88, Eu₂O₃ 1.32, Gd₂O₃ 1.00, Tb₂O₃ 0.94; 6 – PbO 2.42, Y₂O₃ 2.08; 7 – PbO 1.77, Y₂O₃ 2.71; 8 – Y₂O₃ 0.76; 9 – F 2.37, -O=F₂ 1.00; 10 – F 2.78, -O=F₂ 1.17; 13 – Cl 0.7, -O=Cl₂ 0.16. All these correspond to following formula coefficients: 3 – Y 0.08; 4 – Pb 0.02, Sm 0.02, Gd 0.01, Y 0.01, Lu 0.01; 5 – Y 0.02, Sm 0.01, Eu 0.02, Gd 0.01, Tb 0.01; 6 – Pb 0.05, Y 0.08; 7 – Pb 0.03, Y 0.09; 8 – Y 0.06. Low totals of analyses of thorium and uranium minerals are connected with submicron inclusions of organic matter in them and also with their metamict (in case of thorite, semi-metamict) state (Ermolaeva et al., in press). By data of the IRS, only steacyite has perfect crystal structure. For analyses 9-13 the formula coefficients is not given, since the method of their calculation, resulting in integer coefficients in ideal formulas, was not found.

present, that do not have analogues among known in nature mineral species. Chemical compositions of these phases are specific and characterized by wide set of rare elements. These are the minerals with following hypothetical ideal formulas: (Th,REE,Ca)₁₋₃Si(O,OH)₄nH₂O (analyses 4 and 5); (Th,REE,Ca)(Ti,Nb)SiO₆nH₂O (analyses 6 and 7); NaUSi₆O₁₄(OH)nH₂O (analysis 8), etc.

In some analyses there are small amounts of accessory components, which nature is not clear. Some of accessory components could be captured by an electron beam from phases intergrowing with the analysed minerals. Thus, in chemical composition of thorite, forming inclusions in «carbocer» (analyses 1 and 2 in Table 2), there are Ca and S. Possibly, the increased content of calcium in thorite is caused by the ingrowths of calcite, and sulphur can be included in the chemical composition of organic compounds.

On Figure 8 there is an BSE image of a peripheral part of the belovite crystal from the Shomiokitovoe pegmatite body (Fig. 3b). Around the grain of belovite there is a crust, consisting of intimately intergrowing grains of the Sr-REE carbonates (burbankite and remondite-(Ce)), in the interstices between them there are microscopic inclusions of SBM (see chemical compositions in Table 3). The presence of SBM in this sample (the black parts with roundish faces on Fig. 8) was confirmed by the IR spectroscopy method. Nearing to the peripheral zone of a margin, which is enriched by bitumens, the relative impoverish of carbonates by Sr and enrichment by Ca, REE, and Th take place.

From the above data, it is evident that some group of rare elements (above all Th, but also U, REE, and a number of other elements) in hydrothermal parageneses of Khibiny and Lovozero are constantly closely connected, often at a level of microintergrowths, with organic matter. The diversity of mineral phases in these intergrowths is astonishing, including phases, which do not have analogues by chemical composition in nature. We should note that above-described steacyite is the first finding of this mineral in the Khibiny massif, and findings of remondite-(Ce) and belovite-(La) are the first in the Lovozero massif. These minerals were detected by the IR spectra and by chemical composition.

On Figure 9 one can see an example of the fourth type of microheterogeneous formations, containing SBM, a fragment of polymictic pseudomorph after steenstrupine. Such pseudomorphs are widespread in the Shkatulka pegmatite. The spatial distribution of different minerals in them has irregular, mosaic character. In

Table 3. Chemical compositions of minerals from margin around belovite-(Ce) crystal (the Shomiokitovoe pegmatite body, the Lovozero massif), Fig. 3b

