

Compositions of Minerals of the Lamprophyllite Group from Alkaline Massifs Worldwide

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Abstract—The analysis of a data base on the compositions of lamprophyllites from alkaline massifs worldwide enabled us to discuss the isomorphic substitutions in structures of the minerals of this group, as well as variations of their compositions and typomorphic features in different alkaline massifs. It is shown that the lamprophyllite composition is related to geochemical features of the corresponding massif. However, there is no simple relation between the element contents in lamprophyllite and the host massif.

Minerals of the lamprophyllite group (Sr, Ba, K, Na)₂Na(Na, Mn, Fe, Ca, Mg)₂Ti[Ti₂O₂(Si₂O₇)₂](0, OH, F)₂ are usual accessory phases of igneous complexes oversaturated with respect to alkalis. They normally crystallize at the later stages of magma differentiation and during the postmagmatic processes up to the latest stages of mineral formation.

The wide crystallization range of lamprophyllites makes it reasonable to study their typomorphic (particularly chemical) features.

A data base was created for this purpose, which comprises the compositions of minerals of the lamprophyllite group from alkaline complexes worldwide. It includes published analyses, authors' data, and several analyses graciously provided by N.V. Chukanov and D.V. Lisitsin. The analyses were carried out by wet chemistry or obtained with electron microprobe and by interpreting of the mineral structures.

The representative analyses of minerals of the lamprophyllite group are listed in Table 1.

The crystal structures of lamprophyllite and the other minerals of its group (baritolamprophyllite and K-baritolamprophyllite) were determined in samples from many alkaline complexes [12-17]. As a result, the lamprophyllite structure is now well known. However, some problems of isomorphic substitutions in its structure are not yet solved (see below).

Several sites can be distinguished in the lamprophyllite structure, i.e., Si, Ti(1), Ti(2), Na, M(1), M(2), 0(1)...0(6), and H. The structure is based on the three-sheet layer composed of the central trioctahedral sheet with Na, Ti(2), and M(2) sites and side nets built up of Si²⁰⁷ diorthogroups linked by five-coordinated Ti(1) polyhedra. The atoms between the layers occupy the M(1) sites. The distribution of cations over the sites is shown in Table 2.

All of the oxygen atoms in the trioctahedral sheets [except for O(1) of hydroxyl groups that is replaced by F and Cl] are shared with Ti-Si-O nets.

The lamprophyllite structure is devoid of vacancies that could be occupied by any additional (foreign) cations (R.K. Rastsvetaeva, personal communication).

As a result, the cation total in a correct formula calculation should not exceed 12. The lamprophyllite formulas are calculated on the basis of four Si atoms. It is suggested in this case that all Al atoms occupy the Ti sites. Another calculation procedure is based on the assumption that Al atoms occupy the sites with tetrahedral coordination together with Si. We calculated the mineral formulas by both methods and analyzed the distribution of total cation amounts (Table 3).

The statistic data obtained are more consistent with the substitution of Al for Si, rather than for Ti.

Based on these data, we used the second calculation procedure and controlled the cation totals. The analyses with cation totals deviating by more than 3a from 12 were not considered. The analyses with total amounts of Sr, Ba, and K above two formula units by more than 0.2 were also considered as unsatisfactory.

The coefficients of correlation between individual cations in the lamprophyllite structure calculated from these data are shown in Table 4.

This table demonstrates that the best correlation is observed between Sr and Ba, which is related to the occupation of the M(1) site by these two elements. According to structural data [14, 16, 17], potassium also occupies the M(1) site and correlates negatively with Sr and positively with Ba. The latter is caused by the similarity of K and Ba ionic radii. The calculated partial coefficient of correlation¹ between Ba and K is

¹The partial coefficient of correlation is a measure of linear correlation between any two variables from the X_1, X_2, \dots, X_n group when the effect of the other variables is eliminated [18].