No. of analysis	1	2	3	4	5	6	7	8
Mineral	Belovite-(La)	Belovite-(Ce)	Belovite-(Ce)	Burbankite	Burbankite-	Burbankite-	Remondite-(Ce)	Remondite-(Ce)
Contents of components, wt %								
Na ₂ O	5.08	5.20	4.90	9.27	10.29	12.96	13.33	13.88
CaO	bdl	bdl	bdl	bdl	bdl	2.95	4.47	5.49
SrO	37.31	38.90	39.40	32.33	32.97	19.30	16.07	11.02
BaO	3.87	3.93	3.88	2.51	3.14	1.20	2.11	2.38
Y ₂ O ₃	bdl	bdl	bdl	1.53	2.06	1.23	1.39	2.47
La ₂ O ₃	9.10	9.58	10.04	8.56	8.75	11.87	10.73	11.12
Ce ₂ O ₃	8.89	10.87	10.76	9.10	8.99	11.92	12.70	13.24
Pr ₂ O ₃	0.29	0.60	0.66	0.50	bdl	bdl	1.34	0.92
Nd ₂ O ₃	1.15	1.64	2.06	1.51	1.64	2.06	2.12	2.40
ThO ₂	bdl	bdl	bdl	bdl	bdl	0.89	0.63	0.79
SiO ₂	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl
P ₂ O ₅	28.22	28.89	29.22	bdl	bdl	bdl	bdl	bdl
F	2.83	2.79	2.53	bdl	bdl	bdl	bdl	bdl
-O=F ₂	1.19	1.17	1.07	bdl	bdl	bdl	bdl	bdl
Total	95.55	101.23	102.38	65.31	67.84	64.38	64.89	63.71
Formula coefficients								
Na	1.24	1.24	1.15	2.22	2.41	2.93	2.92	3.04
Ca	—	—	—	—	—	0.37	0.54	0.66
Sr	2.72	2.77	2.77	2.32	2.30	1.32	1.06	0.72
Ba	0.19	0.19	0.18	0.12	0.13	0.05	0.10	0.11
Y	—	—	—	0.10	0.12	0.08	0.09	0.15
La	0.42	0.43	0.45	0.38	0.36	0.50	0.44	0.47
Ce	0.41	0.49	0.48	0.40	0.36	0.50	0.52	0.54
Pr	0.01	0.03	0.03	0.02	—	—	0.06	0.04
Nd	0.05	0.07	0.09	0.07	0.07	0.09	0.09	0.10
Th	—	—	—	—	—	0.02	0.02	0.02
Si	—	—	—	—	—	—	—	—
P	3.00	3.00	3.00	—	—	—	—	—
F	1.12	1.08	0.97	—	—	—	—	—
Method of calculation, f. c.	PO ₄ =3	PO ₄ =3	PO ₄ =3	CO ₃ =5	CO ₃ =5	CO ₃ =5	CO ₃ =5	CO ₃ =5

Note: bdl means that content of the component is below detection limits

the Shkatulka pegmatite, at hydrothermal stage, during formation of pseudomorphs after steenstrupine-(Ce), i.e. mineral with «average» cerium-dominated composition of the REE and containing the Th and U admixtures, the deep separation of components, close to each other by their chemical characteristics, took place. We can observe not only a separation of Th and U (with formation of their proper phases) and their separation from rare-earth elements but also the fractionating of the REE among themselves; as a result, the minerals with strongly pronounced maximums of La, Ce, Nd, and Y in the REE spectra are formed. It is most possible that these processes, proceeding in so small objects, are caused by formation of the metalloorganic complex compounds, in which Th, U, and individual

REE show the maximally contrast properties. Origin of the late proper minerals of Ti, Y, Ce, La, Nd, Sr, Th, and U was partly accompanied by the introduction of a number of elements. In particular, some pseudomorphs are significantly enriched by titanium and thorium in comparison with unaltered steenstrupine.