Table 1. Representative analyses of minerals of the lamprophyllite group

Ordinal no.	Na ₂ O	K ₂ O	MgO	CaO	SrO	BaO	MnO	FeO	Al ₂ O ₃	Fe ₂ O ₃	SiO ₂	TiO ₂	Nb ₂ O ₅	H ₂ O	F	Cl	ThO ₂	La ₂ O ₃	Ce ₂ O ₃	Total	-O=F
1	11.34	1.61	0.74	1.09	11.71	7.65	0.78	5.06	0.12	n.a.	30.06	27.92	0.11	n.a.	1.87	n.a.	–	0.00	2.70	102.76	101.88
2	9.99	2.41	0.39	1.12	6.94	11.89	1.03	4.14	n.a.	1.32	29.80	29.49	n.a.	0.81	1.65	n.a.	n.a.	n.a.	n.a.	100.98	100.20
3	12.10	0.62	0.44	4.30	11.50	0.00	5.06	0.00	2.00	2.48	29.98	29.57	0.11	1.58	n.a.	n.a.	n.a.	n.a.	n.a.	99.74	
4	9.60	1.64	0.66	1.27	8.69	9.51	1.40	3.20	0.90	1.44	30.40	29.50	0.27	1.79	n.a.	–	n.a.	n.a.	n.a.	100.27	
5	9.20	2.30	0.41	1.90	6.54	15.60	0.53	3.19	0.17	n.a.	29.10	28.80	n.a.	n.a.	1.64	n.a.	n.a.	n.a.	n.a.	99.38	98.61
6	11.99	0.94	1.03	0.26	3.48	20.06	1.60	1.27	0.04	n.a.	29.90	28.68	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	99.25	
7	9.67	1.06	0.39	0.56	4.74	26.31	0.84	n.a.	–	1.20	27.96	26.34	n.a.	n.a.	n.a.	n.a.	–	–	–	99.07	
8	11.14	0.94	0.34	0.36	0.65	24.12	1.10	0.71	0.04	n.a.	28.75	27.80	n.a.	1.83	1.18	n.a.	n.a.	n.a.	n.a.	98.96	98.40
9	9.20	0.65	0.71	0.29	17.11	5.68	4.95	1.58	0.26	n.a.	30.22	28.42	0.34	n.a.	n.a.	–	–	–	–	99.41	
10	10.57	1.89	0.53	0.88	11.40	8.67	2.38	1.75	0.60	–	29.00	28.94	0.30	1.56	1.60	n.a.	n.a.	n.a.	n.a.	100.07	99.32
11	10.63	1.17	0.67	1.74	14.07	2.31	4.29	1.91	0.44	0.54	30.70	29.14	0.15	n.a.	0.84	0.28	n.a.	n.a.	n.a.	98.88	98.48
12	10.04	2.97	1.46	1.44	9.53	4.23	2.16	3.49	0.76	2.68	30.78	28.91	0.24	n.a.	1.63	n.a.	n.a.	n.a.	n.a.	100.32	99.55
13	12.45	0.46	0.63	0.91	14.72	0.97	3.86	2.29	0.20	n.a.	31.14	30.16	0.11	n.a.	1.96	n.a.	0.22	0.06	0.45	100.59	99.67
14	12.59	1.15	n.a.	0.34	1.80	19.27	3.60	0.23	0.31	n.a.	27.53	25.54	3.09	1.82	1.36	n.a.	n.a.	n.a.	n.a.	98.63	97.99
15	11.16	0.46	0.44	0.63	15.02	1.10	3.18	3.34	0.27	n.a.	30.64	30.39	0.45	n.a.	1.40	0.00	–	0.07	0.52	99.07	98.41
16	8.40	0.79	0.32	0.46	11.93	8.18	2.43	2.31	0.20	n.a.	31.17	28.03	0.67	n.a.	1.57	0.00	0.02	0.01	0.35	96.84	96.10
17	11.57	0.82	0.18	0.14	7.35	15.01	2.18	1.19	0.32	n.a.	30.04	28.10	0.30	n.a.	1.97	n.a.	n.a.	n.a.	0.12	99.29	98.36
18	12.58	0.52	0.52	0.55	14.83	0.65	2.96	3.69	0.14	n.a.	32.27	29.84	0.38	n.a.	2.73	n.a.	n.a.	n.a.	0.02	101.68	100.40
19	11.27	0.45	0.42	0.41	14.65	0.87	6.14	2.85	0.13	n.a.	30.51	29.42	0.25	n.a.	0.93	0.01	–	0.16	0.24	98.71	98.27
20	12.59	0.41	0.66	0.42	15.49	0.77	2.08	3.93	0.19	n.a.	30.90	29.45	0.20	n.a.	1.71	n.a.	0.15	0.05	0.45	99.45	98.65

Note: (1) Niva (authors' data), (2) Botogol [1]; (3) Strelka [2]; (4) Turii Mys [3]; (5) Oldoinyo Lengai [4]; (6) Gardiner [5]; (7) Bearpaw [6]; (8) Inagli [7]; (9) Pilanesberg (authors' data); (10) Khibiny [8]; (11) Khibiny [9]; (12) Khibiny [10]; (13) Lovozero, Lephe-Nelm (authors' data); (14) Lovozero, Yubileinaya [11]; (15, 16) Lovozero, differentiated complex (authors' data); (17, 18) Lovozero, eudialyte complex (authors' data), core and rim of a crystal; (19, 20) Lovozero, porphyritic lujavrites (authors' data). Dash means content below detection limit, n.a. is not analyzed.

Table 2. Occupation of cation sites in lamprophyllites (data of structure interpretation)

M(1)	Na	M(2)	Ti(1)	Ti(2)	Si	Reference
Sr _{1.2} K _{0.65} Ba _{0.15}						[12]
Sr _{1.2} K _{0.65} Ba _{0.15}	Na	Na _{1.05} (Fe, Mn, Mg) _{0.95}	Ti ₂	Ti	Si	[14]
Sr _{1.1} Ba _{0.9}	Na	Na _{1.8} Mn _{0.2}	Ti _{1.4} Fe _{0.6} ³⁺	Ti _{0.7} Mg _{0.3}	Si	[15]
KBa	Na	Na _{1.2} (Fe, Mn) _{0.8}	Ti ₂	Ti	Si	[16]
Ba ₂	Na	Na _{1.74} Mn _{0.26} Na _{1.74} Mg _{0.14} Ca _{0.12}	Ti _{1.6} Fe _{0.4} Ti _{1.8} Al _{0.2}	Ti Ti	Si	[17]

Table 3. Mean totals of cations in lamprophyllite formulas

Analyses are recalculated on the basis of	Si = 4	Si + Al = 4
Mean values for all analyses	12.299 ± 0.085	12.073 ± 0.088
Mean values for analyses within 3σ interval:		
all analyses	12.320 ± 0.059	12.104 ± 0.070
microprobe analyses	12.09 ± 0.05	12.00 ± 0.05
chemical analyses	12.50 ± 0.09	12.29 ± 0.08

Table 4. Coefficients of correlation between element concentrations in minerals of the lamprophyllite group