The typical chemical compositions of new-formed minerals in such pseudomorphs are given in the Table 4. Among them, together with known mineral species (including rhabdophane-(Ce), rhabdophane-(Nd), monazite-(La), and belovite-(Ce), which presence is confirmed also by the IR spectroscopy data), the minerals are widespread that have been not earlier described. Their chemical compositions correspond to the lanthanum analogue of

vitusite-(Ce) (analysis 7), the neodymium analogue of abenakiite-(Ce) (analysis 16), the minerals with following hypothetical ideal formulas: $\text{Na}_{2.5}\text{ThTiSi}_8(\text{O},\text{OH})_{24}\cdot n\text{H}_2\text{O}$ (analysis 1); $\text{Na}_2\text{U}_2\text{Si}_3\text{O}_{11}\cdot n\text{H}_2\text{O}$ (analysis 3); $\text{Na}_2\text{USi}_4\text{O}_{11}\cdot n\text{H}_2\text{O}$ (analyses 4, 5); $\text{Na}(\text{U},\text{Th})\text{Si}_3\text{O}_8(\text{OH})\cdot n\text{H}_2\text{O}$ (analysis 6); $\text{Na}_2\text{Th}_3\text{Si}_8\text{O}_{23}\cdot n\text{H}_2\text{O}$ (analysis 11); $\text{Na}_5\text{REE}_2(\text{Si},\text{P})_6\text{O}_{18}\cdot n\text{H}_2\text{O}$ (analysis 12); and $(\text{Na},\text{Ca})_4(\text{Mn},\text{Fe})(\text{Y},\text{HREE},\text{Th},\text{U})_2\text{Si}_{12}\text{O}_{30}\cdot n\text{H}_2\text{O}$ (analysis 15). During calculation of the formulae, the valency 4 was assumed for uranium, taking into account its joint entry in some phases together with thorium, and also paragenesis with SBM, which formation demands the reducing medium. In the Shkatulka pegmatite, the dispersed organic matter is present in most pseudomorphs after steenstrupine (see the IR spectrum 2 on Fig. 6). To all appearances, the reduced total sums of analyses of mineral phases are connected with that (Table 4).

Conclusions

1. Thin intergrowths of SBM with the rare elements minerals are the typical formations of the hydrothermal zones of agpaitic pegmatites of the Khibiny and Lovozero massifs.

2. For all studied minerals of Th and REE from the late assemblages in pegmatites, the high contents of the oxidized aromatic compounds, captured during crystallization, are characteristic. Rarely around crystals, of these minerals the crusts enriched by organic matter are observed. Neither early minerals of Th and REE no minerals of hydrothermal stage, which do not contain Th and REE, as a rule, have this peculiarity.

3. The aggregations of the oxygen-bearing bitumen matters, enriched by aromatic components and formed in alkaline pegmatites at the low-temperature stages, almost always contain the abundant microscopic ingrowths of minerals, in which composition Th, Ln, and Ca, and sometimes also U, Y, Sr, Ba, Nb, and Ti are the main components.

4. In the Shkatulka pegmatite, the substitution of steenstrupine by the late minerals is accompanied by the introduction of organic matter and rare elements and the high degree of separation of Ti, Ce, La, Nd, Y, Sr, Th, U among different phases, right up to formation of the proper minerals of all these elements. As a result, mineralogy of the heterophase formations, containing SBM, is extremely diverse. Here, not only minerals species, new for Khibiny (steacyite) and Lovozero (remondite-(Ce), belovite-(La)), but also a number of phases, which do not have ana-

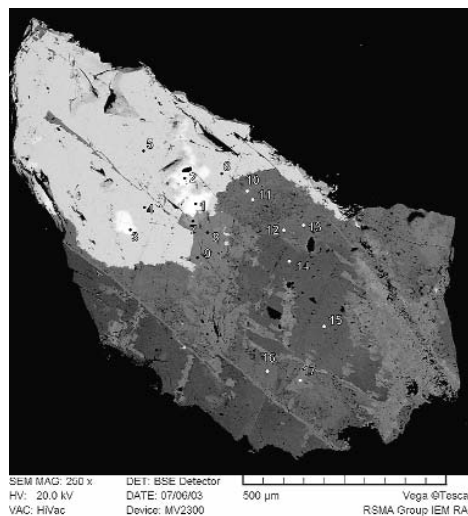


Fig. 7. Crystal of the REE carbonate (analysis 13 in Table 1) in SBM (sample Kh9). Image in back-scattered electrons and in characteristic radiations of different elements.