Element	Sr	Ba	K	Na	Ca	Mg	Fe	Mn	Zn	Ti	Nb	Zr	Al	F	Cl
Sr	1.00														
Ba	-0.91	1.00													
K	-0.68	0.62	1.00												
Na	0.38	-0.39	-0.59	1.00											
Ca	-0.19	0.01	0.34	-0.14	1.00										
Mg	-0.03	-0.06	0.02	0.02	0.24	1.00									
Fe	-0.12	-0.07	0.46	-0.22	0.39	0.21	1.00								
Mn	0.43	-0.39	-0.39	0.09	-0.30	-0.30	-0.49	1.00							
Zn	-0.08	-0.14	-0.18	-0.01	-0.14	-0.49	-0.22	0.18	1.00						
Ti	0.05	-0.01	0.06	0.23	-0.03	-0.22	-0.12	0.11	-0.02	1.00					
Nb	-0.51	0.50	0.31	0.01	-0.09	-0.23	-0.12	-0.07	0.32	0.05	1.00				
Zr	-0.38	0.37	0.11	0.22	0.42	0.09	0.17	-0.17	-0.06	-0.08	0.59	1.00			
Al	-0.12	0.00	0.11	-0.22	0.33	0.32	0.01	0.02	0.84	-0.19	-0.04	-0.30	1.00		
F	-0.05	0.02	0.23	-0.09	-0.13	-0.03	0.40	-0.36		-0.06	0.16	0.60	-0.39	1.00	
Cl	-0.38	0.35	0.32	-0.20	0.33	0.49	0.47	-0.50		-0.52	-0.12		0.11	0.19	1.00

Note: Significant coefficients are shown in bold.

0.02 with consideration of the Sr effect, i.e., K and Ba collectively replace Sr in the lamprophyllite structure.

The problem of Na and Ca distribution between M(1) and M(2) sites was also discussed in the literature [15, 17, 19]. Our data (Table 5) show no correlation between Na and Ca in lamprophyllite. This fact indicates that these elements occupy different sites in the mineral structure or they are distributed over several sites with complex isomorphic substitutions. The coef-

ficients of Na and Ca correlation with other elements in the M(1) site (structural data) indicate that Na also occupies this site, as it is justified by a large negative coefficient of Na correlation with K, while the coefficient of correlation between Ca and K is positive. Significant correlations between Na and Sr, Na and Ba, and Ca and Sr are induced by the effect of K.²

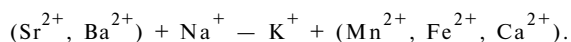
² The induced (false) correlation between two variables is the correlation induced by the effect of the other variables.

Table 5. The main isomorphous admixtures in the M(2) site

Element	The lowest content (f.u.) was found in	The highest content (f.u.) was found in	The lowest mean content (f.u.) was found in	The highest mean content (f.u.) was found in
Mn	Khibiny (0.05) Gardiner (0.05)	Khibiny (0.90)	Oldoinyo Lengai (0.06), s.a. Niva (0.08)	Pilanesberg (0.56)
Fe	Lovozero (0.03)	Murun (0.65) Khibiny (0.63)	Pilanesberg (0.17)	Botogol (0.60), s.a. Murun (0.59) Niva (0.52)
Mg	Khibiny (0.02) Lovozero, eudialyte complex (0.03) Lovozero, pegmatites (0.03)	Khibiny (0.38) Inagli (0.27)	Lovozero, differentiated complex (0.07)	Niva (0.16) Gardiner (0.16) Pilanesberg (0.16)
Ca	Pilanesberg (0.02) Lovozero, eudialyte complex (0.02)	Khibiny (0.60) Strelka (0.57)	Pilanesberg (0.05)	Strelka (0.57), s.a. Oldoinyo Lengai (0.28), s.a. Botogol (0.16), s.a. Turii Mys (0.15) Murun (0.15)

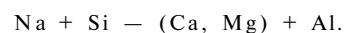
Note: s.a. is single analysis.

Note the high positive coefficients of correlation between K and Fe, as well as between Sr and Mn. Considering the effect of these dependencies, we obtained a positive partial coefficient of correlation between Mn and K. A positive correlation between the concentration of univalent K replacing bivalent Sr and Ba in the M(1) site and the concentrations of Mn, Fe, and Ca replacing univalent Na can be illustrated by the following charge-compensation scheme



As a result, we propose the following formula for the K-lamprophyllite end member: $\text{K}_2\text{Na}(\text{Mn}, \text{Fe}, \text{Ca})_2\text{Ti}[\text{Ti}_2\text{O}_2(\text{Si}_2\text{O}_7)_2](0, \text{OH}, \text{F})_2$.

Aluminum shows significant positive correlations with Ca and Mg and negative, with Na, which can be accounted for by the following substitution scheme:



The compositions of minerals of the lamprophyllite group were compared in triangular plots describing the occupation of M(1) and M(2) + Na sites (Fig. 1). The Ti site has not been considered, because the Nb, the main isomorphous admixture in this site, has not been analyzed in many published lamprophyllite compositions. The O(1) site was also not considered, because most of the analyses do not include Cl and H₂O contents, while F concentrations are reported only for about 70% of the analyzed lamprophyllites.