Fig. 8. Contact zone of belovite with carbonate margin, containing SBM (black parts). Image in back-scattered electrons. Points corresponds to following minerals: 1, 6 – belovite-(La); 2,

logues among the known minerals, were found.

5. The high activity of rare elements and titanium in alkaline hydrothermalites is mainly caused by the presence of complexes with organic compounds, taking part in transportation of these elements.

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Table 4. Chemical composition of minerals from microheterogeneous pseudomorphs after steenstrupine (the Shkatulka pegmatite, Lovozero).

No. of sample	L2							
Mineral	Na,Ti,Th silicate	Sazhinite (Ce)?	Na,U- silicate	Na,U- silicate	Na,U- silicate	Na,U,Th- silicate	«Vitusite- (La)»?	Steenstrupine (Ce) (relic)
No. of analysis	1	2	3	4	5	6	7	8
Content of components, wt %								
Na ₂ O	6.05	4.49	5.38	8.40	7.6	4.92	21.11	5.41
K ₂ O	0.22	1.12	bdl	bdl	bdl	bdl	bdl	bdl
CaO	0.43	0.21	bdl	bdl	bdl	bdl	bdl	0.76
SrO	0.47	0.37	0.40	bdl	bdl	bdl	bdl	1.22
BaO	bdl	0.36	bdl	bdl	bdl	bdl	0.74	0.46
PbO	0.49	bdl	bdl	1.67	0.06	1.76	bdl	0.42
MnO	0.79	bdl	bdl	bdl	bdl	bdl	bdl	5.40
FeO	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.68
La ₂ O ₃	bdl	4.60	bdl	bdl	0.55	0.46	26.73	6.06
Ce ₂ O ₃	0.84	11.63	bdl	bdl	0.81	0.45	8.09	8.41
Pr ₂ O ₃	0.30	1.53	bdl	bdl	bdl	bdl	bdl	0.84
Nd ₂ O ₃	0.31	3.29	bdl	bdl	bdl	bdl	0.90	2.03
Sm ₂ O ₃	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl
ThO ₂	23.17	2.03	1.92	4.25	3.77	14.46	bdl	11.29
UO ₂	bdl	bdl	54.12	34.79	36.12	27.62	0.53	0.95
TiO ₂	6.54	bdl	bdl	bdl	bdl	bdl	bdl	0.55
SiO ₂	40.67	51.86	18.68	30.26	30.81	31.03	bdl	29.32
Nb ₂ O ₅	0.50	bdl	bdl	bdl	bdl	bdl	bdl	bdl
P ₂ O ₅	bdl	bdl	bdl	bdl	bdl	bdl	32.35	5.79
Total	80.78	81.49	80.50	79.37	80.77	80.70	90.55	79.59
Formula coefficients								
Na	2.31	1.01	1.68	2.15	1.78	0.92	2.99	5.52
K	0.06	0.16	—	—	—	—	—	—
Ca	0.09	0.02	—	—	—	—	—	0.42
Sr	0.05	0.02	0.04	—	—	—	—	0.38
Ba	—	0.02	—	—	—	—	0.02	0.09
Pb	0.03	—	—	0.06	0.06	0.05	—	0.06
Mn	0.13	—	—	—	—	—	—	2.40
Fe	—	—	—	—	—	—	—	0.31
La	—	0.20	—	—	0.02	0.02	0.72	1.17
Ce	0.06	0.49	—	—	0.04	0.01	0.22	1.61
Pr	0.02	0.07	—	—	—	—	—	0.17
Nd	0.02	0.14	—	—	—	—	0.02	0.38
Sm	—	—	—	—	—	—	—	—
Th	1.04	0.05	0.07	0.13	0.11	0.32	—	1.35
U	—	—	1.94	1.02	1.05	0.60	0.01	0.11
Ti	0.97	—	—	—	—	—	—	0.22
Si	8.00	6.00	3.00	4.00	4.00	3.00	—	15.42
Nb	0.04	—	—	—	—	—	—	—
P	—	—	—	—	—	—	2.00	2.58
Method of calculation, f. c..	Si=8.00	Si=6.00	Si=3.00	Si=4.00	Si=4.00	Si=3.00	P=2.00	Si+P=18.00