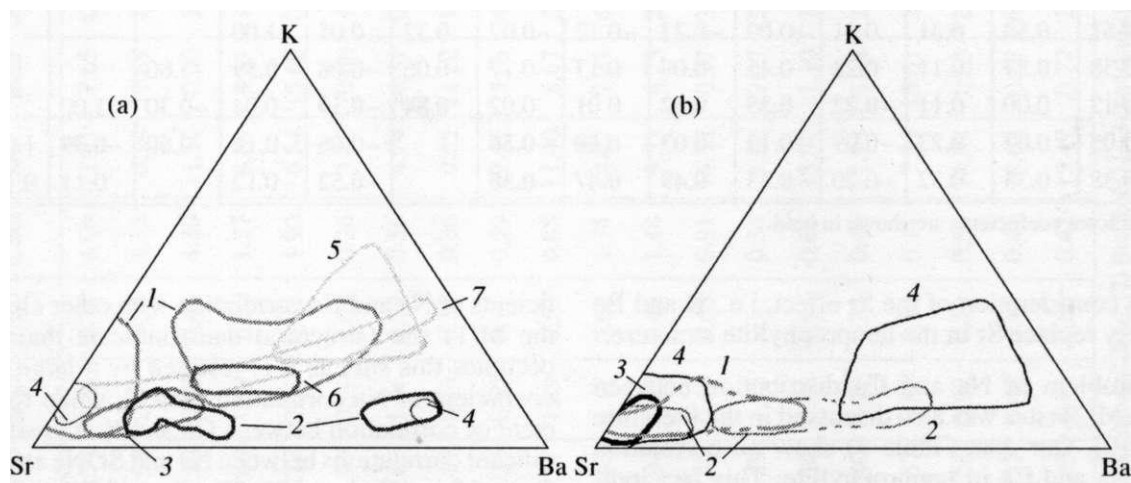


Fig. 1. Compositions of lamprophyllites from alkaline massifs worldwide in the K-Sr-Ba diagram, (a) Fields: (1) Khibiny, (2) Gardiner, (3) Pilanesberg, (4) Bearpaw, (5) Murun, (6) Niva, (7) Inagli. (b) Lovozero Massif; fields: (1) differentiated complex, (2) eudialyte complex, (4) pegmatites.

The M(1) site is generally occupied by Sr, Ba, K, and Na. It probably also incorporates rare earth elements and Y.

The K-Sr-Ba diagram shows that the fields of the lamprophyllite compositions from various massifs significantly overlap. However, three groups of lamprophyllites could be distinguished in this diagram, particularly for the Ba-rich varieties. Lamprophyllites of the first group are enriched in K (Murun, Turii Mys, Inagli, Niva, and Khibiny massifs). Lamprophyllites of the Murun Massif are richest in K (0.61 f.u., on average) in agreement with the elevated potassium contents in the rocks of this massif. The second group comprises lamprophyllites with low K contents (<0.2 f.u.) (Bearpaw, eudialyte and differentiated complexes of the Lovozero Massif, and Pilanesberg). Lamprophyllites from pegmatites of the Lovozero Massif compose the third group with transitional compositions.

The lamprophyllites of some massifs compose two fields: (1) enriched with Sr and (2) enriched with Ba. However, there is no gap between the Sr- and Ba-rich compositions (Fig. 1), which suggests a continuous solid solution series in the lamprophyllite-baritolamprophyllite series. The occurrence of lamprophyllites of two separate compositional groups within one massif could be caused by the evolution of the mineralizing medium. Pekov *et al* [20] explained the transition from lamprophyllite to baritolamprophyllite in the Khibiny Massif by the separation of Sr from Ba at the later pegmatitic stages due to Sr partitioning into carbonates (ancylite and strontianite), which are closely associated with baritolamprophyllite. A similar role in some other massifs could be played by the chevkinite-group minerals, as well as REE phosphates and carbonates (Table 6). Similar evolutionary trends of the lamprophyllite composition in different massifs, including the rocks of the eudialyte complex that have almost no Sr-apatite and contain much smaller amounts of Sr-bearing minerals as compared to lamprophyllite, suggest that there are some other reasons for the transition from lamprophyllite to baritolamprophyllite. We believe that this transition could be related to the accumulation of components of the lower temperature Ba-lamprophyllite in the melt relative to those of the higher temperature Sr-lamprophyllite.

The triangular Na-Sr-Ba, Na-K-Sr, and K-Sr-Ba diagrams were found to be less informative.

Lamprophyllites can be subdivided by dominant cations occupying the M(1) site into Sr-rich and Ba-rich minerals (in the general case, this classification is not equivalent to a formal subdivision into lamprophyllite and baritolamprophyllite). In turn, the Ba-rich lamprophyllites are subdivided into high-, medium-, and low-K varieties.

The rare earth elements and Y are usually not analyzed in lamprophyllites. The available data indicate that the mineral can contain up to 0.02 f.u. La, 0.01 f.u. Nd, and 0.3 f.u. Ce; however, the latter normally does

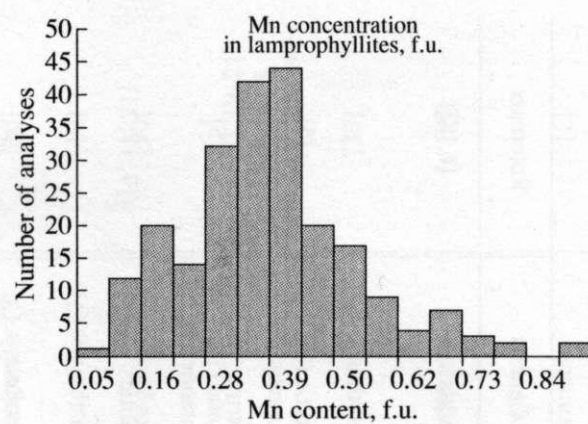


Fig. 2. Mn distribution in lamprophyllites from alkaline complexes worldwide.

not exceed 0.05 f.u. Only lamprophyllites from the Niva Massif have exclusively high Ce contents (0.13–0.23 f.u.). Yttrium contents are typically below 0.005 f.u., i.e., lamprophyllites are enriched in light rare earth elements.

The M(2) site is generally occupied by Na (the Na content not found in the M(1) site is >2 f.u. in 80% of all cases). Data on minor admixtures in the M(2) site are given in Table 5.

The distribution of Mn has a minimum at about 0.2 f.u. (Fig. 2). Such a bimodal distribution allows one to subdivide lamprophyllites into high- and low-Mn varieties.

High-Mn (>0.2 f.u.) lamprophyllites are abundant in the Khibiny, Lovozero, Pilanesberg, Turii Mys, and Strelka massifs, while low-Mn lamprophyllites are typical of the Inagli, Bearpaw, Gardiner, Murun, Oldoinyo Lengai, Botogol, and Niva massifs.

Zinc contents in lamprophyllites normally do not exceed 0.05 f.u. and are usually not analyzed. There is one analysis of lamprophyllite from pegmatite of the Lovozero Massif with 0.4 f.u. Zn. In this case, Zn probably occupies the M(2) site.

Lamprophyllites in some massifs have an almost constant Mn/Fe ratio (Fig. 3), which is low in the Niva Massif (0.15), somewhat higher in the Inagli (0.95) and Bearpaw (0.56) massifs, and extremely high in Pilanesberg (3.90). Some fields are roughly isometric and characterize significant variations in the mineral composition (low-Mn lamprophyllites of the Khibiny Massif, lamprophyllites of pegmatites and the eudialyte complex of the Lovozero Massif and Gardiner complex). Some fields are elongated along the Na-Mn side, for example, very similar fields of lamprophyllites from the rocks of the differentiated complex and porphyritic lujavrites of the Lovozero Massif; some other fields gravitate to the Na-Fe side (lamprophyllites of the Murun Massif). The field of high-Mn lamprophyllites of the Khibiny Massif is small and is located at the right-hand sides of the extended field of the Pilanesberg lamprophyllites and the group of fields enclosing lam-

Table 6. Occurrences and mineral assemblages of lamprophyllites in alkaline complexes worldwide

Massif	Rock	Mineral assemblage	Lamprophyllite type	Genesis	Reference
Bearpaw	Pegmatite	Nepheline, microcline, phlogopite-annite, magnetite, rutile, zircon, thorite, betafite, Ce-loparite, crichtonite, ilmenite, pyrophanite, aegirine, sphene, minerals of the chevkinite group	Sr-lamprophyllite with rims of Ba-lamprophyllite	Pegmatitic	[6, 12]
Gardiner	Pegmatites and veins	Natrolite, sphene; lorenzenite, melanite, pectolite, magnetite, aegirine-augite	Sr- and Ba-lamprophyllites	Pegmatitic (?), metasomatic (?)	[5]
Gardiner	Phonolite dikes (?)	Aegirine, lorenzenite, sodalite, albite, natrolite	High- and low-Mn Sr-lamprophyllite and low-K Ba-lamprophyllite	Magmatic (?), metasomatic (?)	[5]
Inagli	Pegmatite	Lorenzenite, neptunite, vinogradovite, albite, nepheline, eudialyte, aegirine, microcline, leucosphehite, thompsonite		Pegmatitic	[7, 17,21]
Inagli	Metasomatites	Albite, microcline, leucosphehite, batisite, innelite	High-Mn high-K lamprophyllite	Metasomatic	[2]
Koksharovka	Eudialytic lujavrites	Eudialyte, aegirine, potassium feldspar, nepheline		Magmatic (?)	[22]
Lovozero	Rock of the differentiated complex	Nepheline, feldspar, aegirine, ilmenite, loparite	High-Mn Sr-lamprophyllite	Late magmatic (?)	[23] authors' data
Lovozero	Eudialytic lujavrites	Nepheline, feldspar, aegirine, amphibole, murmanite, mosandrite, steenstrupine, monazite, nenadkevichite, vitusite, loparite	High-Mn Sr-lamprophyllite and rare low-K Ba-lamprophyllite	Late magmatic (?)	[23, 24] authors' data
Lovozero	Porphyritic lujavrites	Nepheline, feldspar, aegirine, amphibole	High-Mn Sr-lamprophyllite	Late magmatic (?)	[23] authors' data
Lovozero	Pegmatites	Aegirine, serandite, steenstrupine, narsarsukite, lomonosovite, microcline, sodalite, magnesioarfvedsonite, eudialyte, terskite	High-Mn Sr-lamprophyllite and medium-K Ba-lamprophyllite	Pegmatitic	[11,21,23] Chukanov's and authors' data
Murun	Pegmatite	Odintsovite, aegirine, sphene, feldspar	High-Mn high-K Ba-lamprophyllite, Sr-lamprophyllite	Pegmatitic	[16, 25] Chukanov's data
Niva	Agpaitic syenite	Feldspar, aegirine-diopside to aegirine, amphibole, aenigmatite, natrolite, apatite, shcherbakovite	Low-Mn high-K Ba-lamprophyllite	Magmatic (?)	[26, 27] authors' data

Table 6. (Contd.)