Table 4. (end)

No. of sample Mineral	L3		L4		L5			
	Monazite-(La)?	Rhabdophane -(Ce)?	Na,Th-silicate	Na,REE -silicate	Rhabdophane-Nd	Belovite-(Ce)	Na-Y-Mn silicate	«Abenakeite-(Nd)?»
№ of analysis	9	10	11	12	13	14	15	16
Na ₂ O	1.28	1.62	2.63	15.09	bdl	4.61	8.0	27.14
K ₂ O	bdl	bdl	0.35	bdl	bdl	bdl	0.2	0.02
CaO	1.43	1.19	bdl	bdl	0.69	0.09	1.7	0.22
SrO	4.47	3.69	bdl	bdl	0.98	24.67	bdl	bdl
BaO	1.32	0.87	bdl	bdl	bdl	20.51	bdl	0.37
PbO	bdl	bdl	bdl	bdl	0.73	bdl	bdl	bdl
MnO	0.42	0.68	bdl	bdl	bdl	bdl	2.9	0.17
FeO	bdl	bdl	bdl	bdl	bdl	bdl	1.9	bdl
La ₂ O ₃	26.00	11.32	bdl	2.98	4.20	4.13	bdl	1.05
Ce ₂ O ₃	25.34	25.29	bdl	13.78	19.83	9.40	0.4	8.83
Pr ₂ O ₃	2.33	3.41	bdl	2.61	4.04	1.20	bdl	2.03
Nd ₂ O ₃	3.52	11.48	bdl	11.45	22.48	5.39	1.0	13.40
Sm ₂ O ₃	bdl	bdl	bdl	3.16	7.53	1.08	1.0	4.79
ThO ₂	1.02	bdl	51.19	1.70	0.11	bdl	3.2	0.19
UO ₂	bdl	bdl	bdl	bdl	1.01	bdl	2.8	bdl
TiO ₂	bdl	bdl	bdl	bdl	bdl	bdl	0.6	bdl
SiO ₂	3.10	2.66	31.24	33.21	bdl	bdl	53.4	12.51
Nb ₂ O ₅	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl
P ₂ O ₅	23.89	23.37	bdl	1.72	27.99	27.25	bdl	15.44
Total	94.12	85.58	85.41	87.23*	89.59	98.33	89.5**	90.11***
Formula coefficients								
Na	0.11	0.14	1.30	5.06	—	1.16	3.48	24.70
K	—	—	0.11	—	—	—	0.06	0.01
Ca	0.07	0.06	—	—	0.03	0.01	0.41	0.11
Sr	0.11	0.10	—	—	0.02	1.86	—	—
Ba	0.02	0.02	—	—	—	1.04	—	0.07
Pb	—	—	—	—	0.01	—	—	—
Mn	0.02	0.03	—	—	—	—	0.55	0.07
Fe	—	—	—	—	—	—	0.36	—
La	0.41	0.19	—	0.19	0.07	0.195	—	0.18
Ce	0.40	0.41	—	0.87	0.31	0.45	0.03	1.52
Pr	0.04	0.06	—	0.16	0.06	0.06	—	0.35
Nd	0.05	0.18	—	0.71	0.34	0.25	0.08	2.25
Sm	—	—	—	0.19	0.11	0.05	0.08	0.77
Th	0.01	—	2.98	0.07	—	—	0.16	0.02
U	—	—	—	—	0.01	—	0.14	—
Ti	—	—	—	—	—	—	0.10	—
Si	0.07	0.12	8.00	5.75	—	—	12.00	5.87
Nb	—	—	—	—	—	—	—	—
P	0.93	0.88	—	0.25	1.00	3.00	—	6.13
Method of calculation, f. c. .	P + Si = 1.00	P + Si = 1.00	Si = 8.00	Si + P = 6.00	P = 1.00	P = 3.00	Si = 12.00	Si + P = 12.00