Massif	Rock	Mineral assemblage	Lamprophyllite type	Genesis	Reference
Oldoinyo Lengai	Combeite nephelinite	Combeite, sodalite, apatite, nepheline, pyroxene, melanite, delhayelite, Ce-Nb-Sr perovskite, Ca-Na-Sr-K phosphate, magnetite (rare)	Low-Mn high-K Ba-lamprophyllite	Late magmatic	[4]
Parana	Fenites	Sr-chevkinite, Sr-loparite, aegirine, nepheline, sanidine	Low-Mn Sr-lamprophyllite	Metasomatic	[28]
Pilanesberg	Nepheline syenite	Microcline, nepheline, aegirine, calcite, analcime, pectolite, fluorite	High-Mn Sr-lamprophyllite	Magmatic (?)	[21] authors' data
Strelka	Metasomatites	Eudialyte, lorenzenite, rhyncholite, lomonosovite	High-Mn Sr-lamprophyllite	Metasomatic	[2]
Turii Mys	Fenites	Aegirine, natrolite, quartz, labuntsovite, calcite, sphene, woehlerite, eudialyte	High-Mn high-K Ba-lamprophyllite	Hydrothermal	[1,3,29]
Khibiny	Khibinite	Ilmenite, amphibole		Late magmatic (?)	[10]
Khibiny	Melteigite-urtite	Nepheline		Late magmatic (?)	[10]
Khibiny	Rischorrite	Nepheline, aegirine, amphibole		Late magmatic (?)	[10]
Khibiny	Apatite-nepheline rocks	Nepheline, aegirine, amphibole		Late magmatic (?)	[10]
Khibiny	Pegmatites	Nepheline, feldspars, aegirine, eudialyte, lomonosovite, ancylite, strontianite, apatite, cancrinite, villiaumite, analcime, pectolite	Sr-lamprophyllite and high-'K Ba-lamprophyllite, usually high-Mn	Pegmatitic	[1, 8, 10, 19-21] Chukanov's and Lisitsin's data
Khibiny	Fenites	Ilmenite, sphene, lorenzenite, eudialyte, nepheline, feldspar, pyroxene		Metasomatic	[30]
Khibiny	Apophyllite veins	Sodalite, natrolite, cancrinite, microcline, rhyncholite, apophyllite, loparite, opal, fluorite, calcite, aegirine, eudialyte, apatite, arfvedsonite	High-Mn Sr-lamprophyllite	Hydrothermal	[9]
Yllymakh	Metasomatites	Sr-lamprophyllite and high-K Ba-lamprophyllite, usually high-Mn	High-Mn Sr-lamprophyllite	Metasomatic	[2]

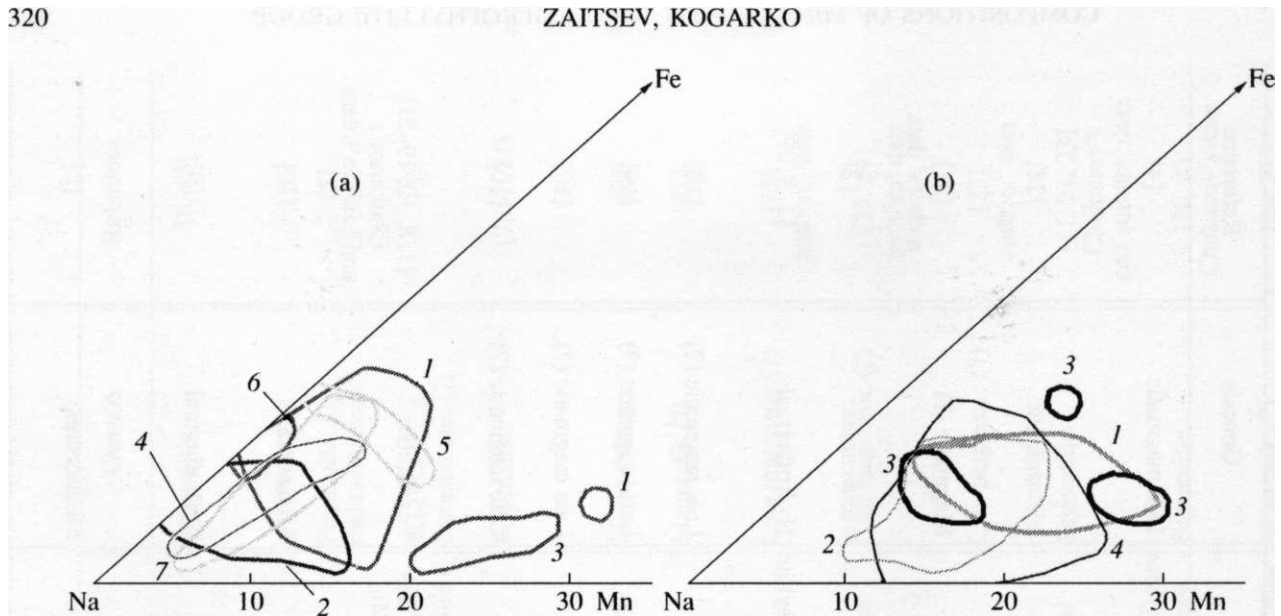


Fig. 3. Compositions of lamprophyllites from alkaline massifs worldwide in the Fe-Na-Mn diagram. See Fig. 1 for explanation of fields.

prophyllites from the differentiated complex and porphyritic lujavrites of the Lovozero Massif.

Thus, the occupation of the M(2) site in lamprophyllites varies between different massifs and within individual massifs.

Titanium is probably replaced by Fe, Mg, and Al in the lamprophyllite structure [15, 17]. However, among these elements, only Mg shows a significant negative correlation with Ti.

By analogy with other "titanosilicate micas", we believe that the Ti site can also be occupied by Nb and Zr. This is verified by the significant negative coefficient of Nb correlation with Ti. Concentrations of Zr and Nb are low: mean Nb contents are 0.01-0.03 f.u. (up to 0.05 in rare analyses). Khomyakov [11] described lamprophyllite with 0.2 f.u. Nb from the Yubileynaya vein in the Lovozero Massif. Zirconium is normally not analyzed. Its contents in the available microprobe and chemical analyses do not exceed 0.04 f.u.

The O(1) site is included in the hydroxyl group, which is replaced by F and Cl. The fluorine contents in lamprophyllite normally range from 0.5 to 1.0 f.u. However, low-F lamprophyllites (0.32 f.u., on average) are typical of the Inagli Massif, while high-F lamprophyllite varieties (up to 2 f.u.) are observed in the Turii Mys and Khibiny massifs. The F-rich analogs of lamprophyllite, baritolamprophyllite, and K-baritolamprophyllite could be described as new mineral species.