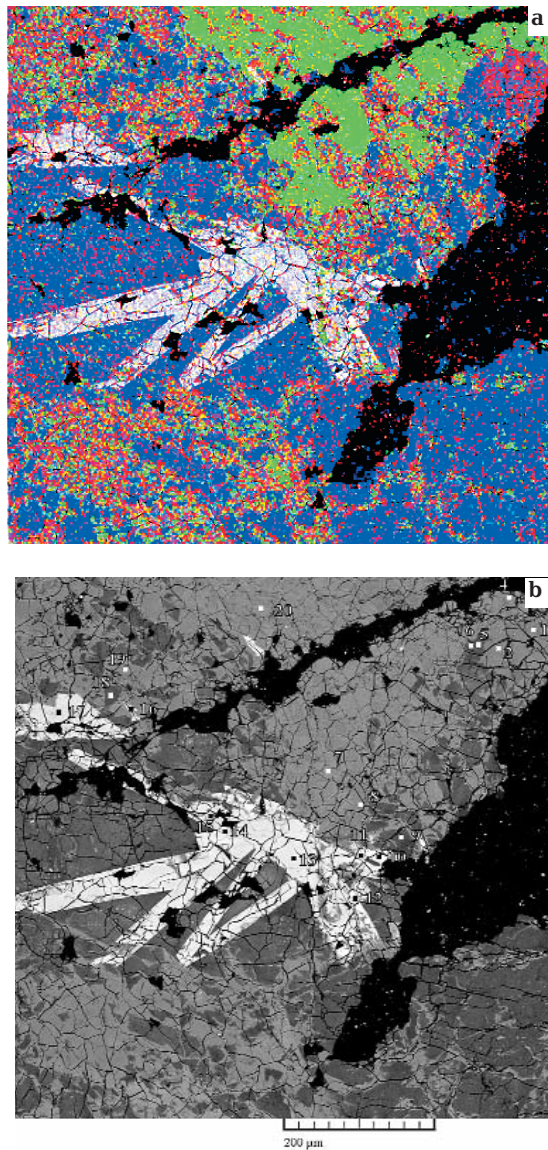
Note: bdl means that content of the component is below detection limits.

Method of calculation of formula coefficients for steenstrupine was selected in accordance with general formula for minerals of the steenstrupine-(Ce) – thorostenstrupine series (Pekov et al., 1997).

Totals of analyses include: *1.53% Gd₂O₃ (respectively Gd0.09); **12.4% Y₂O₃ (respectively Y1.48); ***0.12% Y₂O₃, 0.70% Eu₂O₃, 1.82% Gd₂O₃, 1.31% SO₂ (respectively Y_{0.03}, Eu_{0.11}, Gd_{0.28}, S_{0.54}).

Understated totals of some analyses are caused by dispersed inclusions of SBM.

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5 – belovite-(Ce); 7-11, 17 – burbankite; 12-16 – remondite-(Ce)

Fig. 9. Fragment of polymictic pseudomorph after steenstrupine (sample L2): a – image in imposed characteristic radiation Th M 2 (red colour), P $K_{\alpha 1}$ (green), and Si $K_{\alpha 1}$ (blue); b – points of analyses, corresponding to the Na-Ti-Th silicate (1, 2), vitusite-(La) (3, 4, 7, 20), sazhinite-(Ce) (5, 6, 9, 18), steenstrupine-(Ce) (8, 19), phase $\text{Na}_2\text{U}_2\text{Si}_2\text{O}_{11} \cdot n\text{H}_2\text{O}$ (10, 12), the

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