Data on the Cl concentrations in lamprophyllite are scarce. The available analyses contain up to 0.15 f.u. Cl.

The lamprophyllite compositions can be classified by cation amounts in the M(1) site and by Mn content. The distribution of lamprophyllites of various chemical types are characterized in Table 6.

We compared these data with the distribution of K and Mn in alkaline complexes containing lamprophyllite (Table 7). There is a positive correlation between Mn concentrations in rocks and lamprophyllites for the Khibiny, Lovozero, and Pilanesberg massifs. However,

Table 7. K₂O and MnO contents in the rocks of some alkaline massifs

Massif	K ₂ O, %	MnO, %	Reference
Khibiny	6.15	0.20	[31]
Lovozero Massif			
differentiated complex	5.31	0.29	[23]
eudialyte complex	4.60	0.45	[23]
Oldoinyo Lengai, lavas	4.38-5.43	0.34-0.39	[4]
Pilanesberg, foyaites	5.41	0.60	[32]
lujavrites	2.78	0.62	[32]

the relatively Mn-rich rocks of Oldoinyo Lengai Volcano include low-Mn lamprophyllites.

Among the massifs under consideration, the Khibiny Massif has the highest K₂O content in its rocks. The Ba-lamprophyllites from this massif are richest in potassium. The high-K Ba-lamprophyllite is also typical of Oldoinyo Lengai, whose lavas are comparable with the rocks of the eudialyte complex of the Lovozero Massif in K₂O concentrations. The latter, however, includes low-K lamprophyllites.

The paragenetic analysis shows that lamprophyllites are usually confined to the latest differentiates that are enriched in incompatible elements accumulated during magma evolution. The crystallization of minerals of the lamprophyllite group corresponds to a certain level of alkaline magma differentiation. The variations of the lamprophyllite compositions comply with the evolution of highly differentiated alkaline magmas. The lamprophyllite composition is related to the initial magma composition and physicochemical conditions (pressure, temperature, and fluid component fugacities), which affect the thermodynamic activities of the lamprophyllite components.

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REFERENCES

- Kapustin, Yu.L., Recent Finds of Barytolamprophyllite and the Lamprophyllite Formula, *Dokl. Akad. Nauk SSSR*, 1973, vol. 210, no. 4, pp. 921-924.
- Kravchenko, S.M., Kapustin, Yu.L., Kataeva, Z.T., and Bykova, A.P., Aegirite Mineralization of Mesozoic Alkaline Potassium-Rich Metasomatites of the Central Aldan, *Dokl. Akad. Nauk SSSR*, 1982, vol. 263, no. 2, pp. 435-439.
- Evdokimov, M.D., *Fenite Tur'inskogo shchelochnogo kompleksa KoUskogo poluostrova (mineral'nye assotsiatsii i geokhimicheskie osobennosti)* (Fenites of Tur'ya Alkaline Complex of the Kola Peninsula), Leningrad: Lening. Gos. Univ., 1982.
- Dawson, J.B., Peralkaline Nephelinite-Natrocarnatite Relationships at Oldoinyo Lengai, Tanzania, *J. Petrol.*, 1998, vol. 39, no. 11-12, pp. 2077-2094.
- Johnsen, O., Nielsen, T.F.D., and Ronsbo, J.G., Lamprophyllite and Barytolamprophyllite from the Tertiary Gardiner Complex, East Greenland, *Neues Jahrb. Mineral.*, 1994, no. 7, pp. 328-336.
- Chakhmouradian, A.R. and Mitchell, R.H., Primary, Aegirite, and Deuteric Stages in the Evolution of Accessory Sr, REE, Ba, and Nb-Mineralization in Nepheline-Syenite Pegmatites at Pegmatite Peak, Bearpaw Mts, Montana, *Mineral. Petrol.*, 1999, vol. 67, nos. 1-2, pp. 85-110.
- Lazebnik, K.A., Zayakina, N.V., and Paukevich, G.S., Strontium-Free Lamprophyllite: A New Member of the Lamprophyllite Group, *Dokl. Ross. Akad. Nauk*, 1998, vol. 361, no. 6, pp. 799-802.
- Kalenchuk, G.E. and Zabavnikova, N.I., Determination of Alkali and Alkali-Earth Elements in Lamprophyllite and Specification of Its Formula, in *Khimicheskie i fiziko-khimicheskie metody analiza rud, porod i mineralov* (Chemical and Physicochemical Methods for Analyzing Ores, Rocks, and Minerals), Moscow, 1974, pp. 26-30.
- Barabanov, V.F., The Mineralogy of Apophyllite Veins of the Yukspor Mountain, the Khibina Tundra, in *Voprosy geologii i mineralogii Kovskogo poluostrova* (Geological and Mineralogical Problems of Kola Peninsula), Moscow: Akad. Nauk SSSR, 1960, vol. 3, pp. 161-218.
- Mineralogiya Khibinskogo massiva* (The Mineralogy of Khibina Pluton), Chukhrov, F.V., Ed., Nauka, 1978.
- Khomyakova, A.P., *Mineralogiya uVtraagpaitovykh shchelochnykh porod* (The Mineralogy of Ultraaegirite Alkaline Rocks), Moscow: Nauka, 1990.
- Woodrow, P.J., The Crystal Structure of Lamprophyllite, *Nature* (London), 1964, vol. 204, no. 4956, p. 375.
- Safyanov, Yu.N., Vasil'eva, V.N., Golovachev, V.P., et al., Crystal Structure of Lamprophyllite, *Dokl. Akad. Nauk SSSR*, 1983, vol. 269, no. 1, pp. 117-120.
- Rastsvetaeva, R.K., Sokolova, M.N., and Gusev, A.I., Specified Structure of Lamprophyllite, *Mineral. Zh.*, 1990, vol. 12, no. 5, pp. 25-28.
- Rastsvetaeva, R.K. and Dorfman, M.D., Crystal Structure of Ba-Lamprophyllite in the Lamprophyllite-Barytolamprophyllite Isomorphous Series, *Kristallografiya*, 1995, vol. 40, no. 6, pp. 1026-1029.
- Rastsvetaeva, R.K., Evsyunin, V.G., and Konev, A.A., Crystal Structure of K-Barytolamprophyllite, *Kristallografiya*, 1995, vol. 40, no. 3, pp. 517-519.
- Rastsvetaeva, R.K. and Chukanov, N.V., The Crystal Structure of the Recently Identified Ba-Rich Lamprophyllite with a Primitive Lattice, *Dokl. Ross. Akad. Nauk*, 1999, vol. 386, no. 4, pp. 492-495.
- Afifi, A.A. and Azen, S.P., *Statistical Analysis: A Computer-Oriented Approach*, New York: Academic, 1979. Translated under the title *Statisticheskii analiz: podkhod s ispol'zovaniem EVM*, Moscow: Mir, 1982.
- Belyaevskaya, G.P. and Borutskii, B.E., The Accordance of the Chemical Composition of Lamprophyllite with Its Crystal Structure, *Dokl. Ross. Akad. Nauk*, 1993, vol. 328, no. 1, pp. 90-93.
- Pekov, I.V., Chukanov, N.V., and Turchkova, A.G., The Mineralogy and Behavior of Barium in Alkaline Differentiates of the Khibina Pluton, Kola Peninsula, *Tezisy dokladov XIX Vserossiiskogo seminar a s uchastiem strati SNG "Geokhimiya magmatischeskikh porod"* (Abstracts of Pap. XIX Vseross. Conf. with CIS Participants "Geochemistry Magmatic Rocks"), Moscow, 2000, pp. 111-112.
- Mineraly, spravochnik* (Minerals. Reference Book), Moscow: Nauka, 1972, vol. 3, issue 1.
- Zalishchak, B.L., *Koksharovskii massiv uVtroosnovnykh i shchelochnykh porod (Yuzhnoe Primor'e)* (The Koksharov Pluton of Ultrabasic and Alkaline Rocks in the Southern Primor'e), Moscow: Nauka, 1969.
- Bussen, IV. and Sakharov, A.S., *Petrologiya Lovozerskogo massiva* (The Petrology of the Lovozero Pluton), Nauka: Leningrad, 1972.

24. Kogarko, L.N., Williams, C.T., and Wooley, A.R., Chemical Evolution and Petrogenetic Implications of Loparite in the Layered, Agpaitic Lovozero Complex, Kola Peninsula, Russia, *Mineral. Petrol.*, 2002, vol. 74, pp. 1-74.
25. Konev, A.A., Vorob'ev, E.I., and Lazebnik, K.A., *Mineralogiya Murunskogo shchelochnogo massiva* (The Mineralogy of the Murun Alkaline Pluton), Novosibirsk: Ob'ed. Inst. Geol. Geoflz. Nauchno-Issled. Tsent. Sib. Otd. Ross. Akad. Nauk, 1996.
26. Arzamastsev, A.A., Chashchin, V.V., and Arzamastseva, L.V., The Niva Pluton: An Agpaitic Magmatism Occurrence Recently Found in the Kola Alkaline Province, *Dokl. Ross. Akad. Nauk*, 1999, vol. 365, no. 5, pp. 653-656.
27. Arzamastseva, L.V., Belyatskii, B.V., and Arzamastsev, A.A., An Agpaitic Magmatism Occurrence Recently Found in the Kola Alkaline Province: Isotope-Geochemical Studies of Rocks and Xenoliths, *Tezisy dokladov XIX Vserossiiskogo seminara s uchastiem stran SNG "Geokhimiya magmaticheskikh porod"* (Abstracts of Pap. XIX Vseross. Conf. with CIS Participants "Geochemistry Magmatic Rocks"), Moscow, 2000, pp. 17-18.
28. Haggerty, S.E. and Mariano, A.N., Strontian-Loparite and Strontio-Chevkenite: Two New Minerals in Rheomorphic Fenites from the Parana Basin Carbonatites, South America, *Contrib. Mineral. Petrol.*, 1983, vol. 84, pp. 365-381.
29. *Kaledonskii kompleks uVtraosnovnykh, shchelochnykh porod i karbonatitov Kol'skogo poluostrova i Karelii* (Caledonian Complex of Ultrabasic-Alkaline Rocks and Carbonatites in the Kola Peninsula and Karelia), Kukharenko, A.A., Ed., Moscow: Nedra, 1965.
30. Tikhonenkova, R.P. and Skosyreva, M.V., Accessory Minerals from Fenites of the Khibina Pluton, in *Mineralogiya pegmatitov i gidrotermalitov shchelochnykh massivov* (The Mineralogy of Pegmatites and Hydrothermally Altered Rocks of Alkaline Plutons), Moscow: Nauka, 1967, pp. 85-102.
31. Galakhov, A.V., *Petrologiya Khibinskogo shchelochnogo massiva* (The Petrology of the Khibina Alkaline Pluton), Leningrad: Nauka, 1975.
32. Shand, S.J., The Geology of Pilansberg in the Western Transvaal: A Study of Alkaline Rocks and Ring Intrusions, *Trans. Geol. Soc. South Africa*, 1928, vol. 31.